

PUBLICLY AVAILABLE SPECIFICATION

PRE-STANDARD



**The Qi wireless power transfer system – Power class 0 specification –
Part 2: Reference Designs Version.1.1.2**

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.240.99; 33.160.99; 35.200

ISBN 978-2-8322-4459-3

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

THE QI WIRELESS POWER TRANSFER SYSTEM – POWER CLASS 0 SPECIFICATION –

Part 2: Reference Designs Version.1.1.2

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100/2827/PAS	100/2862/RVDPAS

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1 General

1.1 Introduction

The Wireless Power Consortium (WPC) is a worldwide organization that aims to develop and promote global standards for wireless power transfer in various application areas. A first application area is wireless charging of low and medium power devices, such as mobile phones and tablet computers. The Wireless Power Consortium maintains the Qi logo for this application area.

1.2 Scope

This document, *Part 4: Reference Designs*, comprises reference designs for Power Class 0 Base Stations and Mobile Devices. Power Class 0 is the WPC designation for flat-surface devices, such as chargers, mobile phones, tablets, cameras, and battery packs, in the Baseline Power Profile (≤ 5 W) and Extended Power Profile (≤ 15 W).

1.2.1 Current Specification structure (introduced in version 1.2.1)

The Qi Wireless Power Transfer System for Power Class 0 Specification consists of the following documents.

- *Parts 1 and 2: Interface Definitions*
 - *Part 1: Primary Interface Definition*
 - *Part 2: Secondary Interface Definition*
- *Part 3: Compliance Testing*
- ***Part 4: Reference Designs*** (this document)

NOTE WPC publications prior to version 1.2.1 were structured differently, and are listed in Section 1.2.2 below. In particular, the Low Power and Medium Power publications were divided into separate System Description documents. Beginning with version 1.2.1, the Low Power and Medium Power System Descriptions have been merged into the Specification structure shown in this section. Additionally, the terms *Low Power* and *Medium Power* have been replaced in the current Specification by the terms *Baseline Power Profile* and *Extended Power Profile* respectively.

1.2.2 Earlier Specification structure (version 1.2.0 and below)

Before release 1.2.1, the Wireless Power Transfer specification comprised the following documents.

- System Description, Wireless Power Transfer, Volume I: Low Power, Part 1: Interface Definition.
- System Description, Wireless Power Transfer, Volume I: Low Power, Part 2: Performance Requirements.
- System Description, Wireless Power Transfer, Volume I: Low Power, Part 3: Compliance Testing.
- System Description, Qi Wireless Power Transfer, Volume II: Medium Power.

1.3 Main features

- A method of contactless power transfer from a Base Station to a Mobile Device that is based on near field magnetic induction between coils.
- A Baseline Power Profile supporting transfer of up to about 5 W and an Extended Power Profile supporting transfer of up to about 15 W of power using an appropriate Secondary Coil (having a typical outer dimension of around 40 mm).
- Operation at frequencies in the 87...205 kHz range.
- Support for two methods of placing the Mobile Device on the surface of the Base Station:
 - Guided Positioning helps a user to properly place the Mobile Device on the surface of a Base Station that provides power through a single or a few fixed locations of that surface.
 - Free Positioning enables arbitrary placement of the Mobile Device on the surface of a Base Station that can provide power through any location of that surface.
- A simple communications protocol enabling the Mobile Device to take full control of the power transfer.
- Considerable design flexibility for integration of the system into a Mobile Device.
- Very low stand-by power achievable (implementation dependent).

1.4 Conformance and references

1.4.1 Conformance

All provisions in The Qi Wireless Power Transfer System, Power Class 0 Specification are mandatory, unless specifically indicated as recommended, optional, note, example, or informative. Verbal expression of provisions in this Specification follow the rules provided in Annex H of ISO/IEC Directives, Part 2. For clarity, the word “**shall**” indicates a requirement that is to be followed strictly in order to conform to The Qi Wireless Power Transfer System, Power Class 0 Specification, and from which no deviation is permitted. The word “**should**” indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required, or that in the negative form a certain possibility or course of action is deprecated but not prohibited. The word “**may**” indicates a course of action permissible within the limits of The Qi Wireless Power Transfer System, Power Class 0 Specification. The word “**can**” indicates a possibility or capability, whether material, physical, or causal.

1.4.2 References

For undated references, the most recently published Specification applies. The most recent WPC publications can be downloaded from <http://www.wirelesspowerconsortium.com>. (See Section 1.2.1 for a list of documents included in The Qi Wireless Power Transfer System for Power Class 0 Specification.) In addition, the following documents are referenced within The Qi Wireless Power Transfer System for Power Class 0 Specification.

- Product Registration Procedure Web page (WPC Web site for members, Testing & Registration section)
- Qi Product Registration Manual, Logo Licensee/Manufacturer
- Qi Product Registration Manual, Authorized Test Lab
- Power Receiver Manufacturer Codes, Wireless Power Consortium
- The International System of Units (SI), Bureau International des Poids et Mesures

1.5 Definitions

Active Area	The part of the Interface Surface of a Base Station or Mobile Device through which a sufficiently high magnetic flux penetrates when the Base Station is providing power to the Mobile Device.
Base Station	A device that is able to provide near field inductive power as specified in The Qi Wireless Power Transfer System, Power Class 0 Specification. A Base Station carries a logo to visually indicate to a user that the Base Station complies with The Qi Wireless Power Transfer System, Power Class 0 Specification.
Baseline Power Profile	The minimum set of features applying to Power Transmitters and Power Receivers that can transfer no more than around 5 W of power.
Communications and Control Unit	The functional part of a Power Transmitter or Power Receiver that controls the power transfer. NOTE With regard to implementation, the Communications and Control Unit may be distributed over multiple subsystems of the Base Station or Mobile Device.
Control Point	The combination of voltage and current provided at the output of the Power Receiver, and other parameters that are specific to a particular Power Receiver implementation.
Detection Unit	The functional part of a Power Transmitter that detects the presence of a Power Receiver on the Interface Surface.
Digital Ping	The application of a Power Signal in order to detect and identify a Power Receiver.
Extended Power Profile	The minimum set of features applying to Power Transmitters and Power Receivers that can transfer power above 5 W.
Free Positioning	A method of positioning a Mobile Device on the Interface Surface of a Base Station that does not require the user to align the Active Area of the Mobile Device to the Active Area of the Base Station.
Foreign Object	Any object that is positioned on the Interface Surface of a Base Station, but is not part of a Mobile Device.

Foreign Object Detection

A process that a Power Transmitter or Power Receiver executes in order to determine if a Foreign Object is present on the Interface Surface.

Friendly Metal A part of a Base Station or a Mobile Device in which a Power Transmitter's magnetic field can generate eddy currents.

Guaranteed Power The amount of output power of an appropriate reference Power Receiver that the Power Transmitter ensures is available at any time during the power transfer phase. For Power Transmitters that comply with the Baseline Power Profile, the reference is TPR#1A, which is defined in *Part 3: Compliance Testing*. For Power Transmitters that comply with the Extended Power Profile, the reference is TPR#MP1B, which is also defined in *Part 3: Compliance Testing*.

Guided Positioning A method of positioning a Mobile Device on the Interface Surface of a Base Station that provides the user with feedback to properly align the Active Area of the Mobile Device to the Active Area of the Base Station.

Interface Surface The flat part of the surface of a Base Station that is closest to the Primary Coil(s), or the flat part of the surface of the Mobile Device that is closest to the Secondary Coil.

Maximum Power The maximum amount of power that a Power Receiver expects to provide at its output throughout the power transfer phase. The Maximum Power serves as a scaling factor for the Received Power Values that a Power Receiver reports in its Received Power Packets.

Mobile Device A device that is able to consume near field inductive power as specified in The Qi Wireless Power Transfer System, Power Class 0 Specification. A Mobile Device carries a logo to visually indicate to a user that the Mobile Device complies with the Specification.

Operating Frequency The oscillation frequency of the Power Signal.

Operating Point The combination of the frequency, duty cycle, and amplitude of the voltage that is applied to the Primary Cell.

Packet A data structure for communicating a message from a Power Receiver to a Power Transmitter or vice versa. A Packet consists of a preamble, a header byte, a message, and a checksum. A Packet is named after the kind of message that it contains.

Potential Power	The amount of output power by an appropriate reference Power Receiver that the Power Transmitter can make available during the power transfer phase. For Power Transmitters that comply with the Baseline Power Profile, the reference is TPR#1A, which is defined in <i>Part 3: Compliance Testing</i> . For Power Transmitters that comply with the Extended Power Profile, the reference is TPR#MP1B, which is also defined in <i>Part 3: Compliance Testing</i> .
Power Conversion Unit	The functional part of a Power Transmitter that converts electrical energy to a Power Signal.
Power Factor	The ratio of the active power consumed and the apparent power drawn. The active power is expressed in watts. The apparent power typically is expressed in volt-amperes (VA).
Power Pick-up Unit	The functional part of a Power Receiver that converts a Power Signal to electrical energy.
Power Receiver	The subsystem of a Mobile Device that acquires near field inductive power and controls its availability at its output, as defined in The Qi Wireless Power Transfer System, Power Class 0 Specification. For this purpose, the Power Receiver communicates its power requirements to the Power Transmitter.
Power Signal	The oscillating magnetic flux that is enclosed by a Primary Cell and possibly a Secondary Coil.
Power Transfer Contract	A set of boundary conditions on the parameters that characterize the power transfer from a Power Transmitter to a Power Receiver. Violation of any of these boundary conditions causes the power transfer to abort.
Power Transmitter	The subsystem of a Base Station that generates near field inductive power and controls its transfer to a Power Receiver, as defined in The Qi Wireless Power Transfer System, Power Class 0 Specification.
Primary Cell	A single Primary Coil or a combination of Primary Coils that are used to provide a sufficiently high magnetic flux through the Active Area.
Primary Coil	A component of a Power Transmitter that converts electric current to magnetic flux.

Received Power	The total amount of power dissipated inside a Mobile Device, due to the magnetic field generated by a Power Transmitter. The Received Power includes the power that the Power Receiver makes available at its output for use by the Mobile Device, any power that the Power Receiver uses for its own purposes, as well as any power that is lost within the Mobile Device.
Reference Quality Factor	The quality-factor of Test Power Transmitter #MP1's Primary Coil at an Operating Frequency of 100 kHz, with a Power Receiver positioned on the Interface Surface and no Foreign Object nearby.
Response	A sequence of eight consecutive bi-phase modulated bits transmitted by a Power Transmitter in response to a request from a Power Receiver.
Secondary Coil	The component of a Power Receiver that converts magnetic flux to electromotive force.
Shielding	A component in the Power Transmitter that restricts magnetic fields to the appropriate parts of the Base Station, or a component in the Power Receiver that restricts magnetic fields to the appropriate parts of the Mobile Device.
Specification	The set of documents, Parts 1 through 4, that comprise The Qi Wireless Power Transfer System, Power Class 0 Specification (see Section 1.2.1).
Transmitted Power	The total amount of power dissipated outside the Interface Surface of a Base Station, due to the magnetic field generated by the Power Transmitter.
WPID	A 48-bit number that uniquely identifies a Qi-compliant device.

1.6 Acronyms

AC	Alternating Current
ACK	Acknowledge
AWG	American Wire Gauge
BSUT	Base Station Under Test
CEP	Control Error Packet
DC	Direct Current
DCR	Direct Current Resistance

EM	Electro Magnetic
EMC	Electro Magnetic Compatibility
EMF	Electro Magnetic Fields
EPT	End Power Transfer
ESR	Equivalent Series Resistance
FET	Field Effect Transistor
FOD	Foreign Object Detection
FSK	Frequency-Shift Keying
LSB	Least Significant Bit
MSB	Most Significant Bit
MDUT	Mobile Device Under Test
N.A.	Not Applicable
NAK	Not-Acknowledge
ND	Not-Defined
PID	Proportional Integral Differential
PRx	Power Receiver
PTx	Power Transmitter
RMS	Root Mean Square
TPR	Test Power Receiver
UART	Universal Asynchronous Receiver Transmitter
USB	Universal Serial Bus
WPID	Wireless Power Identifier

1.7 Symbols

C_d	Capacitance parallel to the Secondary Coil [nF]
C_m	Capacitance in the impedance matching network [nF]
C_p	Capacitance in series with the Primary Coil [nF]
C_s	Capacitance in series with the Secondary Coil [nF]
d	Duty cycle of the inverter in the Power Transmitter
d_s	Distance between a coil and its Shielding [mm]
d_z	Distance between a coil and the Interface Surface [mm]
f_{CLK}	Communications bit rate [kHz]
f_d	Resonant detection frequency [kHz]
f_{op}	Operating Frequency [kHz]
f_s	Secondary resonance frequency [kHz]
I_m	Primary Coil current modulation depth [mA]
I_o	Power Receiver output current [mA]
I_p	Primary Coil current [mA]
L_m	Inductance in the impedance matching network [μ H]
L_p	Primary Coil self inductance [μ H]
L_s	Secondary Coil self inductance (Mobile Device away from Base Station) [μ H]
L'_s	Secondary Coil self inductance (Mobile Device on top of Base Station) [μ H]
P_{FO}	Power loss that results in heating of a Foreign Object [W]
P_{PR}	Total amount of power received through the Interface Surface [W]
P_{PT}	Total amount of power transmitted through the Interface Surface [W]
Q	Quality factor
t_{delay}	Power Control Hold-off Time [ms]

t_{CLK}	Communications clock period [μs]
t_{T}	Maximum transition time of the communications [μs]
V_{r}	Rectified voltage [V]
V_{o}	Power Receiver output voltage [V]

1.8 Conventions

This section defines the notations and conventions used in The Qi Wireless Power Transfer System, Power Class 0 Specification.

1.8.1 Cross references

Unless indicated otherwise, cross references to sections include the sub sections contained therein.

1.8.2 Informative text

Informative text is set in italics, unless the complete Section is marked as informative.

1.8.3 Terms in capitals

Terms having a specific meaning in the context of The Qi Wireless Power Transfer System, Power Class 0 Specification are capitalized and defined in Section 1.5.

1.8.4 Units of physical quantities

Physical quantities are expressed in units of the International System of Units.

1.8.5 Decimal separator

The decimal separator is a period.

1.8.6 Notation of numbers

- Real numbers are represented using the digits 0 to 9, a decimal point, and optionally an exponential part. In addition, a positive and/or negative tolerance indicator may follow a real number. Real numbers that do not include an explicit tolerance indicator, are accurate to half the least significant digit that is specified.

EXAMPLE A specified value of $1.23^{+0.01}_{-0.02}$ comprises the range from 1.21 through 1.24; a specified value of $1.23^{+0.01}$ comprises the range from 1.23 through 1.24; a specified value of $1.23_{-0.02}$ comprises the range from 1.21 through 1.23; a specified value of 1.23 comprises the range from 1.225 through 1.234999...; and a specified value of $1.23^{\pm 10\%}$ comprises the range from 1.107 through 1.353.

- Integer numbers in decimal notation are represented using the digits 0 to 9.
- Integer numbers in hexadecimal notation are represented using the hexadecimal digits 0 to 9 and A to F, and are prefixed by “0x” unless explicitly indicated otherwise.
- Single bit values are represented using the words ZERO and ONE.
- Integer numbers in binary notation and bit patterns are represented using sequences of the digits 0 and 1, which are enclosed in single quotes (e.g. ‘01001’). In a sequence of n bits, the most significant bit (MSB) is bit b_{n-1} and the least significant bit (LSB) is bit b_0 . The most significant bit is shown on the left-hand side.
- Numbers that are shown between parentheses are informative.

1.8.7 Bit ordering in a byte

The graphical representation of a byte is such that the most significant bit is on the left, and the least significant bit is on the right. Figure 1 defines the bit positions in a byte.

Figure 1. Bit positions in a byte

MSB				LSB			
b7	b6	b5	b4	b3	b2	b1	b0

1.8.8 Byte numbering

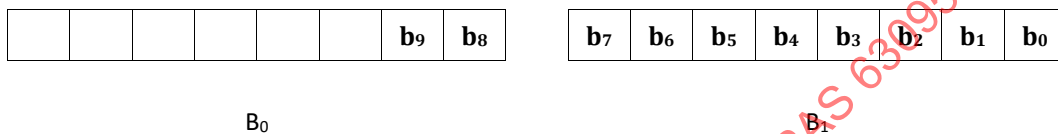
The bytes in a sequence of n bytes are referred to as $B_0, B_1, \dots, B_{n-1}$. Byte B_0 corresponds to the first byte in the sequence; byte B_{n-1} corresponds to the last byte in the sequence. The graphical representation of a byte sequence is such that B_0 is at the upper left-hand side, and byte B_{n-1} is at the lower right-hand side.

1.8.9 Multiple-bit fields

Multiple-bit fields are used in the ID Packet. Unless indicated otherwise, a multiple-bit field in a data structure represents an unsigned integer value. In a multiple-bit field that spans multiple bytes, the MSB of the multiple-bit field is located in the byte with the lowest address, and the LSB of the multiple-bit field is located in the byte with the highest address.

NOTE Figure 2 provides an example of a 6-bit field that spans two bytes.

Figure 2. Example of multiple-bit field



1.9 Operators

This section defines less-commonly used operators that are used in The Qi Wireless Power Transfer System, Power Class 0 Specification. The commonly used operators have their usual meaning.

1.9.1 Exclusive-OR

The symbol ' $\oplus$ ' represents the exclusive-OR operation.

1.9.2 Concatenation

The symbol '||' represents the concatenation of two bit strings. In the resulting concatenated bit string, the MSB of the right-hand side operand directly follows the LSB of the left-hand side operand.

1.10 Measurement equipment

All measurements shall be performed using equipment that has a resolution of at least one quarter of the precision of the quantity that is to be measured, unless indicated otherwise.

EXAMPLE "t_{start}=15 ms" means that the equipment shall be precise to 0.25 ms.

2 Power Transmitter reference designs

2.1 Introduction

The Power Transmitter designs that are defined in this *Part 4: Reference Designs*, are grouped in two basic types.

Type A Power Transmitter designs have one or more Primary Coils. They activate a single Primary Coil at a time and therefore employ a single Primary Cell that coincides with the activated Primary Coil. In addition, type A Power Transmitter designs include means to realize proper alignment of the Primary Coil and Secondary Coil. Depending on this means, a type A Power Transmitter enables either Guided Positioning or Free Positioning.

Type B Power Transmitter designs have an array of Primary Coils. All type B Power Transmitters enable Free Positioning. For that purpose, type B Power Transmitters can activate one or more Primary Coils from the array to realize a Primary Cell at different positions across the Interface Surface.

A Power Transmitter serves only one Power Receiver at a time only. However, a Base Station may contain several Power Transmitters in order to serve multiple Mobile Devices simultaneously. Note that multiple type B Power Transmitters may share (parts of) the multiplexer and array of Primary Coils (see Section 3.3.1.3).

NOTE Power Receivers that use thin magnetic Shielding have been found to experience reduced performance on Power Transmitters that contain a permanent magnet in or near the Active Area. Such Power Receivers may exhibit, for example, less positioning freedom and/or a longer charging time. For this reason Power Transmitter designs A1, A5, and A9 have been deprecated as of version 1.2 of the Qi Power Class 0 Specification.

The remaining Power Transmitter designs provided in this part 4 of the Qi Power Class 0 Specification do not use a permanent magnet. Product implementations based on these designs that include a permanent magnet in or near the Active Area are not compliant with this specification.

2.2 Baseline Power Profile designs that activate a single Primary Coil at a time

This Section 0 defines all type A Power Transmitter designs in the Baseline Power Profile. In addition to the definitions in this section, each Power Transmitter design shall implement the relevant parts of the protocols defined in the *Power Transmitter to Power Receiver communications interface* section in *Parts 1 and 2: Interface Definitions*.

2.2.1 Power Transmitter design A1

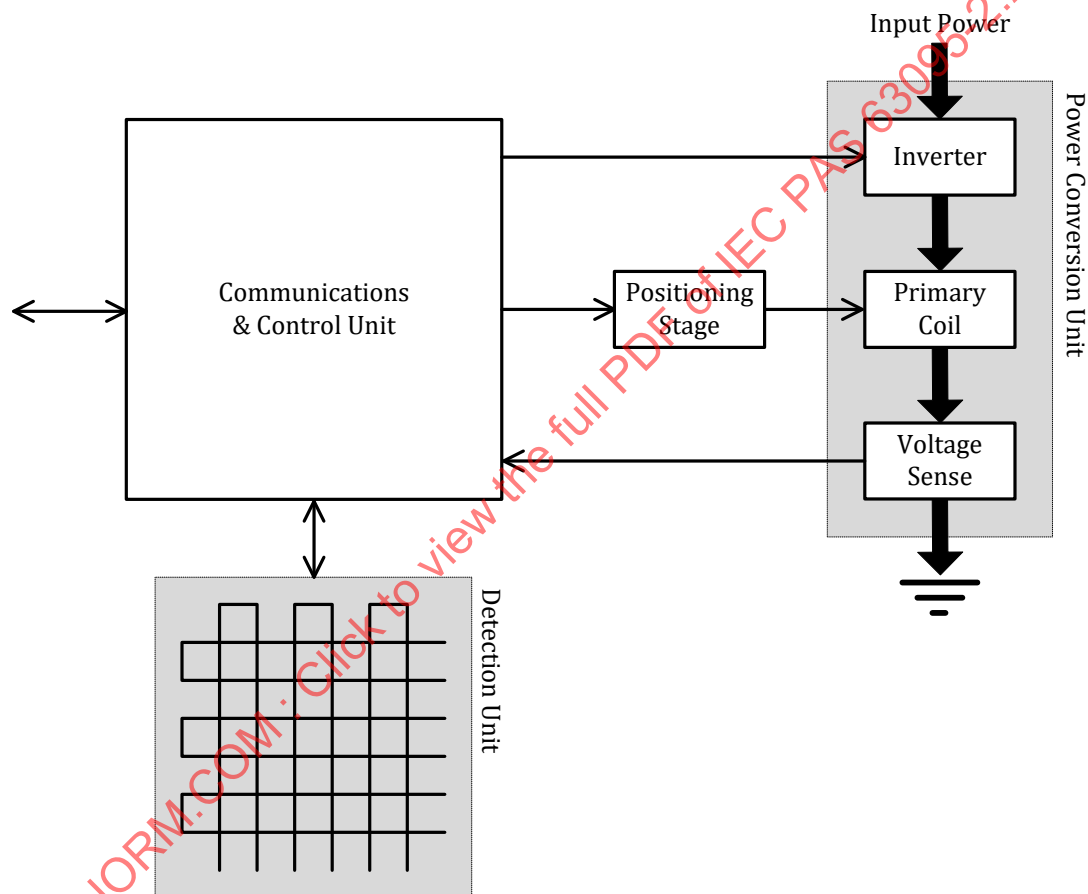
Power Transmitter design A1 has been deprecated. For further information, see the note in Section 2.1.

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2.2.2 Power Transmitter design A2

Power Transmitter design A2 enables Free Positioning. Figure 3 illustrates the functional block diagram of this design, which consists of three major functional units, namely a Power Conversion Unit, a Detection Unit, and a Communications and Control Unit.

Figure 3. Functional block diagram of Power Transmitter design A2



The Power Conversion Unit on the right-hand side of Figure 3 and the Detection Unit of the bottom of Figure 3 comprise the analog parts of the design. The Power Conversion Unit is similar to the Power Conversion Unit of Power Transmitter design A1. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. The Primary Coil is mounted on a positioning stage to enable accurate alignment of the Primary Coil to the Active Area of the Mobile Device. Finally, the voltage sense monitors the Primary Coil voltage.

The Communications and Control Unit on the left-hand side of Figure 3 comprises the digital logic part of the design. This unit is similar to the Communications and Control Unit of Power Transmitter design A1.

The Communications and Control Unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input voltage of the AC waveform to control the power transfer. In addition, the Communications and Control Unit drives the positioning stage and operates the Detection Unit. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

The Detection Unit determines the approximate location of objects and/or Power Receivers on the Interface Surface. This version of *Part 4: Reference Designs* does not specify a particular detection method. However, it is recommended that the Detection Unit exploits the resonance in the Power Receiver at the detection frequency f_d (see *Parts 1 and 2: Interface Definitions*). The reason is that this approach minimizes movements of the Primary Coil, because the Power Transmitter does not need to attempt to identify objects that do not respond at this resonant frequency. The *Moving Primary Coil based Free Positioning* section in *Parts 1 and 2: Interface Definitions* provides an example resonant detection method.

2.2.2.1 Mechanical details

Power Transmitter design A2 includes a single Primary Coil as defined in Section 2.2.2.1.1, Shielding as defined in Section 2.2.2.1.2, an Interface Surface as defined in Section 2.2.2.1.3, and a positioning stage as defined in Section 2.2.2.1.4

2.2.2.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 30 strands of 0.1 mm diameter, or equivalent. As shown in Figure 4. Primary Coil of Power Transmitter design A2, the Primary Coil has a circular shape and consists of multiple layers. All layers are stacked with the same polarity. Table 1 lists the dimensions of the Primary Coil.

Figure 4. Primary Coil of Power Transmitter design A2

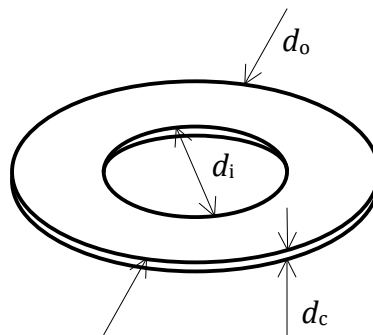


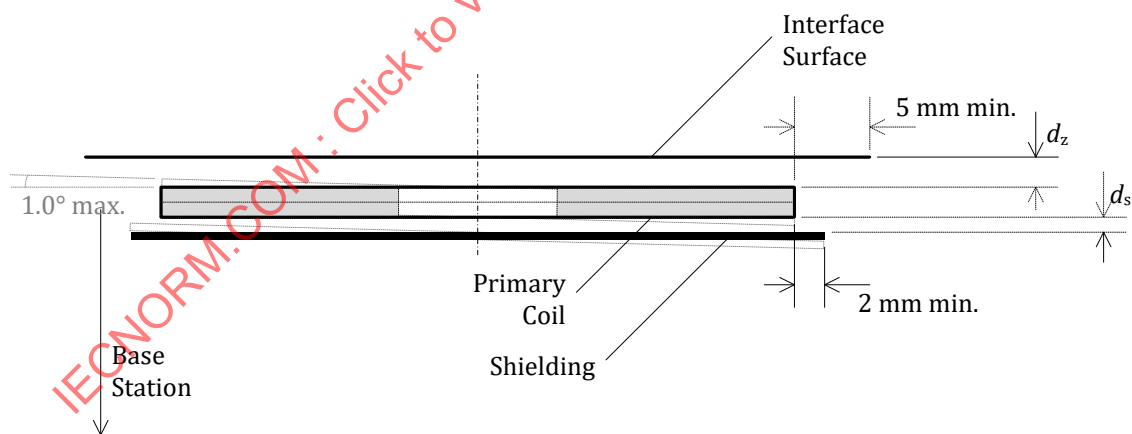
Table 1. Primary Coil parameters of Power Transmitter design A2

Parameter	Symbol	Value
Outer diameter	d_o	40^{+1} mm
Inner diameter	d_i	19^{+1} mm
Thickness	d_c	$2^{+0.2}$ mm
Number of turns per layer	N	10
Number of layers	–	2

2.2.2.1.2 Shielding

As shown in Figure 5, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 0.20 mm and is placed below the Primary Coil at a distance of at most $d_s = 0.1$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- DPR-MF3 — Daido Steel
- HS13-H — Daido Steel

Figure 5. Primary Coil assembly of Power Transmitter design A2

2.2.2.1.3 Interface Surface

As shown in Figure 5, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.5^{+0.5}_{-0}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.2.1.4 Positioning stage

The positioning stage shall have a resolution of 0.1 mm or better in each of the two orthogonal directions parallel to the Interface Surface.

2.2.2.2 Electrical details

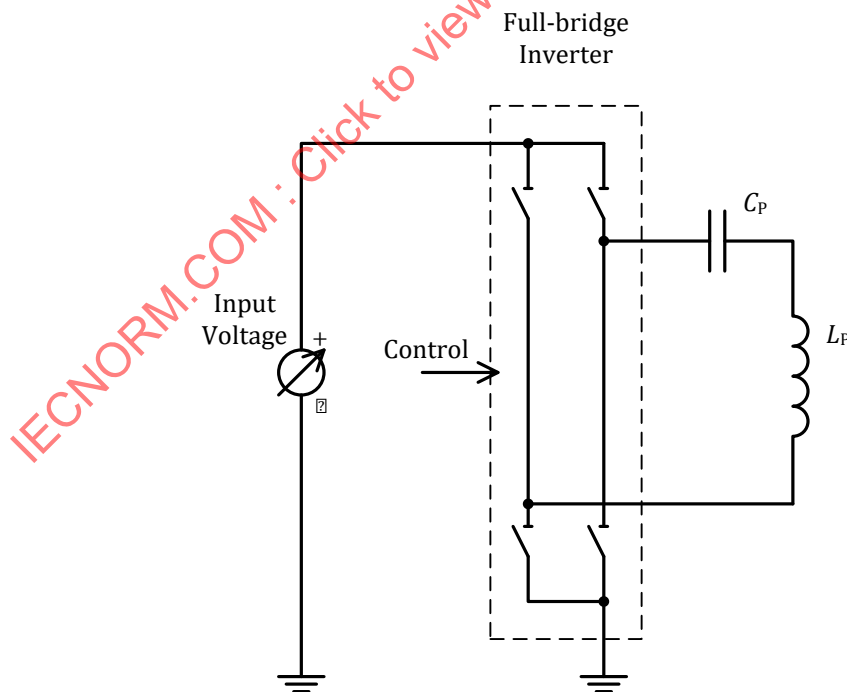
As shown in Figure 6, Power Transmitter design A2 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. At the fixed Operating Frequency of 140 kHz, the assembly of Primary Coil and Shielding has a self inductance $L_P = 24^{\pm 1} \mu\text{H}$. The value of the series capacitance is $C_P = 200^{\pm 5\%} \text{ nF}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 50 V pk-pk.

Power Transmitter design A2 uses the input voltage to the full-bridge inverter to control the amount of power that is transferred. For this purpose, the input voltage range is 3...12 V, where a lower input voltage results in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type A2 Power Transmitter shall be able to control the input voltage with a resolution of 50 mV or better.

When a type A2 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial input voltage of 8 V.

Figure 6. Electrical diagram (outline) of Power Transmitter design A2



Control of the power transfer shall proceed using the PID algorithm, which is defined in the *Power transfer control* section in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type A2 Power Transmitter shall determine the amplitude of the Primary Cell voltage—which is equal to the Primary Coil voltage—with a resolution of 5 mV or better. Finally, Table 2 provides the values of several parameters that are used in the PID algorithm.

Table 2. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA ⁻¹
Integral gain	K_i	0	mA ⁻¹ ms ⁻¹
Derivative gain	K_d	0	mA ⁻¹ ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	–0.5	mV

2.2.3 Power Transmitter design A3

Power Transmitter design A3 enables Free Positioning, and has a design similar to Power Transmitter design A2. See Section 0 for an overview.

2.2.3.1 Mechanical details

Power Transmitter design A3 includes a single Primary Coil as defined in Section 2.2.3.1.1, Shielding as defined in Section 2.2.3.1.2, an Interface Surface as defined in Section 2.2.3.1.3, and a positioning stage as defined in Section 2.2.3.1.4.

2.2.3.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 11 strands of 0.20 mm diameter, or equivalent. As shown in Figure 7, the Primary Coil has a circular shape and consists of a single layer. Table 3 lists the dimensions of the Primary Coil.

Figure 7. Primary Coil of Power Transmitter design A3

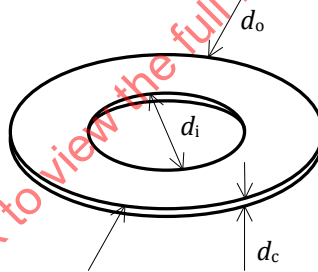


Table 3. Primary Coil parameters of Power Transmitter design A3

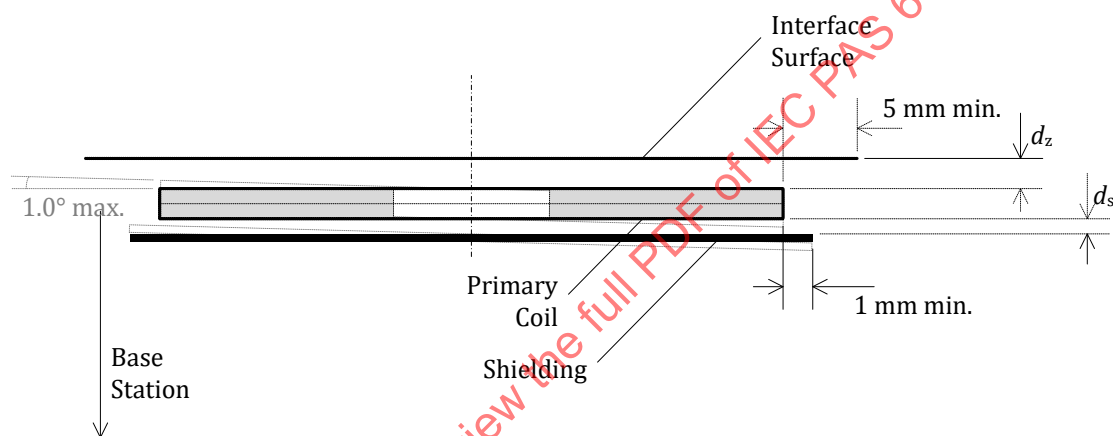
Parameter	Symbol	Value
Outer diameter	d_o	$33^{\pm 1}$ mm
Inner diameter	d_i	$10^{\pm 0.2}$ mm
Thickness	d_c	$1.8^{\pm 0.4}$ mm
Number of turns per layer	N	25
Number of layers	–	1

2.2.3.1.2 Shielding

As shown in Figure 8, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 1 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 0.60 mm and is placed below the Primary Coil at a distance of at most $d_s = 0.4$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- HS13-H — Daido Steel
- KNZWA20B356 — Panasonic

Figure 8. Primary Coil assembly of Power Transmitter design A3



2.2.3.1.3 Interface Surface

As shown in Figure 8, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.5^{+0.5}_{-0}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.3.1.4 Positioning stage

The positioning stage shall have a resolution of 0.1 mm or better in each of the two orthogonal directions parallel to the Interface Surface.

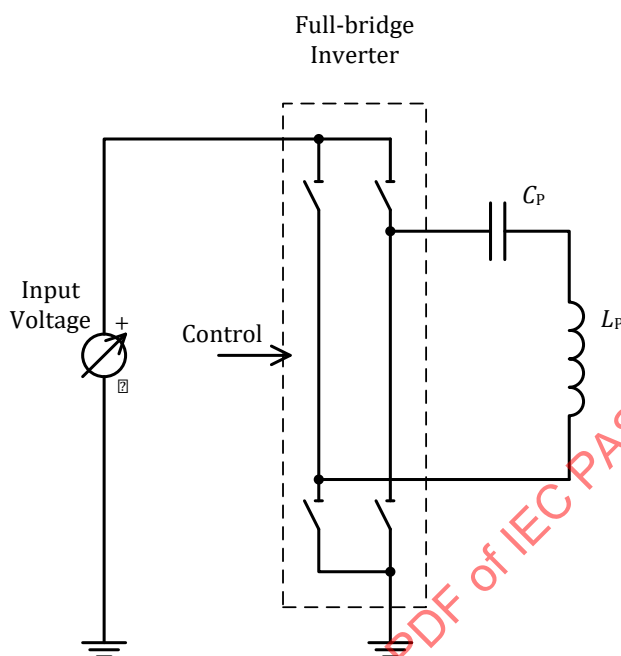
2.2.3.2 Electrical details

As shown in Figure 9, Power Transmitter design A3 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. At an Operating Frequency range between 105 kHz and 140 kHz, the assembly of Primary Coil and Shielding has a self inductance $L_p = 16.5^{\pm 10\%}$ μH . The value of the series capacitance is $C_p = 180^{\pm 5\%}$ nF.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A3 uses the input voltage to the full-bridge inverter to control the amount of power that is transferred. For this purpose, the input voltage range is 3...12 V, where a lower input voltage results in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type A3 Power Transmitter shall be able to control the input voltage with a resolution of 50 mV or better.

When a type A3 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial input voltage of 6 V. It is recommended that the Power Transmitter uses an Operating Frequency of 140 kHz when first applying the Power Signal. If the Power Transmitter does not to receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in Section *Parts 1 and 2: Interface Definitions*. The Power Transmitter may reapply the Power Signal multiple times at other—consecutively lower—Operating Frequencies within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 9. Electrical diagram (outline) of Power Transmitter design A3

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type A3 Power Transmitter shall determine the amplitude of the Primary Cell voltage—which is equal to the Primary Coil voltage—with a resolution of 5 mV or better. Finally, Table 4 provides the values of several parameters, which are used in the PID algorithm.

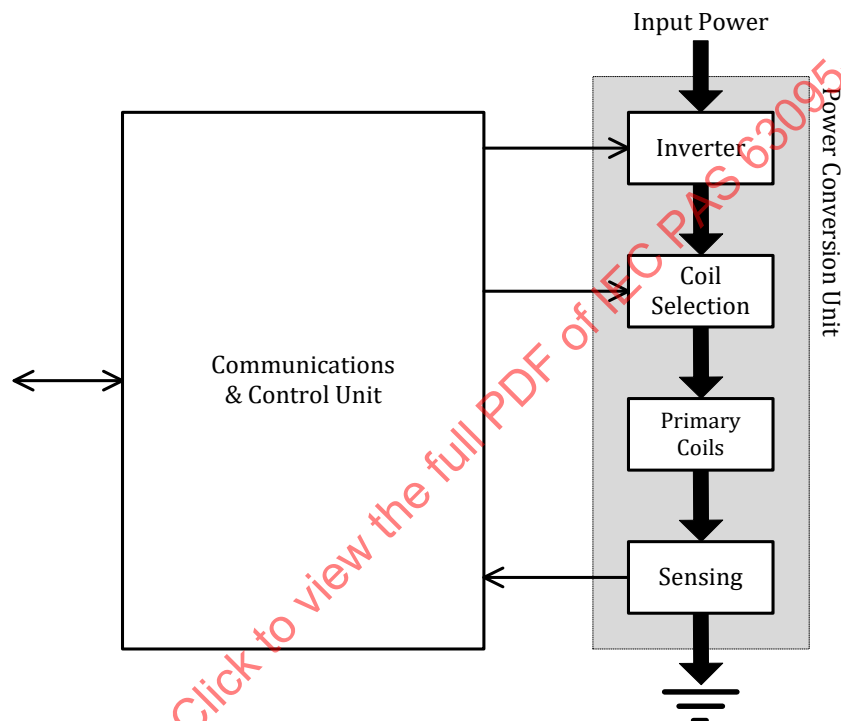
Table 4. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	–0.5	mV

2.2.4 Power Transmitter design A4

Power Transmitter design A4 enables Free Positioning. Figure 10 illustrates the functional block diagram of this design, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 10. Functional block diagram of Power Transmitter design A4



The Power Conversion Unit on the right-hand side of Figure 10 and the Detection Unit of the bottom of Figure 10 comprise the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from two partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the two Primary Coils. Selection of the Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using either Primary Coil. Finally, the voltage sense monitors the Primary Coil voltage and current.

The Communications and Control Unit on the left-hand side of Figure 10 comprises the digital logic part of the design. The Communications and Control Unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the input voltage of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.4.1 Mechanical details

Power Transmitter design A4 includes two Primary Coils as defined in Section 2.2.4.1.1, Shielding as defined in Section 2.2.4.1.2, and an Interface Surface as defined in Section 2.2.4.1.3.

2.2.4.1.1 Primary Coil

The Primary Coils are of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 11, a Primary Coil has a racetrack-like shape and consists of a single layer. Table 5 lists the dimensions of a Primary Coil.

Figure 11. Primary Coil of Power Transmitter design A4

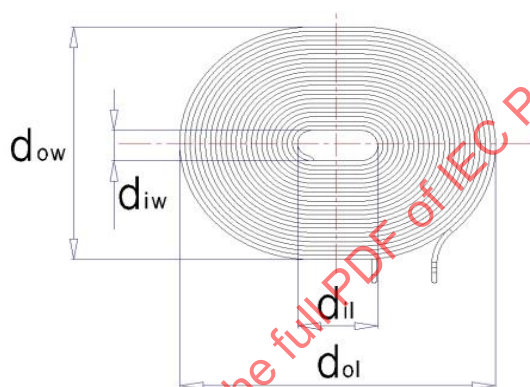
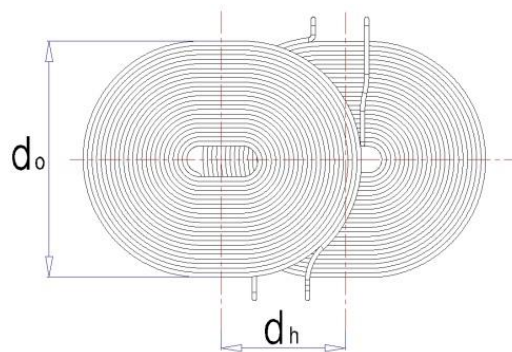


Table 5. Primary Coil parameters of Power Transmitter design A4

Parameter	Symbol	Value
Outer length	d_{ol}	$70^{\pm 0.5}$ mm
Inner length	d_{il}	$15^{\pm 0.5}$ mm
Outer width	d_{ow}	$59^{\pm 0.5}$ mm
Inner width	d_{iw}	$4^{\pm 0.5}$ mm
Thickness	d_c	$1.15^{\pm 0.05}$ mm
Number of turns per layer	N	23.5
Number of layers	–	1

Power Transmitter design A4 contains two Primary Coils, which are mounted in a Shielding block (see Section 2.2.4.1.2) with their long axes coincident, and a displacement of $d_h = 41^{\pm 0.5}$ mm between their centers. See Figure 12.

Figure 12. Dual Primary Coils (top view)

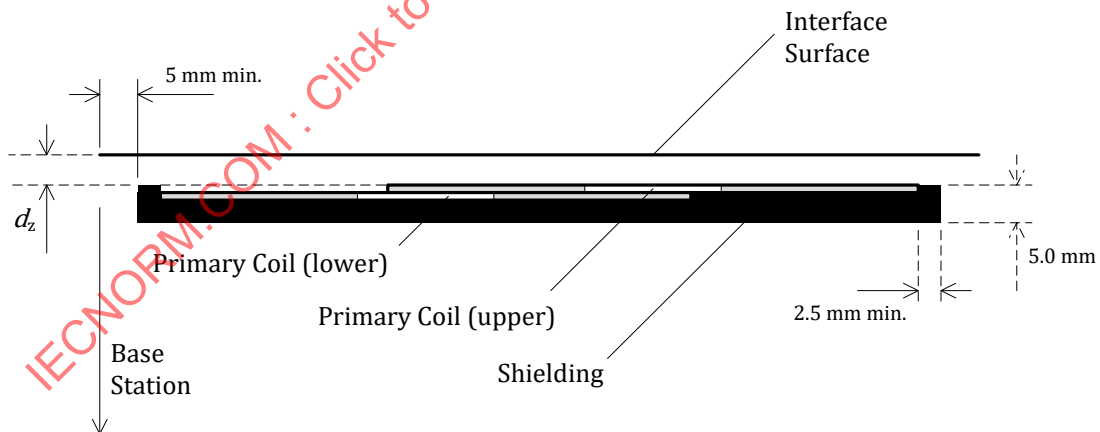


2.2.4.1.2 Shielding

As shown in Figure 13, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coils. The top face of the Shielding block is aligned with the top face of the Primary Coils, such that the Shielding surrounds the Primary Coils on all sides except for the top face. In addition, the Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coils, and has a thickness of at least 5 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Mn-Zn-Ferrite Dust Core — any supplier

Figure 13. Primary Coil assembly of Power Transmitter design A4



2.2.4.1.3 Interface Surface

As shown in Figure 13, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.0^{±0.5}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.4.1.4 Separation between multiple Power transmitters

In a Base Station that contains multiple type A4 Power Transmitters, the Primary Coil assemblies of any pair of Power Transmitter shall not overlap.

NOTE The two Primary Coils within an assembly do overlap as defined in Section 2.2.4.1.1.

2.2.4.2 Electrical details

As shown in Figure 14, Power Transmitter design A4 uses a full-bridge inverter to drive the Primary Coils and a series capacitance. In addition, Power Transmitter design A4 shall operate coil selection switches SWu and SWl such that only a single Primary Coil is connected to the inverter.

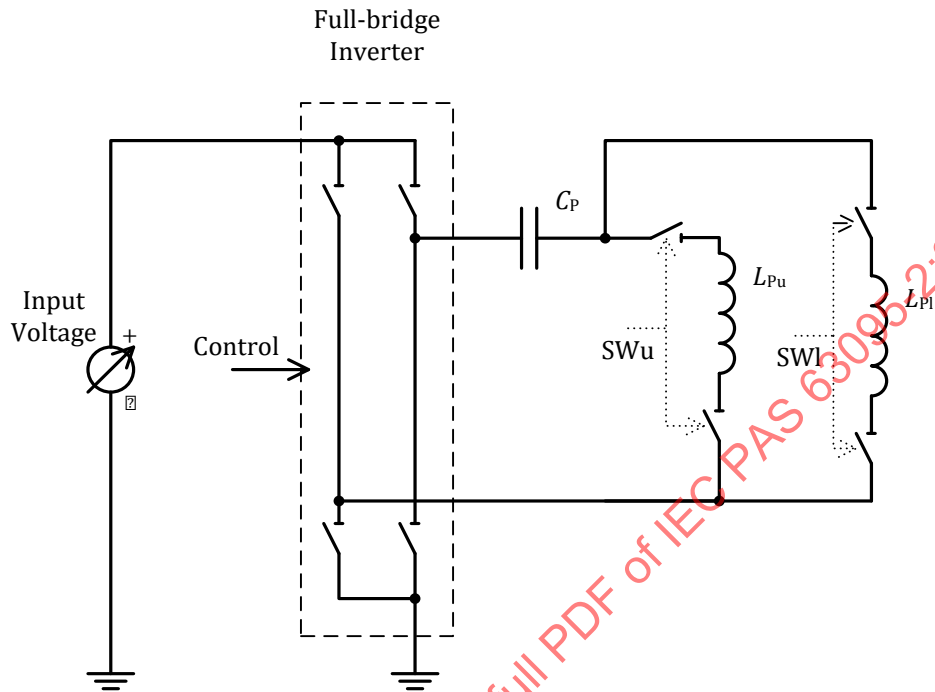
Within the Operating Frequency range of 110...180 kHz, each Primary Coil in the assembly of Primary Coils and Shielding has a self inductance $L_p = 24^{±0.5}$ µH. The value of the series capacitance is $C_p = 100^{±5\%}$ nF. The input voltage to the full-bridge inverter is 5...11 V.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 40 V pk-pk.

Power Transmitter design A4 uses the Operating Frequency and the input voltage to the full-bridge inverter to control the amount of power that is transferred. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type A4 Power Transmitter shall be able to control the frequency with a resolution of 0.5 kHz, and the input voltage with a resolution of 50 mV or better.

When a type A4 Power Transmitter first applies a Power Signal (Digital Ping; see *Part 4: Reference Designs*), the Power Transmitter shall use an Operating Frequency of 130 kHz, and an input voltage of 8 V. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Part 4: Reference Designs*. The Power Transmitter may reapply the Power Signal multiple times at an Operating Frequency of 130 kHz using consecutively higher input voltages within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 14. Electrical diagram (outline) of Power Transmitter design A4



Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(t)}$ introduced in the definition of that algorithm represents Operating Frequency as well as the input voltage to the full-bridge inverter. It is recommended that control of the power occurs primarily by means of adjustments to the Operating Frequency, and that voltage adjustments are made only at the boundaries of the Operating Frequency range. In order to guarantee sufficiently accurate power control, a type A4 Power Transmitter shall determine the amplitude of the Primary Coil current with a resolution of 5 mA or better. Finally, Table 6 and Table 7 provide the values of several parameters, which are used in the PID algorithm.

Table 6. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

Table 7. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	–0.5	mV

2.2.5 Power Transmitter design A5

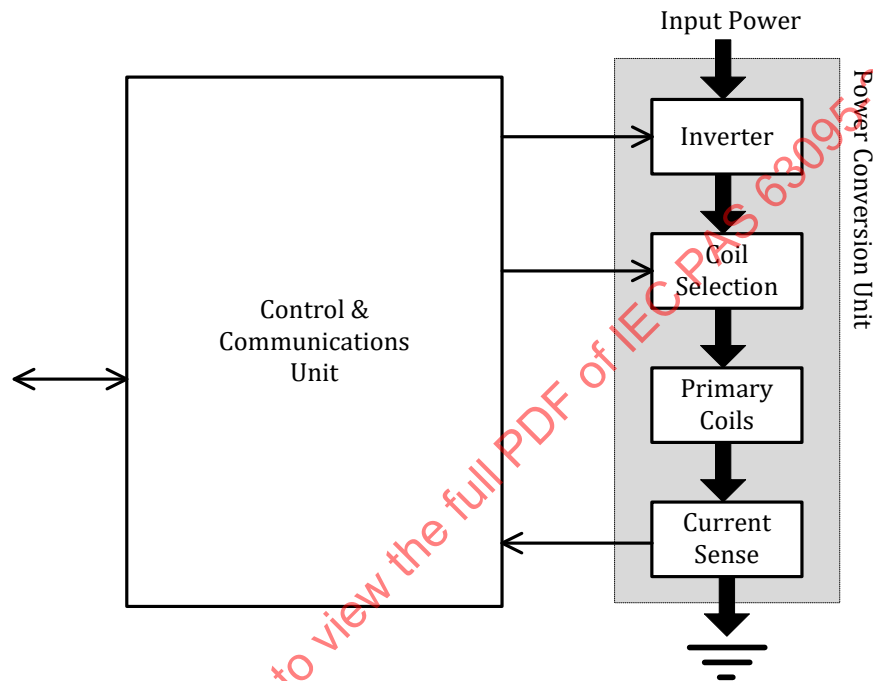
Power Transmitter design A5 has been deprecated. For further information, see the note in Section 2.1.

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2.2.6 Power Transmitter design A6

Figure 15 illustrates the functional block diagram of this design, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 15. Functional block diagram of Power Transmitter design A6



The Power Conversion Unit on the right-hand side of Figure 15 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from a linear array of partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the Primary Coils. Selection of the Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using any of the Primary Coils. Note that the array may consist of a single Primary Coil only, in which case the selection is trivial. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 15 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.6.1 Mechanical details

Power Transmitter design A6 includes one or more Primary Coils as defined in Section 2.2.6.1.1, Shielding as defined in Section 2.2.6.1.2, an Interface Surface as defined in Section 2.2.6.1.3.

2.2.6.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of no. 17 AWG (1.15 mm diameter) type 2 litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 16, the Primary Coil has a rectangular shape and consists of a single layer. Table 8 lists the dimensions of the Primary Coil.

Figure 16. Primary Coil of Power Transmitter design A6

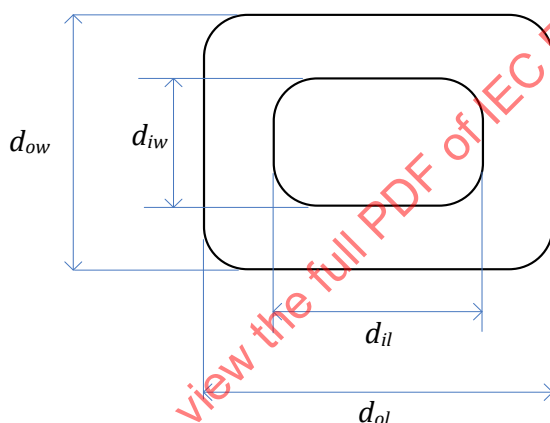
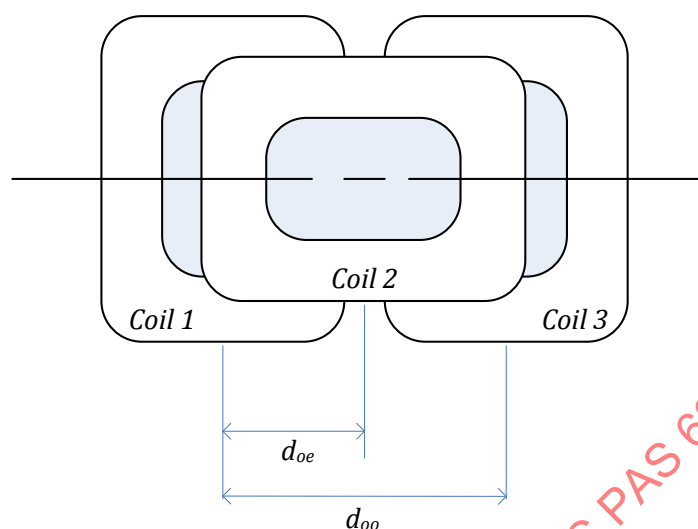


Table 8. Primary Coil parameters of Power Transmitter design A6

Parameter	Symbol	Value
Outer length	d_{ol}	$53.2^{+0.5}$ mm
Inner length	d_{il}	$27.5^{+0.5}$ mm
Outer width	d_{ow}	$45.2^{+0.5}$ mm
Inner width	d_{iw}	$19.5^{+0.5}$ mm
Thickness	d_c	$1.5^{+0.5}$ mm
Number of turns per layer	N	12 turns
Number of layers	–	1

Power Transmitter design A6 contains at least one Primary Coil. Odd numbered coils are placed alongside each other with a displacement of $d_{oo} = 49.2^{+4}$ mm between their centers. Even numbered coils are placed orthogonal to the odd numbered coils with a displacement of $d_{oe} = 24.6^{+2}$ mm between their centers. See Figure 17.

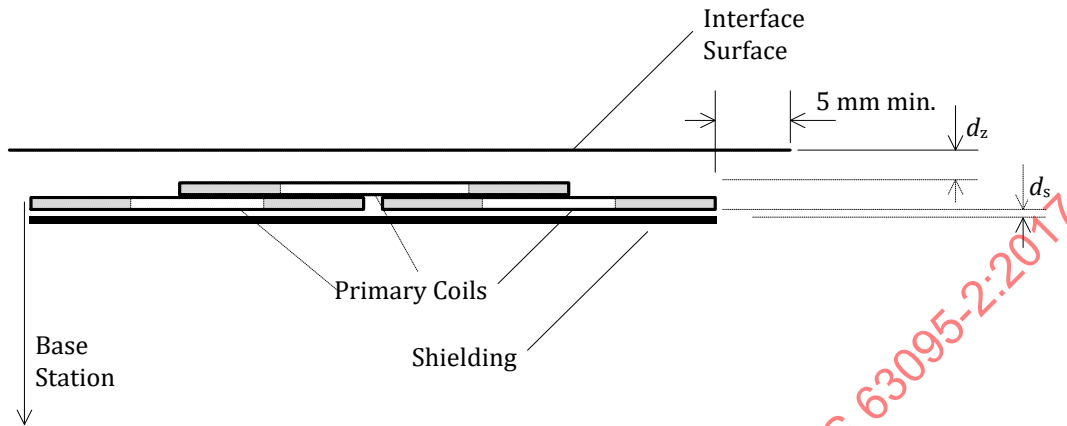
Figure 17. Primary Coils of Power Transmitter design A6

2.2.6.1.2 Shielding

As shown in Figure 18, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least the outer dimensions of the Primary Coils, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 44 — Fair Rite Corporation.
- Material 28 — Steward, Inc.
- CMG22G — Ceramic Magnetics, Inc.
- Kolektor 22G — Kolektor.
- LeaderTech SB28B2100-1 — LeaderTech Inc.
- TopFlux “A” — TopFlux.
- TopFlux “B” — TopFlux.
- ACME K081 — Acme Electronics.
- L7H — TDK Corporation.
- PE22 — TDK Corporation.
- FK2 — TDK Corporation.
- 68 — EMICORE Corp.
- M79 — EMICORE Corp.

Figure 18. Primary Coil assembly of Power Transmitter design A6



2.2.6.1.3 Interface Surface

As shown in Figure 18, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.25}$ mm, across the top face of the Primary Coil. In the case of a single Primary Coil, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 3^{+0.5}_{-0.25}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer dimensions of the Primary Coils.

2.2.6.1.4 Inter coil separation

If the Base Station contains multiple type A6 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 49.2^{+4} mm.

2.2.6.2 Electrical details

As shown in Figure 19, Power Transmitter design A6 uses a half-bridge inverter to drive an individual Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coils and Shielding has a self inductance $L_p = 11.5^{\pm 10\%}$ μH for coils closest to the Interface Surface and inductance $L_p = 12.5^{\pm 10\%}$ μH for coils furthest from the Interface Surface. The value of the series capacitance is $C_p = 0.147^{\pm 5\%}$ μF for coils closest to the Interface Surface and $C_p = 0.136^{\pm 5\%}$ μF for coils furthest from the Interface Surface. The input voltage to the half-bridge inverter is $12^{\pm 5\%}$ V.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A6 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the half-bridge inverter is $f_{op} = 115 \dots 205$ kHz with a duty cycle of 50%; and its duty cycle range is 10...50% at an Operating Frequency of 205 kHz. A higher Operating Frequency or lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the amount of power that is transferred, a type A6 Power Transmitter shall control the Operating Frequency with a resolution of

- $0.01 \times f_{op} - 0.7$ kHz, for f_{op} in the 115...175 kHz range;
- $0.015 \times f_{op} - 1.58$ kHz, for f_{op} in the 175...205 kHz range;

or better. In addition, a type A6 Power Transmitter shall control the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A6 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial Operating Frequency of 175 kHz (and a duty cycle of 50%).

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency or the duty cycle. In order to guarantee sufficiently accurate power control, a type A6 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 9, Table 10, and Table 11 provide the values of several parameters, which are used in the PID algorithm.

Figure 19. Electrical diagram (outline) of Power Transmitter design A6

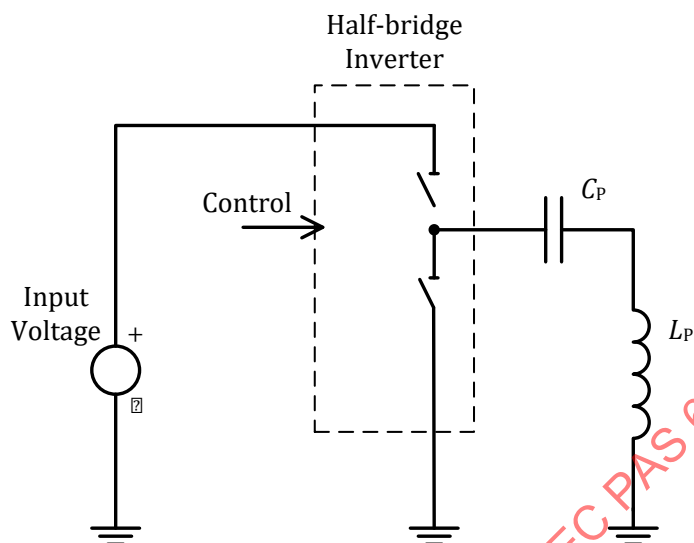


Table 9. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.

Table 10. Operating Frequency dependent scaling factor

Frequency Range [kHz]	Scaling Factor S_v [Hz]
115...140	1.5
140...160	2
160...180	3
180...205	5

Table 11. PID parameters for duty cycle control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	–0.01	%

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2.2.7 Power Transmitter design A7

Power Transmitter design A7 enables Free Positioning, and has a design similar to Power Transmitter design A2. See Section 0 for an overview.

2.2.7.1 Mechanical details

Power Transmitter design A7 includes a single Primary Coil as defined in Section 2.2.7.1.1, Shielding as defined in Section 2.2.7.1.2, an Interface Surface as defined in Section 2.2.7.1.3, and a positioning stage as defined in Section 2.2.7.1.4.

2.2.7.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 100 strands of 0.08 mm diameter, or equivalent. As shown in Figure 20, the Primary Coil has a circular shape and consists of a single layer. Table 12 lists the dimensions of the Primary Coil.

Figure 20. Primary Coil of Power Transmitter design A7

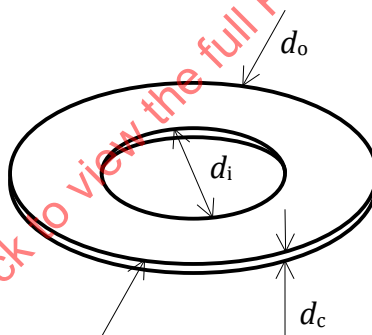


Table 12. Primary Coil parameters of Power Transmitter design A7

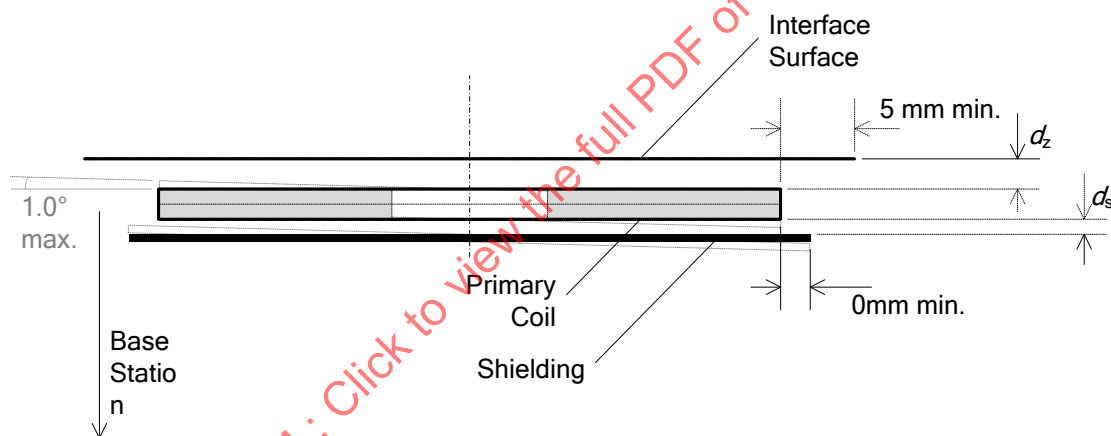
Parameter	Symbol	Value
Outer diameter	d_o	$39^{\pm 2}$ mm
Inner diameter	d_i	$12^{\pm 0.2}$ mm
Thickness	d_c	$1.9^{\pm 0.2}$ mm
Number of turns per layer	N	20
Number of layers	–	1

2.2.7.1.2 Shielding

As shown in Figure 21, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least the edges of the Primary Coil, has a thickness of at least 0.60 mm and is placed below the Primary Coil at a distance of at most $d_s = 0.5\text{mm}$. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- KNZWAB – Panasonic
- KNZWAC – Panasonic
- FK2 – TDK Corporation
- FK5 – TDK Corporation
- PF600F – FDK Corporation

Figure 21. Primary Coil assembly of Power Transmitter design A7



2.2.7.1.3 Interface Surface

As shown in Figure 21, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 3.0 \pm 0.5$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5mm beyond the outer diameter of the Primary Coil.

2.2.7.1.4 Positioning stage

The positioning stage shall have a resolution of 0.1mm or better in each of the two orthogonal directions parallel to the Interface Surface.

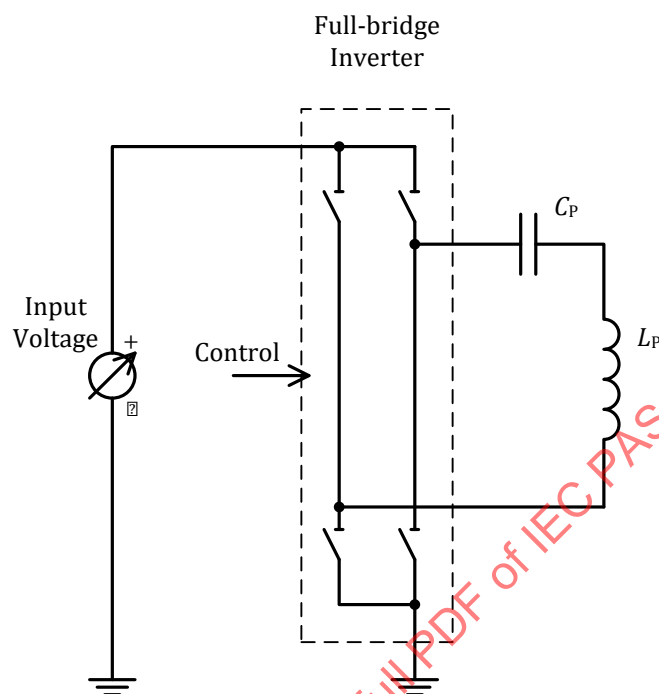
2.2.7.2 Electrical details

As shown in Figure 22, Power Transmitter design A7 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. At an Operating Frequency range between 105 kHz and 140 kHz, the assembly of Primary Coil and Shielding has a self inductance $L_p = 13.6^{\pm 10\%}$ μH . The value of the series capacitance is $C_p = 180^{\pm 5\%}$ nF.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A7 uses the input voltage to the full-bridge inverter to control the amount of power that is transferred. For this purpose, the input voltage range is 3...12 V, where a lower input voltage results in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type A7 Power Transmitter shall be able to control the input voltage with a resolution of 50 mV or better.

When a type A7 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial input voltage of 6.5 V. It is recommended that the Power Transmitter uses an Operating Frequency of 140 kHz when first applying the Power Signal. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may reapply the Power Signal multiple times at other—consecutively lower—Operating Frequencies within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 22. Electrical diagram (outline) of Power Transmitter design A7

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(t)}$ introduced in the definition of that algorithm represents the input voltage to the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type A7 Power Transmitter shall determine the amplitude of the Primary Cell voltage—which is equal to the Primary Coil voltage—with a resolution of 5 mV or better. Finally, Table 13 provides the values of several parameters, which are used in the PID algorithm.

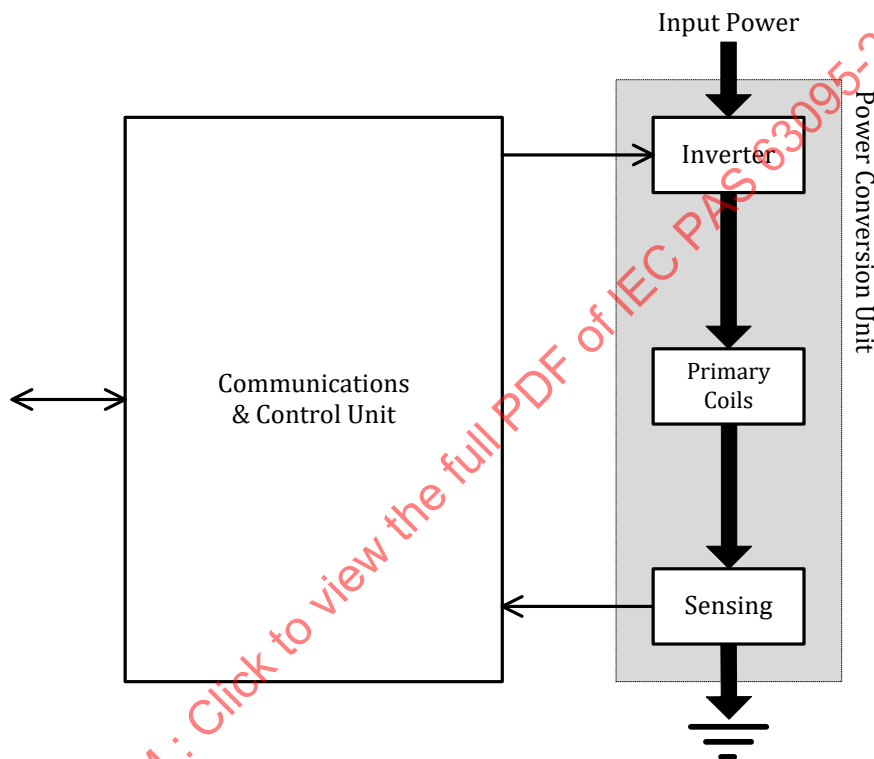
Table 13. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	–0.5	mV

2.2.8 Power Transmitter design A8

Power Transmitter design A8 enables Free Positioning. Figure 23 illustrates the functional block diagram of this design, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 23. Functional block diagram of Power Transmitter design A8



The Power Conversion Unit on the right-hand side of Figure 23 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the voltage and current sense monitors the Primary Coil voltage and current.

The Communications and Control Unit on the left-hand side of Figure 23 comprises the digital logic part of the design. The unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input power and frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.8.1 Mechanical details

Power Transmitter design A8 includes one Primary Coil as defined in Section 2.2.8.1.1, Shielding as defined in Section 2.2.8.1.2, and an Interface Surface as defined in Section 2.2.8.1.3.

2.2.8.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 24, a Primary Coil has a racetrack-like shape and consists of a single layer. Table 14 lists the dimensions of a Primary Coil.

Figure 24. Primary Coil of Power Transmitter design A8

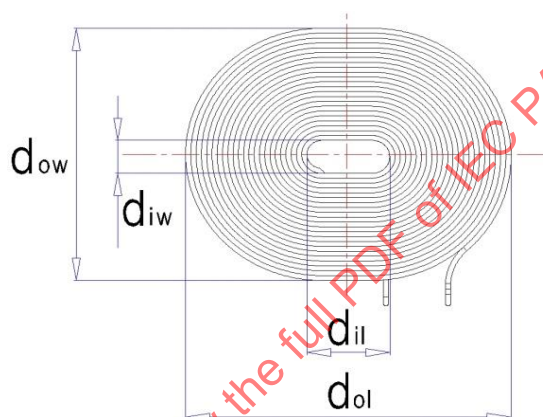


Table 14. Primary Coil parameters of Power Transmitter design A8

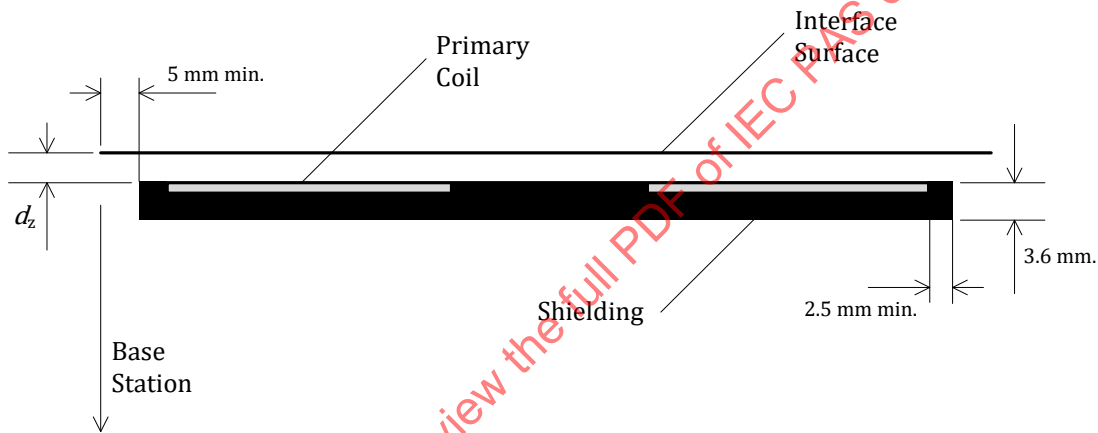
Parameter	Symbol	Value
Outer length	d_{ol}	$70^{\pm 0.5}$ mm
Inner length	d_{il}	$15^{\pm 0.5}$ mm
Outer width	d_{ow}	$59^{\pm 0.5}$ mm
Inner width	d_{iw}	$4^{\pm 0.5}$ mm
Thickness	d_c	$1.2^{\pm 0.15}$ mm
Number of turns per layer	N	23.5
Number of layers	–	1

2.2.8.1.2 Shielding

As shown in Figure 25, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The top face of the Shielding block is aligned with the top face of the Primary Coil, such that the Shielding surrounds the Primary Coil on all sides except for the top face. In addition, the Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coil, and has a thickness of at least 3.1 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Mn-Zn-Ferrite Dust Core— any supplier

Figure 25. Primary Coil assembly of Power Transmitter design A8



2.2.8.1.3 Interface Surface

As shown in Figure 25, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.0^{+0.5}_{-0.5}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.8.1.4 Separation between multiple Power transmitters

If the Base Station contains multiple type A8 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 70 mm.

2.2.8.2 Electrical details

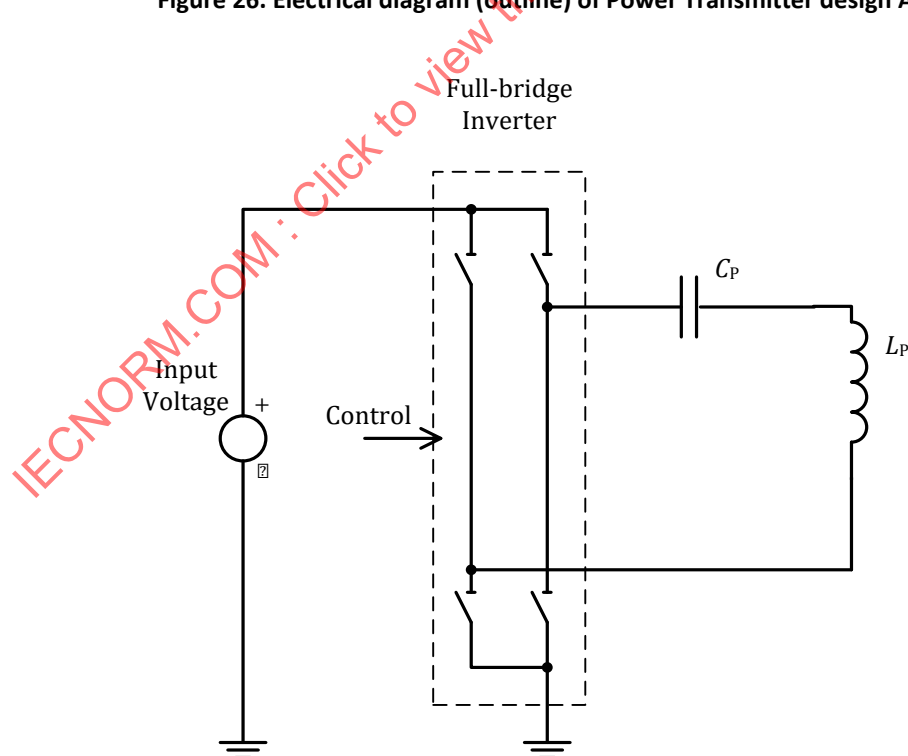
As shown in Figure 26, Power Transmitter design A8 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range of 110...180 kHz, the assembly of Primary Coil and Shielding has a self inductance $L_P = 24^{\pm 0.5} \mu\text{H}$. The value of the series capacitance is $C_P = 100^{\pm 5\%} \text{ nF}$. The input voltage to the full-bridge inverter is $5^{\pm 0.5} \dots 11^{\pm 0.5} \text{ V}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A8 uses the Operating Frequency and the input voltage to the full-bridge inverter to control the amount of power that is transferred. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type A8 Power Transmitter shall be able to control the frequency with a resolution of 0.5 kHz, and the input voltage with a resolution of 50 mV or better.

When a type A8 Power Transmitter first applies a Power Signal (Digital Ping, see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an Operating Frequency of 130 kHz, and an input voltage of 8 V. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may reapply the Power Signal multiple times at an Operating Frequency of 130 kHz using consecutively higher input voltages within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 26. Electrical diagram (outline) of Power Transmitter design A8



Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents Operating Frequency as well as the input voltage to the full-bridge inverter. It is recommended that control of the power occurs primarily by means of adjustments to the Operating Frequency, and that voltage adjustments are made only at the boundaries of the Operating Frequency range. In order to guarantee sufficiently accurate power control, a type A8 Power Transmitter shall determine the amplitude of the Primary Coil current with a resolution of 5 mA or better. Finally, Table 15 and Table 16 provide the values of several parameters, which are used in the PID algorithm.

Table 15. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA ⁻¹
Integral gain	K_i	0	mA ⁻¹ ms ⁻¹
Derivative gain	K_d	0	mA ⁻¹ ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

Table 16. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA ⁻¹
Integral gain	K_i	0	mA ⁻¹ ms ⁻¹
Derivative gain	K_d	0	mA ⁻¹ ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	–0.5	mV

2.2.9 Power Transmitter design A9

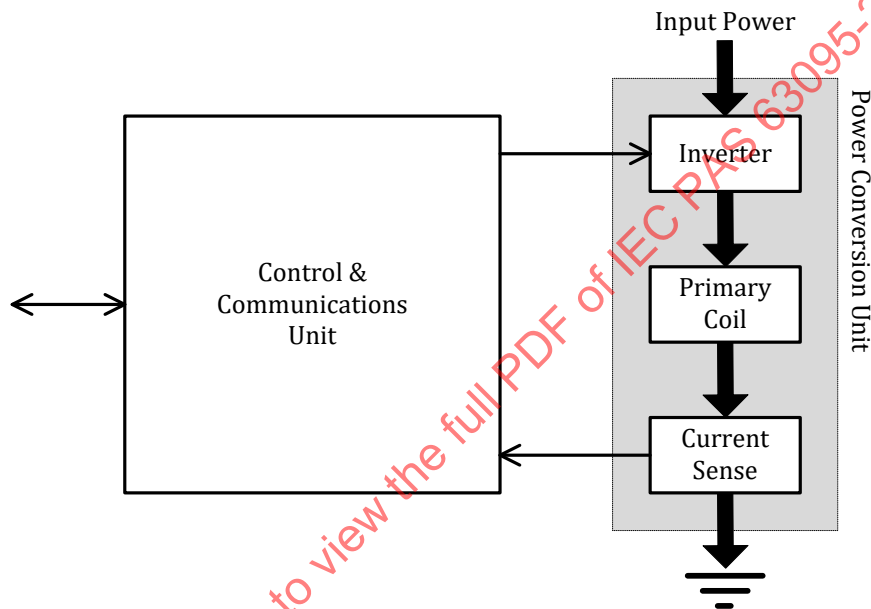
Power Transmitter design A9 has been deprecated. For further information, see the note in Section 2.1.

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2.2.10 Power Transmitter design A10

Power Transmitter design A10 enables Guided Positioning. Figure 27 illustrates the functional block diagram of this design, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 27. Functional block diagram of Power Transmitter design A10



The Power Conversion Unit on the right-hand side of Figure 27 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 27 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.10.1 Mechanical details

Power Transmitter design A10 includes a single Primary Coil as defined in Section 2.2.10.1.1, Shielding as defined in Section 2.2.10.1.2, an Interface Surface as defined in Section 2.2.10.1.3, and an alignment aid as defined in Section 2.2.10.1.4.

2.2.10.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of no. 17 AWG (1.15 mm diameter) type 2 litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 28, the Primary Coil has a circular shape and consists of multiple layers. All layers are stacked with the same polarity. Table 17 lists the dimensions of the Primary Coil.

Figure 28. Primary Coil of Power Transmitter design A10

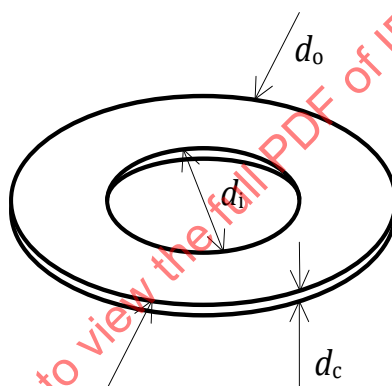


Table 17. Primary Coil parameters of Power Transmitter design A10

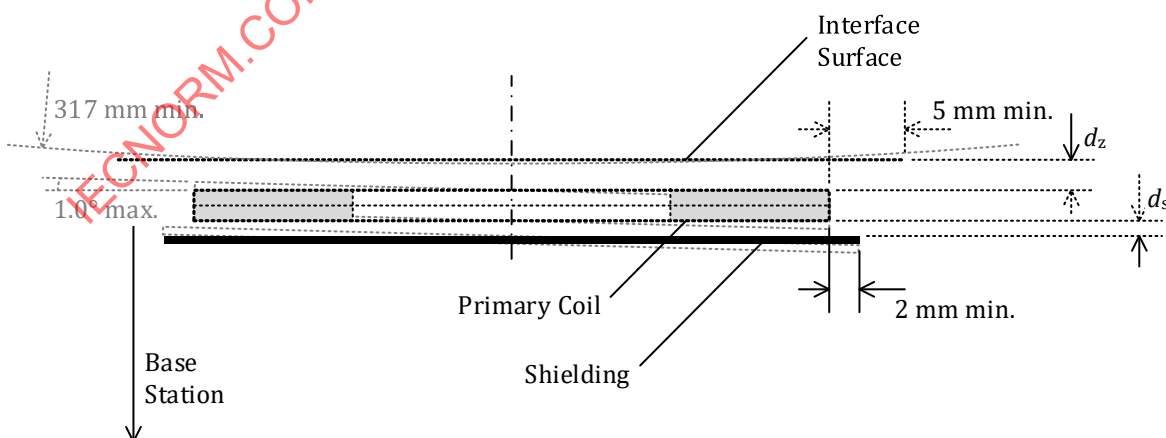
Parameter	Symbol	Value
Outer diameter	d_o	$43^{\pm 0.5}$ mm
Inner diameter	d_i	$20.5^{\pm 0.5}$ mm
Thickness	d_c	$2.1^{+0.5}$ mm
Number of turns per layer	N	10
Number of layers	–	2

2.2.10.1.2 Shielding

As shown in Figure 29, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 44 — Fair Rite Corporation.
- Material 28 — Steward, Inc.
- CMG22G — Ceramic Magnetics, Inc.
- Kolektor 22G — Kolektor.
- LeaderTech SB28B2100-1 — LeaderTech Inc.
- TopFlux “A” — TopFlux.
- TopFlux “B” — TopFlux.
- ACME K081 — Acme Electronics.
- L7H — TDK Corporation.
- PE22 — TDK Corporation.
- FK2 — TDK Corporation.
- 68 — EMICORE Corp.
- M79 — EMICORE Corp.

Figure 29. Primary Coil assembly of Power Transmitter design A10



2.2.10.1.3 Interface Surface

As shown in Figure 29 the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.25}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

NOTE This Primary-Coil-to-Interface-Surface distance implies that the tilt angle between the Primary Coil and a flat Interface Surface is at most 1.0°. Alternatively, in case of a non-flat Interface Surface, this Primary-Coil-to-Interface-Surface distance implies a radius of curvature of the Interface Surface of at least 317 mm, centered on the Primary Coil. See Figure 29.

2.2.10.1.4 Alignment aid

The user manual of the Base Station containing a type A10 Power Transmitter shall have information about the location of its Active Area(s).

For the best user experience, it is recommended to employ at least one user feedback mechanism during Mobile Device positioning to help alignment.

NOTE Examples of Base Station alignment aids to assist the user positioning of the Mobile Device include:

- A marked Interface Surface to indicate the location of the Active Area(s)—e.g. by means of the logo or other visual marking, lighting, etc.
- A visual feedback display—e.g. by means of illuminating an LED to indicate proper alignment.
- An audible or haptic feedback mechanism.

2.2.10.1.5 Inter coil separation

If the Base Station contains multiple type A10 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 50 mm.

2.2.10.2 Electrical details

As shown in Figure 30, Power Transmitter design A10 uses a half-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coil, Shielding, and magnet has a self inductance $L_p = 24^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_p = 100^{\pm 5\%} \text{ nF}$. The input voltage to the half-bridge inverter is $19^{\pm 1} \text{ V}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 200 V pk-pk.

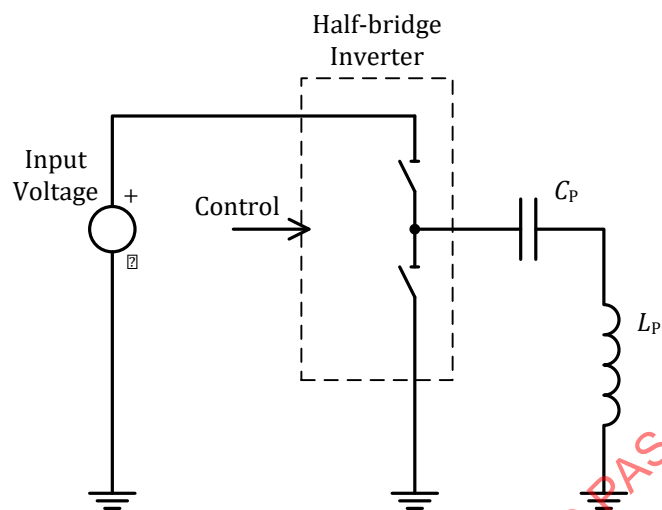
Power Transmitter design A10 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the half-bridge inverter is $f_{op} = 110 \dots 205 \text{ kHz}$ with a duty cycle of 50%; and its duty cycle range is 10...50% at an Operating Frequency of 205 kHz. A higher Operating Frequency or lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the amount of power that is transferred, a type A10 Power Transmitter shall control the Operating Frequency with a resolution of

- $0.01 \times f_{op} - 0.7 \text{ kHz}$, for f_{op} in the 110...175 kHz range;
- $0.015 \times f_{op} - 1.58 \text{ kHz}$, for f_{op} in the 175...205 kHz range;

or better. In addition, a type A10 Power Transmitter shall control the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A10 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial Operating Frequency of 175 kHz (and a duty cycle of 50%).

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency or the duty cycle. In order to guarantee sufficiently accurate power control, a type A10 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 18, Table 19, and Table 20 provide the values of several parameters, which are used in the PID algorithm.

Figure 30. Electrical diagram (outline) of Power Transmitter design A10**Table 18. PID parameters for Operating Frequency control**

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.

Table 19. Operating Frequency dependent scaling factor

Frequency Range [kHz]	Scaling Factor S_v [Hz]
110...140	1.5
140...160	2
160...180	3
180...205	5

Table 20. PID parameters for duty cycle control

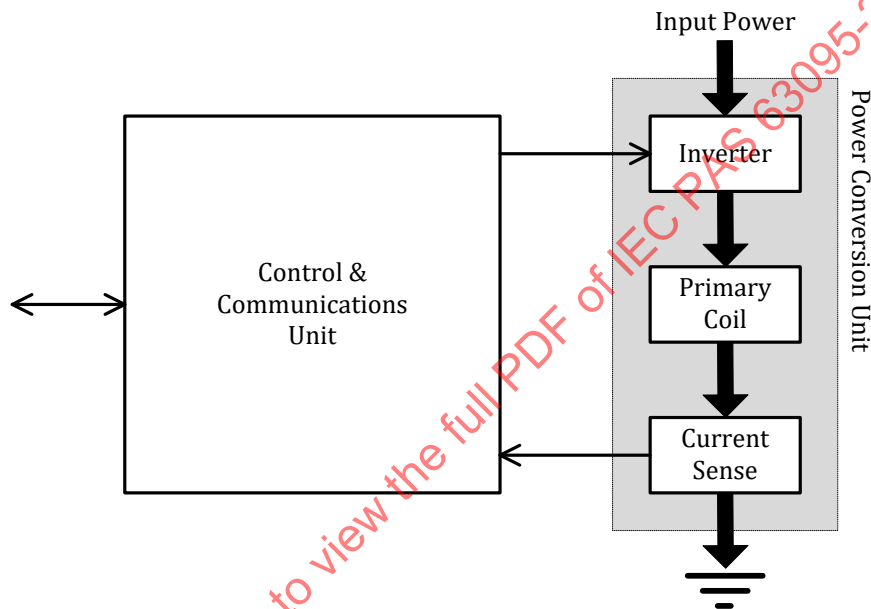
Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	–0.01	%

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2.2.11 Power Transmitter design A11

Power Transmitter design A11 enables Guided Positioning. Figure 31 illustrates the functional block diagram of this design, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 31. Functional block diagram of Power Transmitter design A11



The Power Conversion Unit on the right-hand side of Figure 31 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 31 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.11.1 Mechanical details

Power Transmitter design A11 includes a single Primary Coil as defined in Section 2.2.11.1.1, Shielding as defined in Section 2.2.11.1.2, an Interface Surface as defined in Section 2.2.11.1.3, and an alignment aid as defined in Section 2.2.11.1.4.

2.2.11.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of no. 17 AWG (1.15 mm diameter) type 2 litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 32, the Primary Coil has a circular shape and consists of one or two layers. Table 21 lists the dimensions of the Primary Coil.

Figure 32. Primary Coil of Power Transmitter design A11

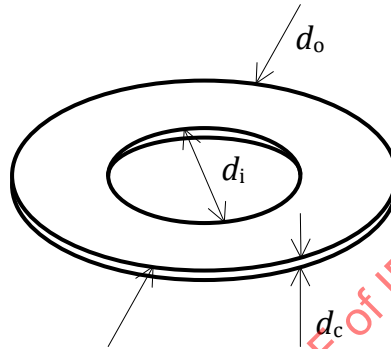


Table 21. Primary Coil parameters of Power Transmitter design A11

Parameter	Symbol	Value
Outer diameter	d_o	$44^{\pm 1.5}$ mm
Inner diameter	d_i	$20.5^{\pm 0.5}$ mm
Thickness	d_c	$2.1^{+0.5}$ mm
Number of turns per layer	N	10 (5 bifilar turns)
Number of layers	–	1 or 2

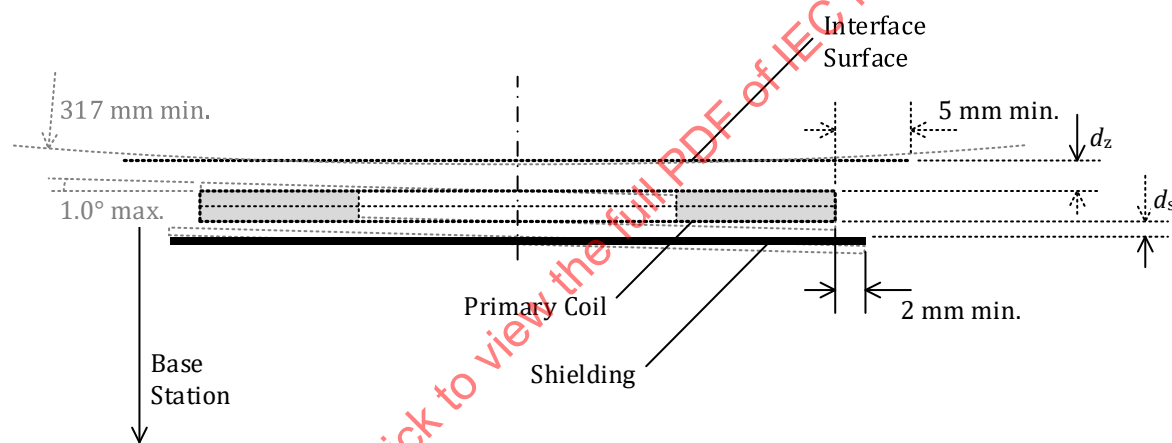
2.2.11.1.2 Shielding

As shown in Figure 33, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 44 — Fair Rite Corporation.
- Material 28 — Steward, Inc.
- CMG22G — Ceramic Magnetics, Inc.
- Kolektor 22G — Kolektor.

- LeaderTech SB28B2100-1 — LeaderTech Inc.
- TopFlux “A” — TopFlux.
- TopFlux “B” — TopFlux.
- ACME K081 — Acme Electronics.
- L7H — TDK Corporation.
- PE22 — TDK Corporation.
- FK2 — TDK Corporation.
- 68 — EMICORE Corp.
- M79 — EMICORE Corp.

Figure 33. Primary Coil assembly of Power Transmitter design A11



2.2.11.1.3 Interface Surface

As shown in Figure 33 the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.25}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

NOTE This Primary-Coil-to-Interface-Surface distance implies that the tilt angle between the Primary Coil and a flat Interface Surface is at most 1.0°. Alternatively, in case of a non-flat Interface Surface, this Primary-Coil-to-Interface-Surface distance implies a radius of curvature of the Interface Surface of at least 317 mm, centered on the Primary Coil. See Figure 33.

2.2.11.1.4 Alignment aid

The user manual of the Base Station containing a type A11 Power Transmitter shall have information about the location of its Active Area(s).

For the best user experience, it is recommended to employ at least one user feedback mechanism during Mobile Device positioning to help alignment.

NOTE Examples of Base Station alignment aids to assist the user positioning of the Mobile Device include:

- A marked Interface Surface to indicate the location of the Active Area(s)—e.g. by means of the logo or other visual marking, lighting, etc.
- A visual feedback display—e.g. by means of illuminating an LED to indicate proper alignment.
- An audible or haptic feedback mechanism.

2.2.11.1.5 Inter coil separation

If the Base Station contains multiple type A11 Power Transmitters the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 50 mm.

2.2.11.2 Electrical details

As shown in Figure 34, Power Transmitter design A11 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coil and Shielding has a self inductance $L_p = 6.3^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_p = 0.4^{\pm 5\%} \mu\text{F}$. The input voltage to the full-bridge inverter is $5^{\pm 5\%} \text{V}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A11 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the full-bridge inverter is $f_{op} = 110 \dots 205 \text{ kHz}$ with a duty cycle of 50%; and its duty cycle range is 10...50% at an Operating Frequency of 205 kHz. A higher Operating Frequency or lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the amount of power that is transferred, a type A11 Power Transmitter shall control the Operating Frequency with a resolution of

- $0.01 \times f_{op} - 0.7 \text{ kHz}$, for f_{op} in the 110...175 kHz range;
- $0.015 \times f_{op} - 1.58 \text{ kHz}$, for f_{op} in the 175...205 kHz range;

or better. In addition, a type A11 Power Transmitter shall control the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A11 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial Operating Frequency of 175 kHz (and a duty cycle of 50%).

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency or the duty cycle. In order to guarantee sufficiently accurate power control, a type A11 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 22, Table 23, and Table 24 provide the values of several parameters, which are used in the PID algorithm.

Figure 34. Electrical diagram (outline) of Power Transmitter design A11

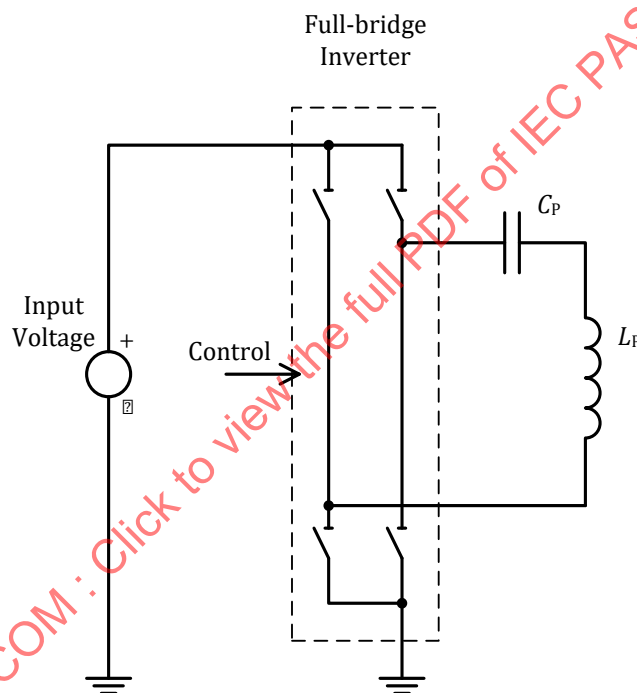


Table 22. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.

Table 23. Operating Frequency dependent scaling factor

Frequency Range [kHz]	Scaling Factor S_v [Hz]
110...140	1.5
140...160	2
160...180	3
180...205	5

Table 24. PID parameters for duty cycle control

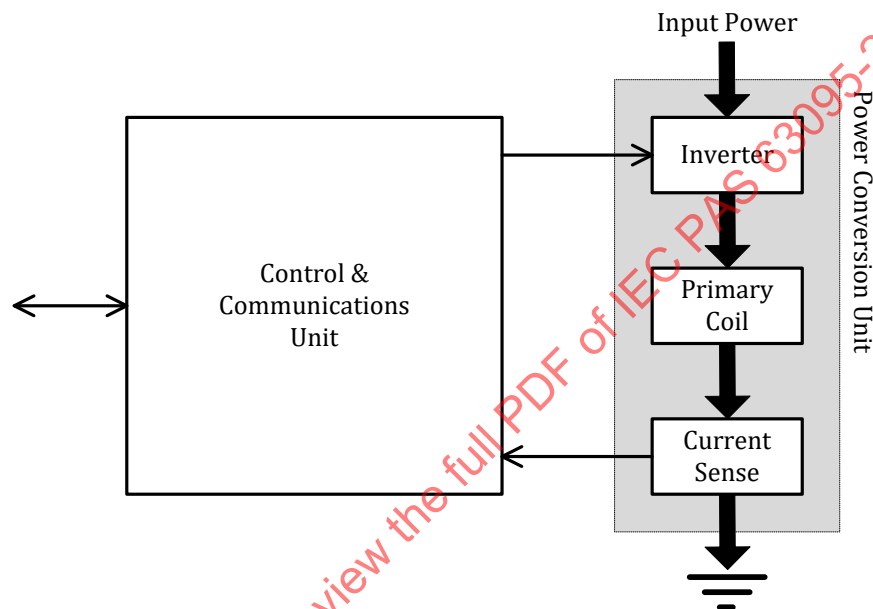
Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-0.01	%

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2.2.12 Power Transmitter design A12

Figure 35 illustrates the functional block diagram of Power Transmitter design A12, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 35. Functional block diagram of Power Transmitter design A12



The Power Conversion Unit on the right-hand side of Figure 35 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 35 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.12.1 Mechanical details

Power Transmitter design A12 includes a single Primary Coil as defined in Section 2.2.12.1.1, Shielding as defined in Section 2.2.12.1.2, and an Interface Surface as defined in Section 2.2.12.1.3.

2.2.12.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 36, a Primary Coil has a racetrack-like shape and consists of a single layer. Table 25 lists the dimensions of a Primary Coil.

Figure 36. Primary Coil of Power Transmitter design A12

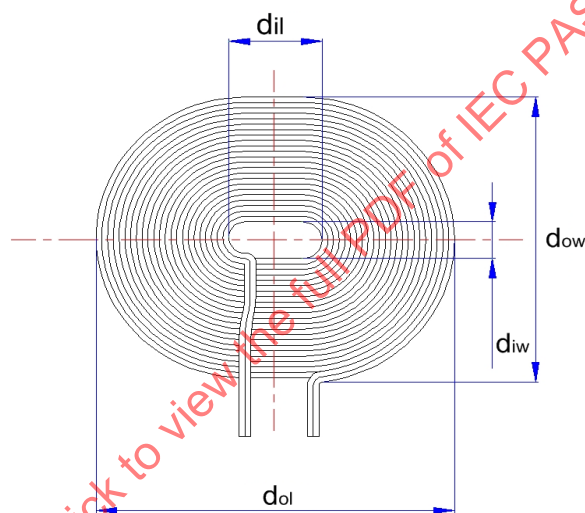


Table 25. Primary Coil parameters of Power Transmitter design A12

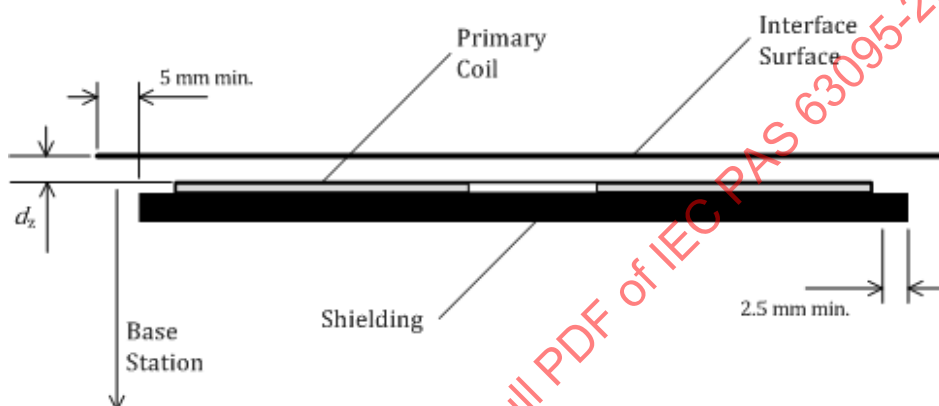
Parameter	Symbol	Value
Outer length	d_{ol}	$70^{\pm 0.5}$ mm
Inner length	d_{il}	$15^{\pm 0.5}$ mm
Outer width	d_{ow}	$59^{\pm 0.5}$ mm
Inner width	d_{iw}	$4^{\pm 0.5}$ mm
Thickness	d_c	$1.2^{\pm 0.15}$ mm
Number of turns per layer	N	12 (bifilar turns)
Number of layers	–	1

2.2.12.1.2 Shielding

As shown in Figure 37, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coil, and has a thickness of at least 0.5 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- PM12PT6576 – TODAISU Corporation

Figure 37. Primary Coil assembly of Power Transmitter design A12



2.2.12.1.3 Interface Surface

As shown in Figure 37, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.0 \pm 0.5$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.12.1.4 Inter coil separation

If the Base Station contains multiple type A12 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 65 mm.

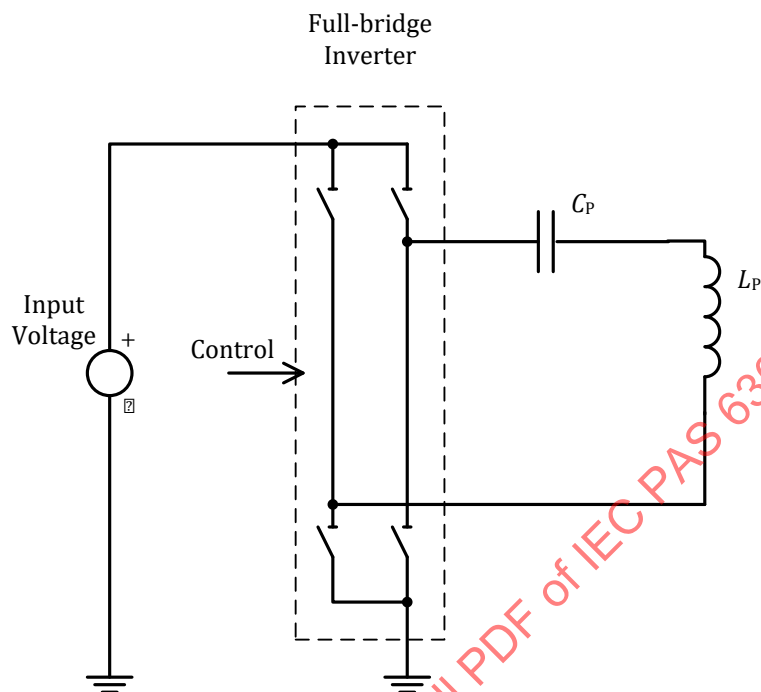
2.2.12.2 Electrical details

As shown in Figure 38, Power Transmitter design A12 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range Specified below, the assembly of Primary Coil and Shielding has a self inductance $L_p = 7^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_p = 400^{\pm 5\%} \text{nF}$. The input voltage to the full-bridge inverter is $5^{\pm 0.5} \text{V}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A12 uses the Operating Frequency and duty cycle of the full-bridge inverter to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the full-bridge inverter is $f_{op} = 110 \dots 205 \text{kHz}$ with a duty cycle of 50% and its duty cycle range is 2 ... 50% at an Operating Frequency of 205 kHz. A higher Operating Frequency and lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type A12 Power Transmitter shall be able to control the frequency with a resolution of 0.5 kHz or better. a type A12 Power Transmitter shall control the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A12 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an initial Operating Frequency of 175 kHz, and a duty cycle of 50%. If the Power Transmitter does not to receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may reapply the Power Signal multiple times at other-consecutively lower-Operating Frequencies within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 38. Electrical diagram (outline) of Power Transmitter design A12

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $\nu^{(t)}$ introduced in the definition of that algorithm represents Operating Frequency or duty cycle. In order to guarantee sufficiently accurate power control, a type A12 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 5 mA or better. Finally, Table 26 and Table 27 provide the values of several parameters, which are used in the PID algorithm.

Table 26. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

Table 27. PID parameters for duty cycle control

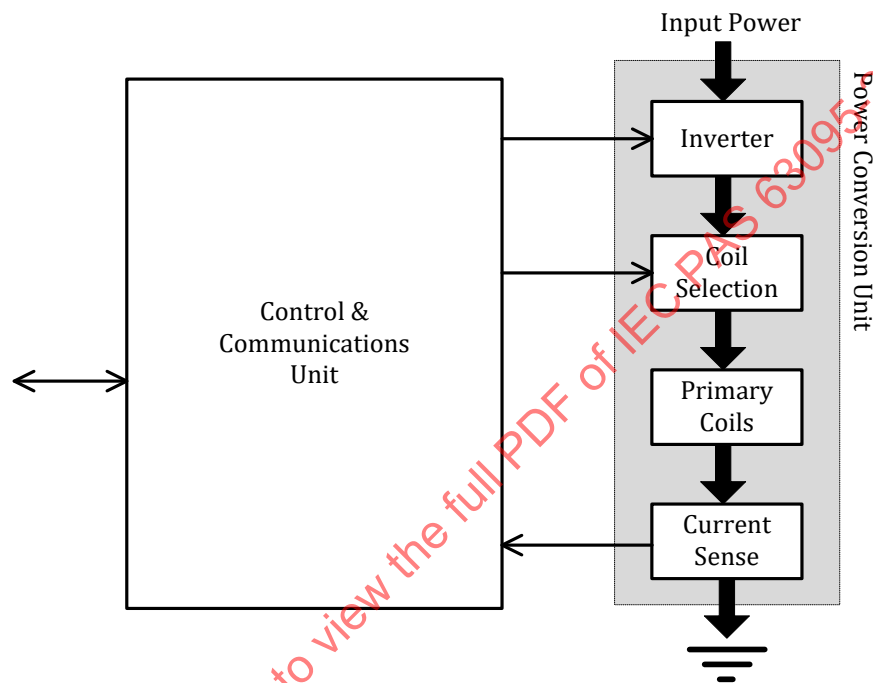
Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	0.1	%

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2.2.13 Power Transmitter design A13

Figure 39 illustrates the functional block diagram of Power Transmitter design A13, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 39. Functional block diagram of Power Transmitter design A13



The Power Conversion Unit on the right-hand side of Figure 39 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from a linear array of partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the Primary Coils. Selection of the Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using any of the Primary Coils. Note that the array may consist of a single Primary Coil only, in which case the selection is trivial. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 39 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.13.1 Mechanical details

Power Transmitter design A13 includes one or more Primary Coils as defined in Section 2.2.13.1.1, Shielding as defined in Section 2.2.13.1.2, an Interface Surface as defined in Section 2.2.13.1.3.

2.2.13.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of no. 17 AWG (1.15 mm diameter) type 2 litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 40, the Primary Coil has a rectangular shape and consists of a single layer. Table 28 lists the dimensions of the Primary Coil.

Figure 40. Primary Coil of Power Transmitter design A13

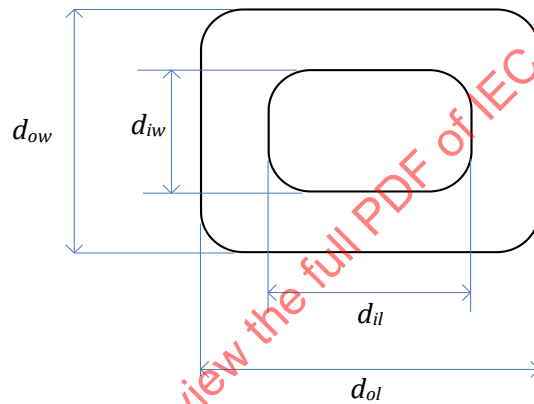
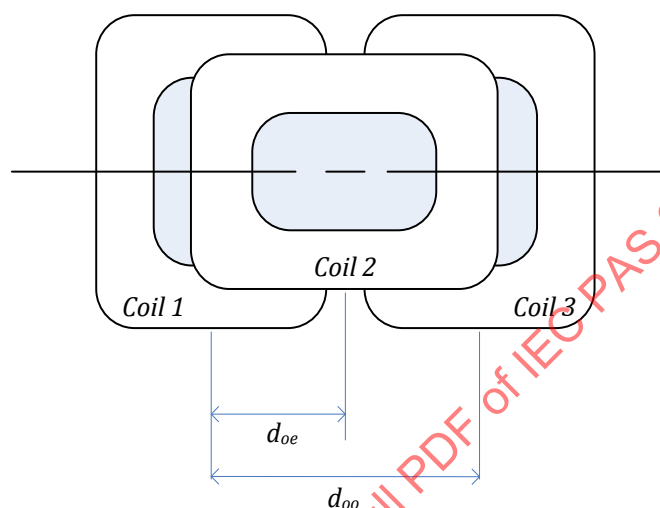


Table 28. Primary Coil parameters of Power Transmitter design A13

Parameter	Symbol	Value
Outer length	d_{ol}	$53.2^{±0.5}$ mm
Inner length	d_{il}	$27.5^{±0.5}$ mm
Outer width	d_{ow}	$45.2^{±0.5}$ mm
Inner width	d_{iw}	$19.5^{±0.5}$ mm
Thickness	d_c	$1.5^{±0.5}$ mm
Number of turns per layer	N	12 turns
Number of layers	–	1

Power Transmitter design A13 contains at least one Primary Coil. Odd numbered coils are placed alongside each other with a displacement of $d_{oo} = 49.2^{\pm 4}$ mm between their centers. Even numbered coils are placed orthogonal to the odd numbered coils with a displacement of $d_{oe} = 24.6^{\pm 2}$ mm between their centers. See Figure 41.

Figure 41. Primary Coils of Power Transmitter design A13



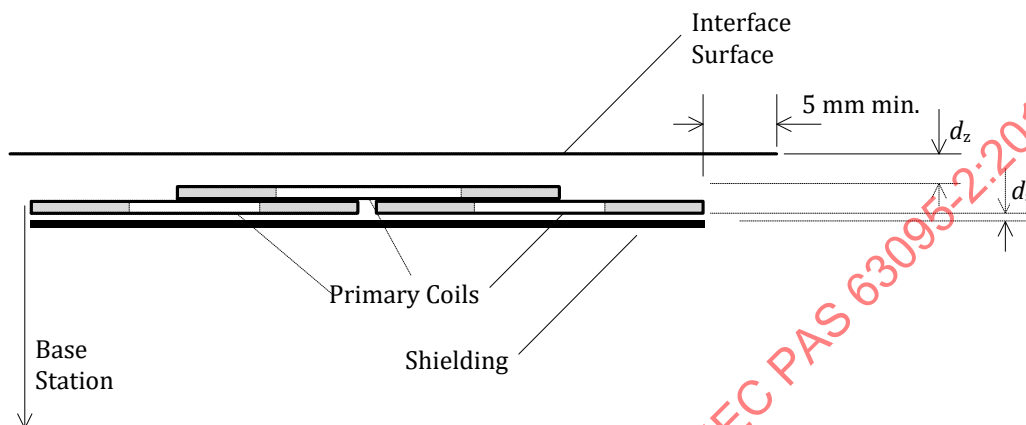
2.2.13.1.2 Shielding

As shown in Figure 42, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least the outer dimensions of the Primary Coils, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 44 — Fair Rite Corporation.
- Material 28 — Steward, Inc.
- CMG22G — Ceramic Magnetics, Inc.
- Kolektor 22G — Kolektor.
- LeaderTech SB28B2100-1 — LeaderTech Inc.
- TopFlux “A” — TopFlux.
- TopFlux “B” — TopFlux.
- ACME K081 — Acme Electronics.
- L7H — TDK Corporation.

- PE22 — TDK Corporation.
- FK2 — TDK Corporation.

Figure 42. Primary Coil assembly of Power Transmitter design A13



2.2.13.1.3 Interface Surface

As shown in Figure 42, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 3^{\pm 1}$ mm, across the top face of the Primary Coil. In the case of a single Primary Coil, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 4.5^{\pm 1}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer dimensions of the Primary Coils.

2.2.13.1.4 Inter coil separation

If the Base Station contains multiple type A13 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least $49.2^{\pm 4}$ mm.

2.2.13.2 Electrical details

As shown in Figure 43, Power Transmitter design A13 uses a full-bridge inverter to drive an individual Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coils and Shielding has a self inductance $L_p = 11.5^{\pm 10\%}$ μH for coils closest to the Interface Surface and inductance $L_p = 12.5^{\pm 10\%}$ μH for coils furthest from the Interface Surface. The value of inductances L_1 and L_2 is $1^{\pm 20\%}$ μH . The value of the total series capacitance is $1/C_{\text{ser1}} + 1/C_{\text{ser2}} = 1/200^{\pm 10\%}$ 1/nF. The value of the parallel capacitance is $C_{\text{par}} = 400^{\pm 10\%}$ nF.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A13 uses the input voltage of the inverter to control the amount of power that is transferred. For this purpose, the input voltage has a range of 1...12 V, with a resolution of 10 mV or better. The Operating Frequency is $f_{\text{op}} = 105 \dots 115$ kHz, with a duty cycle of 50%.

When a type A13 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial voltage of $3.5^{\pm 0.5}$ V for a bottom Primary Coil, and $3.0^{\pm 0.5}$ V for a top Primary Coil, and a recommended Operating Frequency of 110 kHz.

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the inverter. In order to guarantee sufficiently accurate power control, a type A13 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 29 provides the values of several parameters, which are used in the PID algorithm.

Figure 43. Electrical diagram (outline) of Power Transmitter design A13

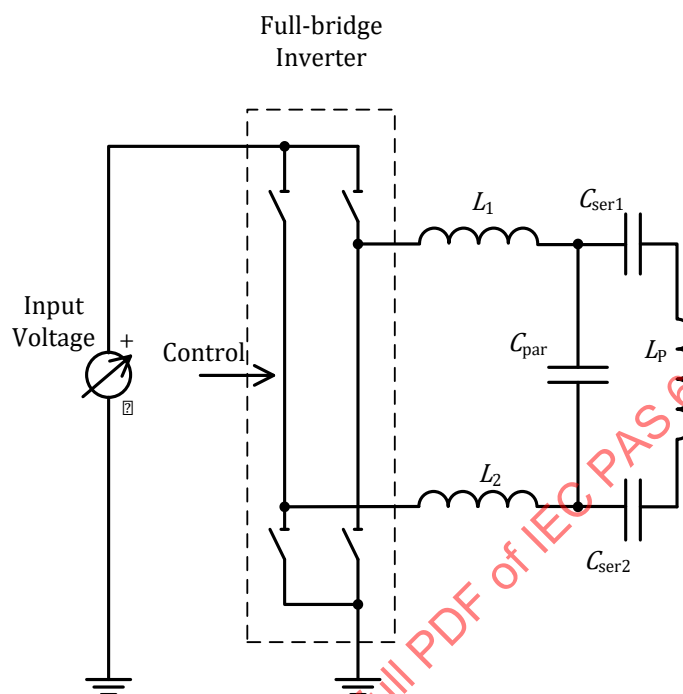


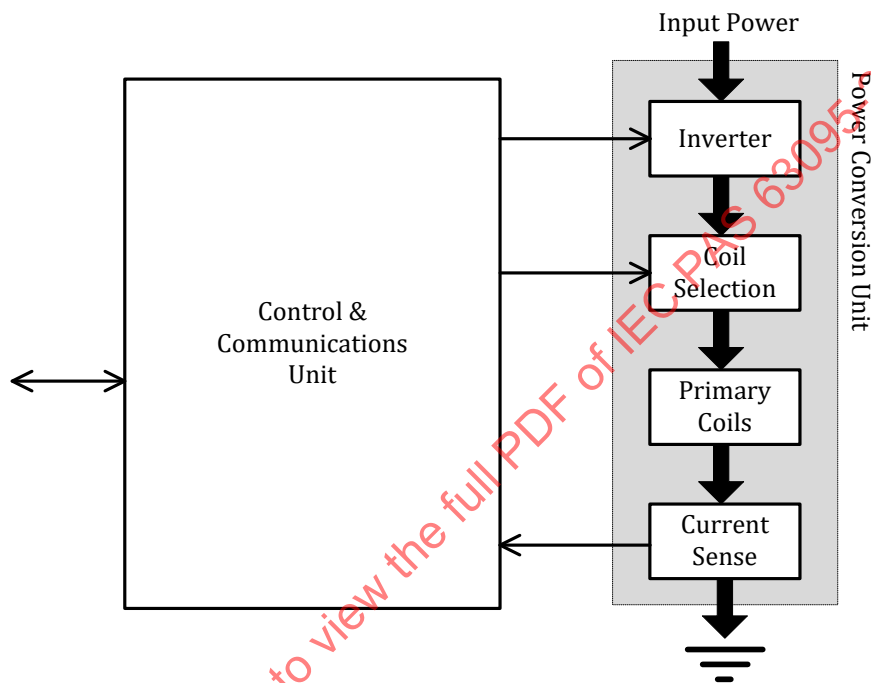
Table 29. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	0.03	mA^{-1}
Integral gain	K_i	0.01	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-1	mV

2.2.14 Power Transmitter design A14

Figure 44 illustrates the functional block diagram of Power Transmitter design A14, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 44. Functional block diagram of Power Transmitter design A14



The Power Conversion Unit on the right-hand side of Figure 44 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from a linear array of partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the Primary Coils. Selection of the Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using any of the Primary Coils. Note that the array may consist of a single Primary Coil only, in which case the selection is trivial. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 44 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.14.1 Mechanical details

Power Transmitter design A14 includes one or more Primary Coils as defined in Section 2.2.14.1.1, Shielding as defined in Section 2.2.14.1.2, an Interface Surface as defined in Section 2.2.14.1.3.

2.2.14.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 45, the Primary Coil has a racetrack-like shape and consists of a single layer. Table 30 lists the dimensions of the Primary Coil.

Figure 45. Primary Coil of Power Transmitter design A14

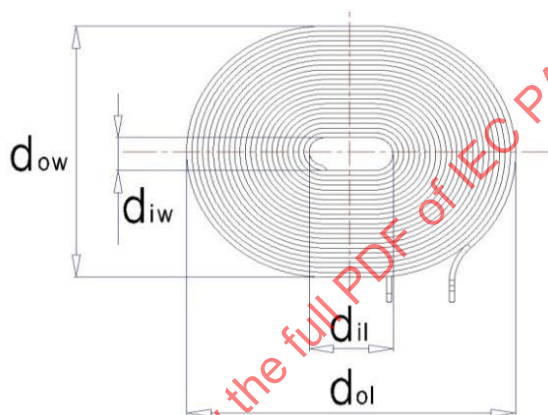
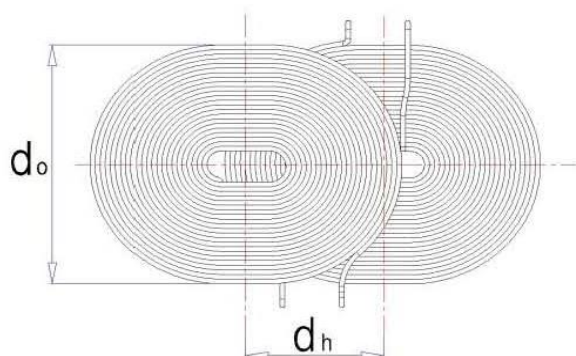


Table 30. Primary Coil parameters of Power Transmitter design A14

Parameter	Symbol	Value
Outer length	d_{ol}	$70^{\pm 0.5}$ mm
Inner length	d_{il}	$16^{\pm 1.0}$ mm
Outer width	d_{ow}	$59^{\pm 0.5}$ mm
Inner width	d_{iw}	$4.5^{\pm 0.5}$ mm
Thickness	d_c	$1.3^{\pm 0.1}$ mm
Number of turns per layer	N	23.5
Number of layers	–	1

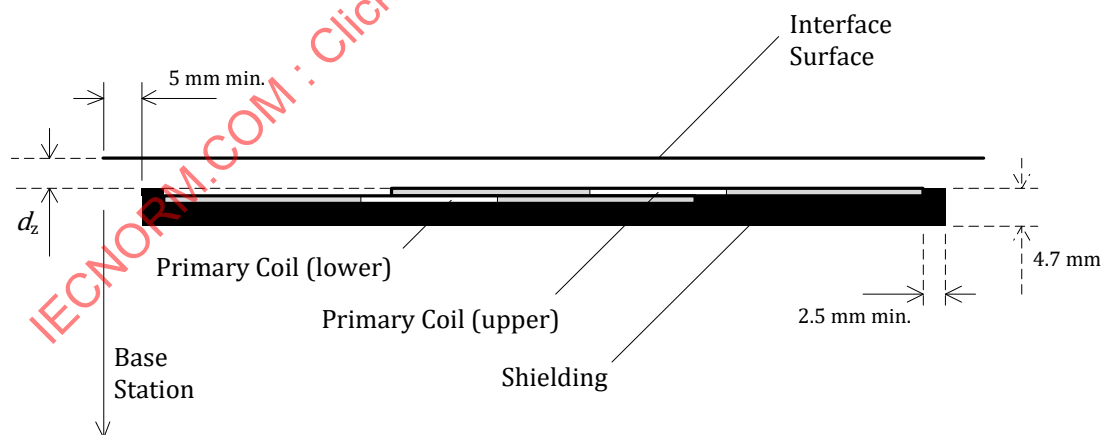
Power Transmitter design A14 contains two Primary Coils, which are mounted in a Shielding block (see Section 2.2.14.1.2) with their long axes coincident, and a displacement of $d_h = 38^{\pm 0.5}$ mm between their centers. See Figure 46.

Figure 46. Primary Coils of Power Transmitter design A14

2.2.14.1.2 Shielding

As shown in Figure 47, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The top face of the Shielding block is aligned with the top face of the Primary Coils, such that the Shielding surrounds the Primary Coils on all sides except for the top face. In addition, the Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coils, and has a thickness of at least 4.7 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Mn-Zn-Ferrite Dust Core – any supplier

Figure 47. Primary Coil assembly of Power Transmitter design A14

2.2.14.1.3 Interface Surface

As shown in Figure 47, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.0^{+0.5}_{-0}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer edges of the Primary Coils.

2.2.14.1.4 Inter coil separation

If the Base Station contains multiple type A14 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 70 mm.

2.2.14.2 Electrical details

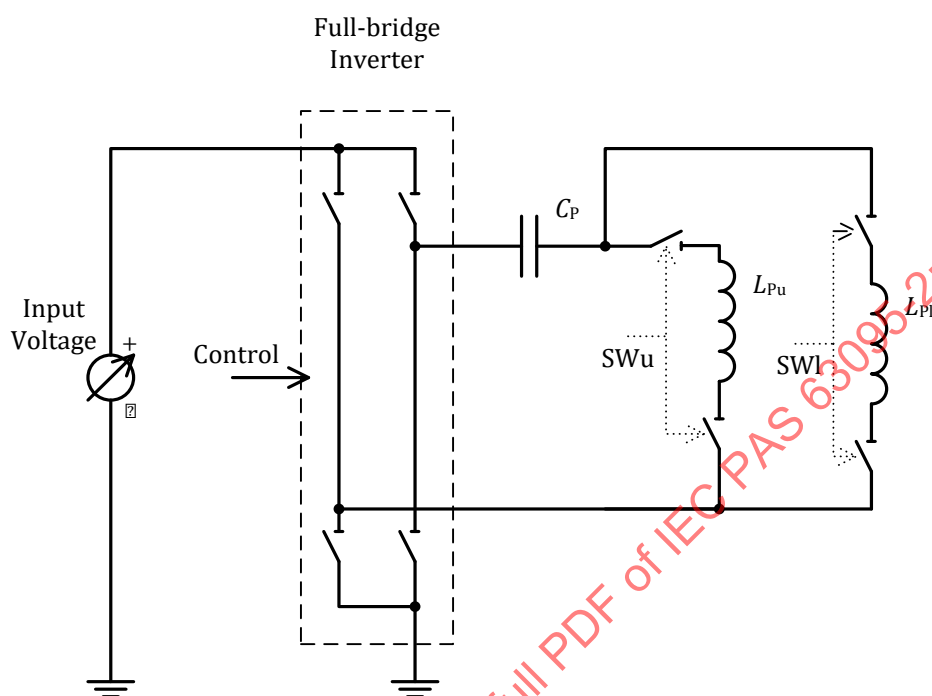
As shown in Figure 48, Power Transmitter design A14 uses a full-bridge inverter to drive the Primary Coils and a series capacitance. In addition, Power Transmitter design A14 shall operate coil selection switches SWu and SWl such that only a single Primary Coil is connected to the inverter.

Within the Operating Frequency range Specified below, the assembly of Primary Coils and Shielding has a self inductance $L_p = 24^{+1.0}_{-0}$ μ H. The value of the series capacitance is $C_p = 100^{+5\%}_{-0}$ nF. The input voltage to the full-bridge inverter is $12^{+10\%}_{-0}$ V.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 Vpk-pk.

Power Transmitter design A14 uses the Operating Frequency and duty cycle of the full-bridge inverter to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the full-bridge inverter is $f_{op} = 110 \dots 205$ kHz with a duty cycle of 50% and its duty cycle range is 2...50% at an Operating Frequency of 110...205 kHz. A higher Operating Frequency and lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type A14 Power Transmitter shall be able to control the frequency with a resolution of 0.5 kHz or better, and the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A14 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an initial Operating Frequency of 142 kHz, and a duty cycle of 50%. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may reapply the Power Signal multiple times at other-consecutively lower-Operating Frequencies within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 48. Electrical diagram (outline) of Power Transmitter design A14

Control of the power transfer shall proceed using the PID algorithm, which is defined in Section *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents Operating Frequency or duty cycle. In order to guarantee sufficiently accurate power control, a type A14 Power Transmitter shall determine the amplitude of the Primary Cell current-which is equal to the Primary Coil current-with a resolution of 5 mA or better. Finally, Table 31 and Table 32 provide the values of several parameters, which are used in the PID algorithm.

Table 31. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

Table 32. PID parameters for duty cycle control

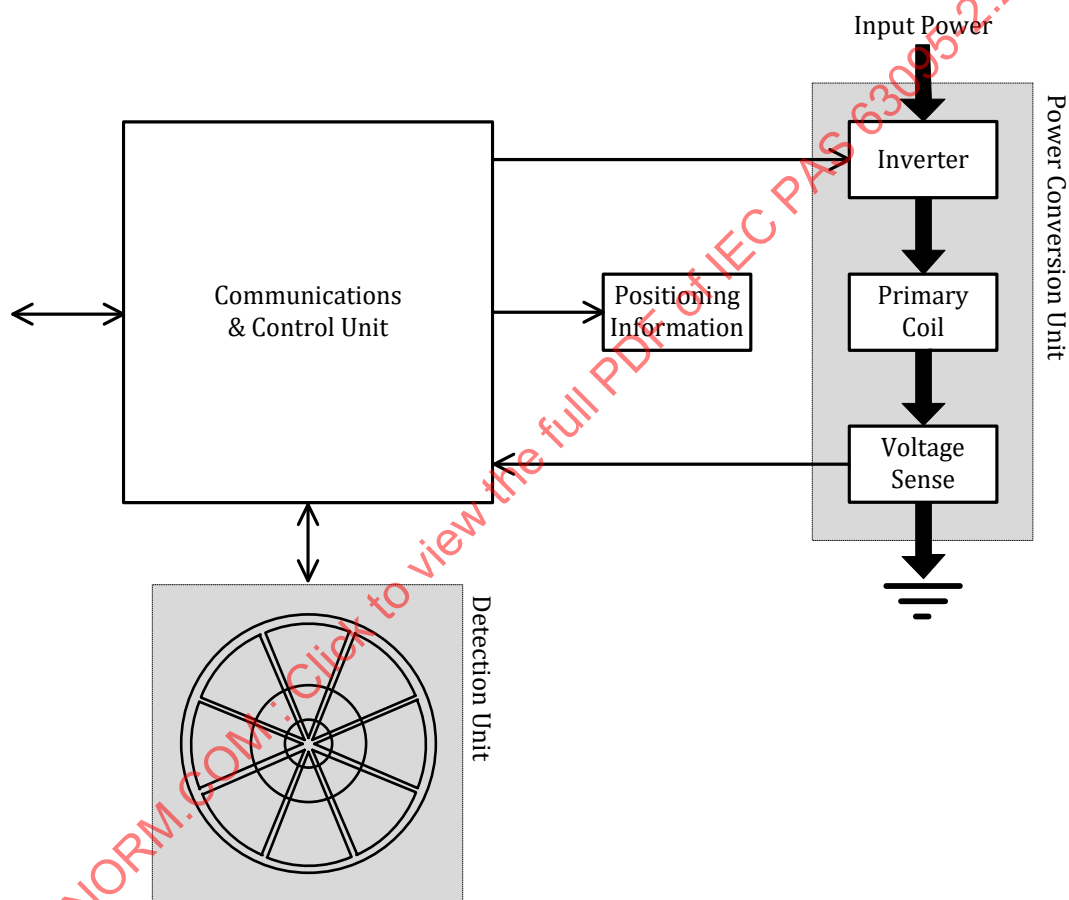
Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	0.1	%

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2.2.15 Power Transmitter design A15

Figure 49 illustrates the functional block diagram of Power Transmitter design A15, which consists of three major functional units, namely a Power Conversion Unit, a Detection Unit, and a Communications and Control Unit.

Figure 49. Functional block diagram of Power Transmitter design A15



The Power Conversion Unit on the right-hand side of Figure 49 and the Detection Unit at the bottom of Figure 49 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the voltage sense monitors the Primary Coil voltage.

The Communications and Control Unit on the left-hand side of Figure 49 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

The Detection Unit determines the approximate location of objects and/or Power Receivers on the Interface Surface. This version of *Part 4: Reference Designs* does not specify a particular detection method. However, it is recommended that the Detection Unit exploits the resonance in the Power Receiver at the detection frequency f_d (see the *Power Receiver Design Requirements* section in *Parts 1 and 2: Interface Definitions*). The reason is that this approach minimizes movements of the Secondary Coil, because the Power Transmitter does not need to inform the user about objects that do not respond at this resonant frequency. *Parts 1 and 2: Interface Definitions* provides an example resonant detection method.

2.2.15.1 Mechanical details

Power Transmitter design A15 includes a single Primary Coil as defined in Section 2.2.15.1.1, Shielding as defined in Section 2.2.15.1.2, an Interface Surface as defined in Section 2.2.15.1.3, and an alignment aid as defined in Section 2.2.15.1.4.

2.2.15.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 100 strands of 0.08 mm diameter, or equivalent. As shown in Figure 50, the Primary Coil has a circular shape and consists of a single layer. Table 33 lists the dimensions of the Primary Coil.

NOTE This Primary Coil is identical to the Primary Coil of Power Transmitter Design A7.

Figure 50. Primary Coil of Power Transmitter design A15

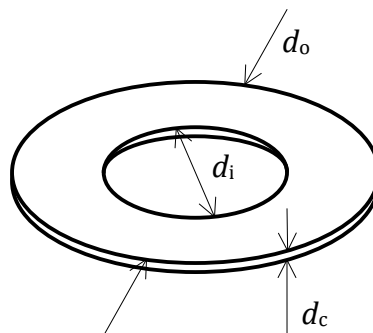


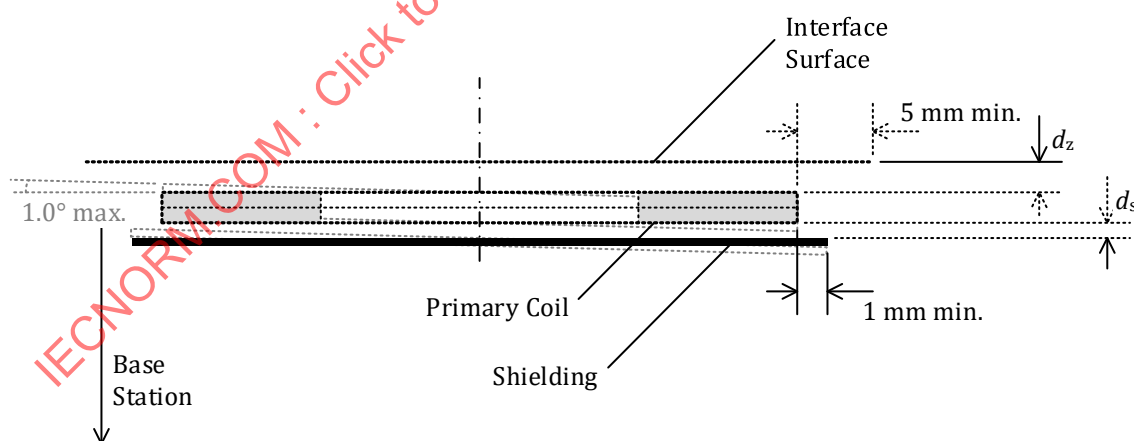
Table 33. Primary Coil parameters of Power Transmitter design A15

Parameter	Symbol	Value
Outer diameter	d_o	$39^{\pm 2}$ mm
Inner diameter	d_i	$12^{\pm 0.2}$ mm
Thickness	d_c	$1.9^{\pm 0.2}$ mm
Number of turns per layer	N	20
Number of layers	–	1

2.2.15.1.2 Shielding

As shown in Figure 51, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 1 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 0.60 mm and is placed below the Primary Coil at a distance of at most $d_s = 1.5$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- ACME K081 — Acme Electronics
- FLX-221 — Toda Kogyo Corp
- FSF501 — MARUWA

Figure 51. Primary Coil assembly of Power Transmitter design A15

2.2.15.1.3 Interface Surface

As shown in Figure 51, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 3.0^{+0.5}_{-0}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.15.1.4 Alignment aid

The alignment aid consists of a visual, audible or tactile indication, which helps a user to guide a Power Receiver into the Active Area of the Interface Surface by giving directional feedback.

NOTE An example is a LED indicator, which shows at least two directions.

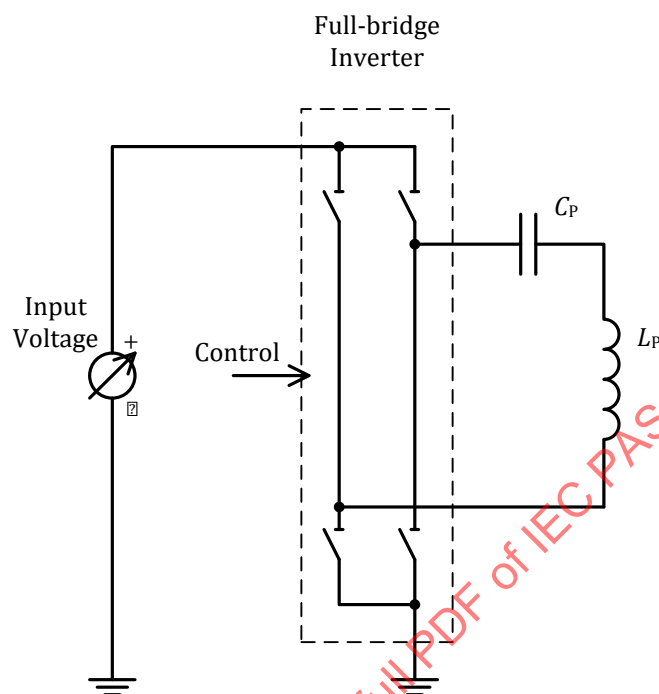
2.2.15.2 Electrical details

As shown in Figure 52, Power Transmitter design A15 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. At an Operating Frequency range between 105 kHz and 140 kHz, the assembly of Primary Coil and Shielding has a self inductance $L_p = 13.6^{+10\%}_{-5\%}$ μ H. The value of the series capacitance is $C_p = 180^{+5\%}_{-5\%}$ nF.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A15 uses the input voltage to the full-bridge inverter to control the amount of power that is transferred. For this purpose, the input voltage range is 3...12 V, where a lower input voltage results in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type A15 Power Transmitter shall be able to control the input voltage with a resolution of 50 mV or better.

When a type A15 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial input voltage of 5.7 V. It is recommended that the Power Transmitter uses an Operating Frequency of 140 kHz when first applying the Power Signal. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may reapply the Power Signal multiple times at other—consecutively lower—Operating Frequencies within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 52. Electrical diagram (outline) of Power Transmitter design A15

Control of the power transfer shall proceed using the PID algorithm, which is defined in Section *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type A15 Power Transmitter shall determine the amplitude of the Primary Cell voltage—which is equal to the Primary Coil voltage—with a resolution of 5 mV or better. Finally, Table 34 provides the values of several parameters, which are used in the PID algorithm.

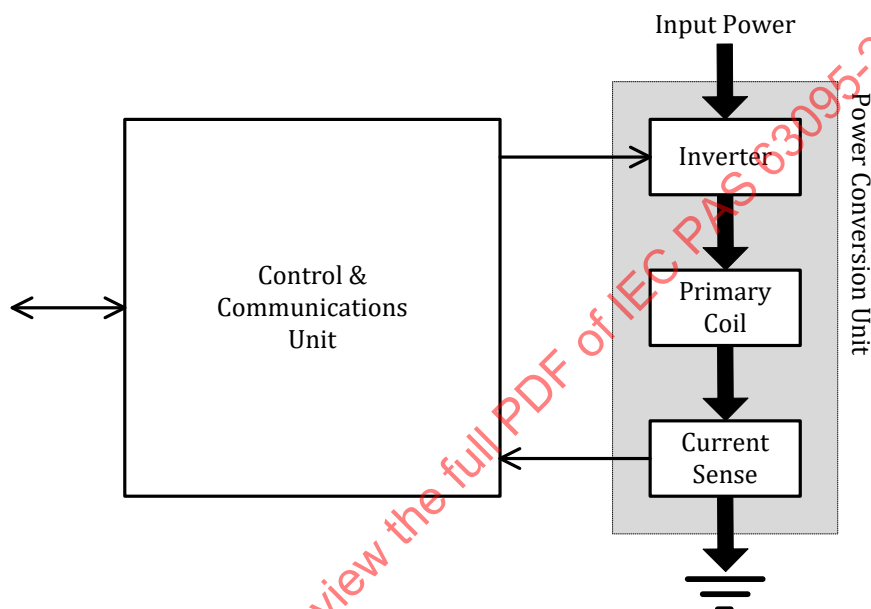
Table 34. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	–0.5	mV

2.2.16 Power Transmitter design A16

Figure 53 illustrates the functional block diagram of Power Transmitter design A16, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 53. Functional block diagram of Power Transmitter design A16



The Power Conversion Unit on the right-hand side of Figure 53 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 53 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.16.1 Mechanical details

Power Transmitter design A16 includes a single Primary Coil as defined in Section 2.2.16.1.1, Shielding as defined in Section 2.2.16.1.2, an Interface Surface as defined in Section 2.2.16.1.3, and an alignment aid as defined in Section 2.2.16.1.4.

2.2.16.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 54, the Primary Coil has a triangular shape and consists of a single layer. Table 35 lists the dimensions of the Primary Coil.

Figure 54. Primary Coil of Power Transmitter design A16

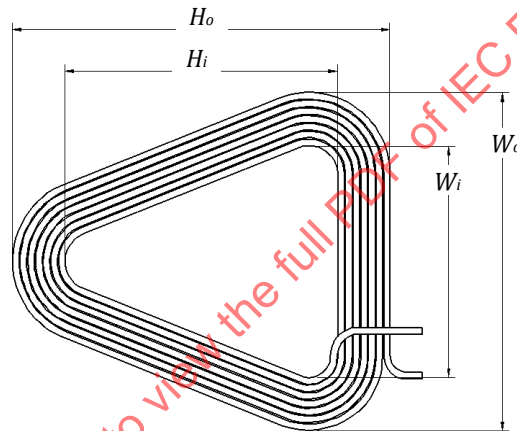


Table 35. Primary Coil parameters of Power Transmitter design A16

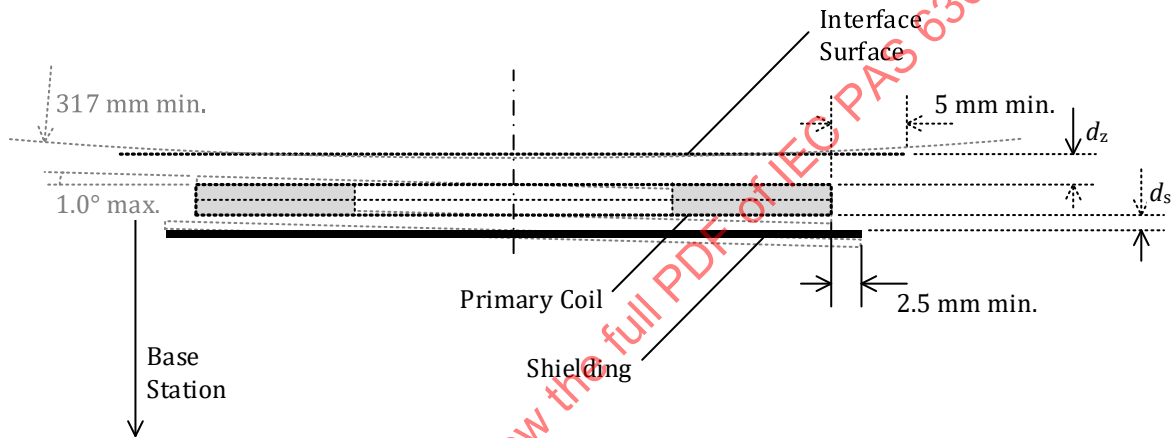
Parameter	Symbol	Value
Outer height	H_o	$59^{\pm 0.5}$ mm
Inner height	H_i	$43^{\pm 0.5}$ mm
Outer width	W_o	$52^{\pm 0.5}$ mm
Inner width	W_i	$36^{\pm 0.5}$ mm
Thickness	d_c	$1.1+0.3$ mm
Number of turns per layer	N	7
Number of layers	–	1

2.2.16.1.2 Shielding

As shown in Figure 55, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2.5 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to the following materials:

- Mn-Zn ferrite (any supplier).

Figure 55. Primary Coil assembly of Power Transmitter design A16



2.2.16.1.3 Interface Surface

As shown in Figure 55, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.5}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

NOTE This Primary-Coil-to-Interface-Surface distance implies that the tilt angle between the Primary Coil and a flat Interface Surface is at most 1.0° . Alternatively, in case of a non-flat Interface Surface, this Primary-Coil-to-Interface-Surface distance implies a radius of curvature of the Interface Surface of at least 317 mm, centered on the Primary Coil. See Figure 55.

2.2.16.1.4 Alignment aid

The user manual of the Base Station containing a type A16 Power Transmitter shall have information about the location of its Active Area(s).

For the best user experience, it is recommended to employ at least one user feedback mechanism during Mobile Device positioning to help alignment.

NOTE Examples of Base Station alignment aids to assist the user positioning of the Mobile Device include:

- A marked Interface Surface to indicate the location of the Active Area(s)—e.g. by means of the logo or other visual marking, lighting, etc.
- A visual feedback display—e.g. by means of illuminating an LED to indicate proper alignment.
- An audible or haptic feedback mechanism.

2.2.16.1.5 Inter coil separation

If the Base Station contains multiple type A16 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall not overlap.

2.2.16.2 Electrical details

As shown in Figure 56, Power Transmitter design A16 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coil, Shielding, and magnet has a self inductance $L_p = 6.3^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_p = 0.4^{\pm 5\%} \mu\text{F}$. The input voltage to the full-bridge inverter is $5^{\pm 5\%} \text{ V}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A16 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the full-bridge inverter is $f_{op} = 110 \dots 205 \text{ kHz}$ with a duty cycle of 50%; and its duty cycle range is 10...50% at an Operating Frequency of 205 kHz. A higher Operating Frequency or lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the amount of power that is transferred, a type A16 Power Transmitter shall control the Operating Frequency with a resolution of

- $0.01 \times f_{op} - 0.7 \text{ kHz}$, for f_{op} in the 110...175 kHz range;
- $0.015 \times f_{op} - 1.58 \text{ kHz}$, for f_{op} in the 175...205 kHz range;

or better. In addition, a type A16 Power Transmitter shall control the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A16 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial Operating Frequency of 175 kHz (and a duty cycle of 50%).

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency or the duty cycle. In order to guarantee sufficiently accurate power control, a type A16 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 36, Table 37, and Table 38 provide the values of several parameters, which are used in the PID algorithm.

Figure 56. Electrical diagram (outline) of Power Transmitter design A16

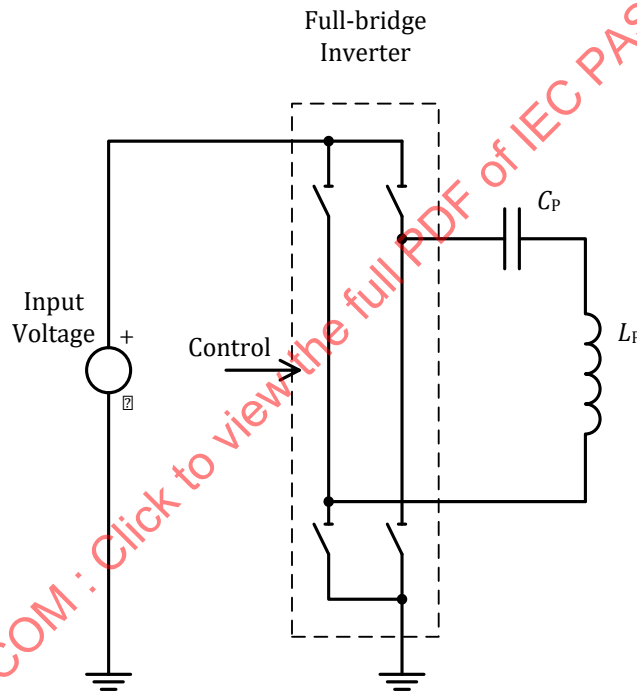


Table 36. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.

Table 37. Operating Frequency dependent scaling factor

Frequency Range [kHz]	Scaling Factor S_v [Hz]
110...140	1.5
140...160	2
160...180	3
180...205	5

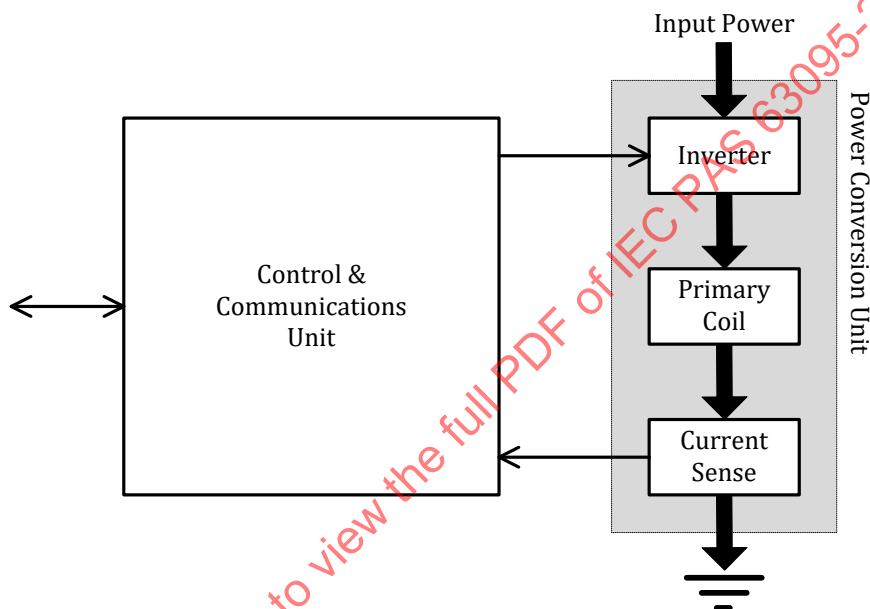
Table 38. PID parameters for duty cycle control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	–0.01	%

2.2.17 Power Transmitter design A17

Power Transmitter design A17 enables Guided Positioning. Figure 57 illustrates the functional block diagram of this design, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 57. Functional block diagram of Power Transmitter design A17



The Power Conversion Unit on the right-hand side of Figure 57 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus one or more capacitors. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 57 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the rail voltage of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.17.1 Mechanical details

Power Transmitter design A17 includes a single Primary Coil as defined in Section 2.2.17.1.1, Shielding as defined in Section 2.2.17.1.2, an Interface Surface as defined in Section 2.2.17.1.3, and an alignment aid as defined in Section 2.2.17.1.4.

2.2.17.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of no. 17 AWG (1.15 mm diameter) type 2 litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 58, the Primary Coil has a circular shape and consists of multiple layers. All layers are stacked with the same polarity. Table 39 lists the dimensions of the Primary Coil.

Figure 58. Primary Coil of Power Transmitter design A17

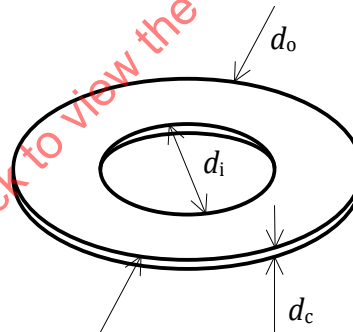


Table 39. Primary Coil parameters of Power Transmitter design A17

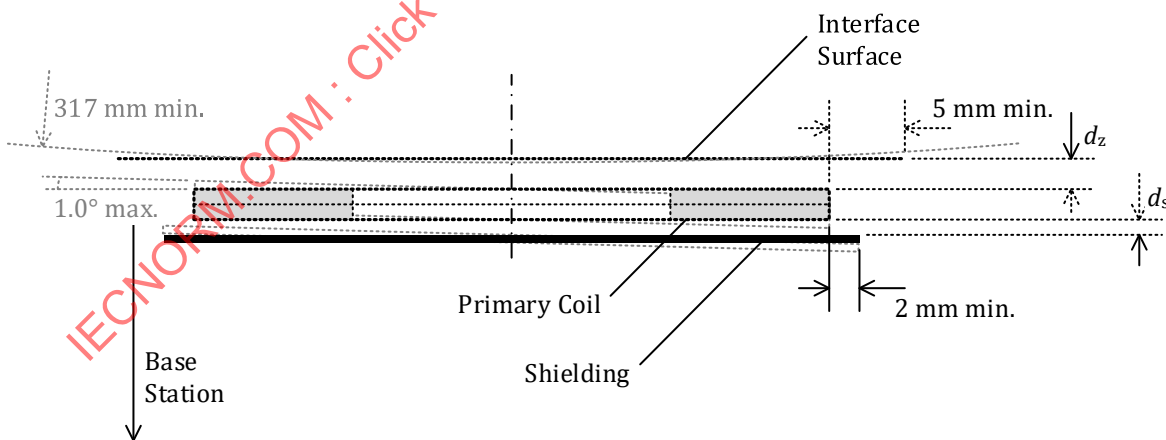
Parameter	Symbol	Value
Outer diameter	d_o	$43^{\pm 0.5}$ mm
Inner diameter	d_i	$20.5^{\pm 0.5}$ mm
Thickness	d_c	$2.1^{+0.5}$ mm
Number of turns per layer	N	10
Number of layers	–	2

2.2.17.1.2 Shielding

As shown in Figure 59, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 44 — Fair Rite Corporation.
- Material 28 — Steward, Inc.
- CMG22G — Ceramic Magnetics, Inc.
- Kolektor 22G — Kolektor.
- LeaderTech SB28B2100-1 — LeaderTech Inc.
- TopFlux “A” — TopFlux.
- TopFlux “B” — TopFlux.
- ACME K081 — Acme Electronics.
- L7H — TDK Corporation.
- PE22 — TDK Corporation.
- FK2 — TDK Corporation.

Figure 59. Primary Coil assembly of Power Transmitter design A17



2.2.17.1.3 Interface Surface

As shown in Figure 59, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 7^{+0.5}_{-5.25}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

NOTE This Primary-Coil-to-Interface-Surface distance implies that the tilt angle between the Primary Coil and a flat Interface Surface is at most 1.0°. Alternatively, in case of a non-flat Interface Surface, this Primary-Coil-to-Interface-Surface distance implies a radius of curvature of the Interface Surface of at least 317 mm, centered on the Primary Coil. See Figure 59.

2.2.17.1.4 Alignment aid

The user manual of the Base Station containing a type A17 Power Transmitter shall have information about the location of its Active Area(s).

For the best user experience, it is recommended to employ at least one user feedback mechanism during Mobile Device positioning to help alignment.

NOTE Examples of Base Station alignment aids to assist the user positioning of the Mobile Device include:

- A marked Interface Surface to indicate the location of the Active Area(s)—e.g. by means of the logo or other visual marking, lighting, etc.
- A visual feedback display—e.g. by means of illuminating an LED to indicate proper alignment.
- An audible or haptic feedback mechanism.

2.2.17.1.5 Inter coil separation

If the Base Station contains multiple type A17 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 50 mm.

2.2.17.2 Electrical details

As shown in Figure 60, Power Transmitter design A17 uses a full-bridge inverter to drive the resonant network including filter inductors, a primary Coil with a series and parallel capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coil and Shielding has a self-inductance $L_p = 24^{\pm 10\%} \mu\text{H}$. The value of inductances L_1 and L_2 is $2.2^{\pm 20\%} \mu\text{H}$. The value of the total series capacitance is $C_{\text{ser}1} + C_{\text{ser}2} = 100^{\pm 5\%} \text{nF}$, where the individual series capacitances may have any value less than the sum. The value of the parallel capacitance is $C_{\text{par}} = 200^{\pm 5\%} \text{nF}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A17 uses the input voltage to the inverter to control the amount of power transferred. For this purpose, the input voltage has a range 1.4...15 V, with a resolution of 10 mV or better; a higher input voltage results in more power transferred. The Operating Frequency is $f_{\text{op}} = 105 \dots 116 \text{ kHz}$ with a duty cycle of 50%

When a type A17 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an input voltage of 5.75 V, and a recommended Operating Frequency of 111 kHz.

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage. In order to guarantee sufficiently accurate power control, a type A17 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 40 provides the values of several parameters, which are used in the PID algorithm.

Figure 60. Electrical diagram (outline) of Power Transmitter design A17

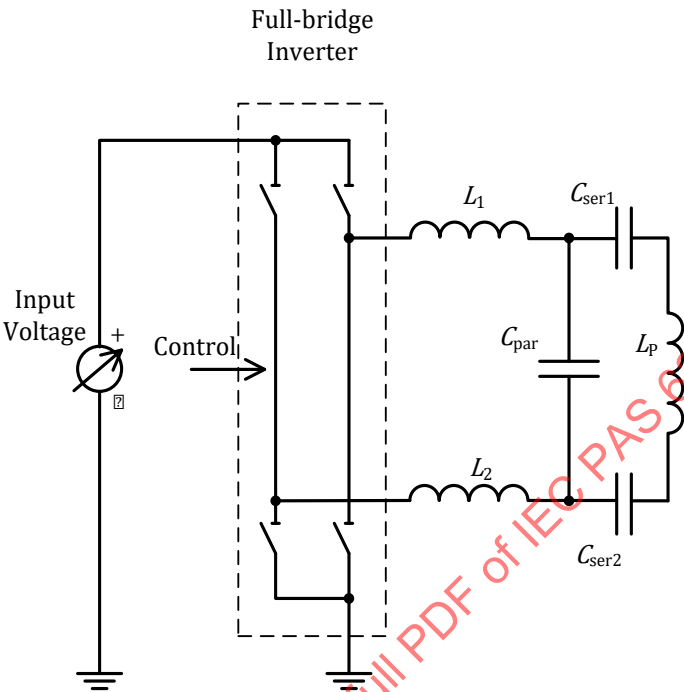


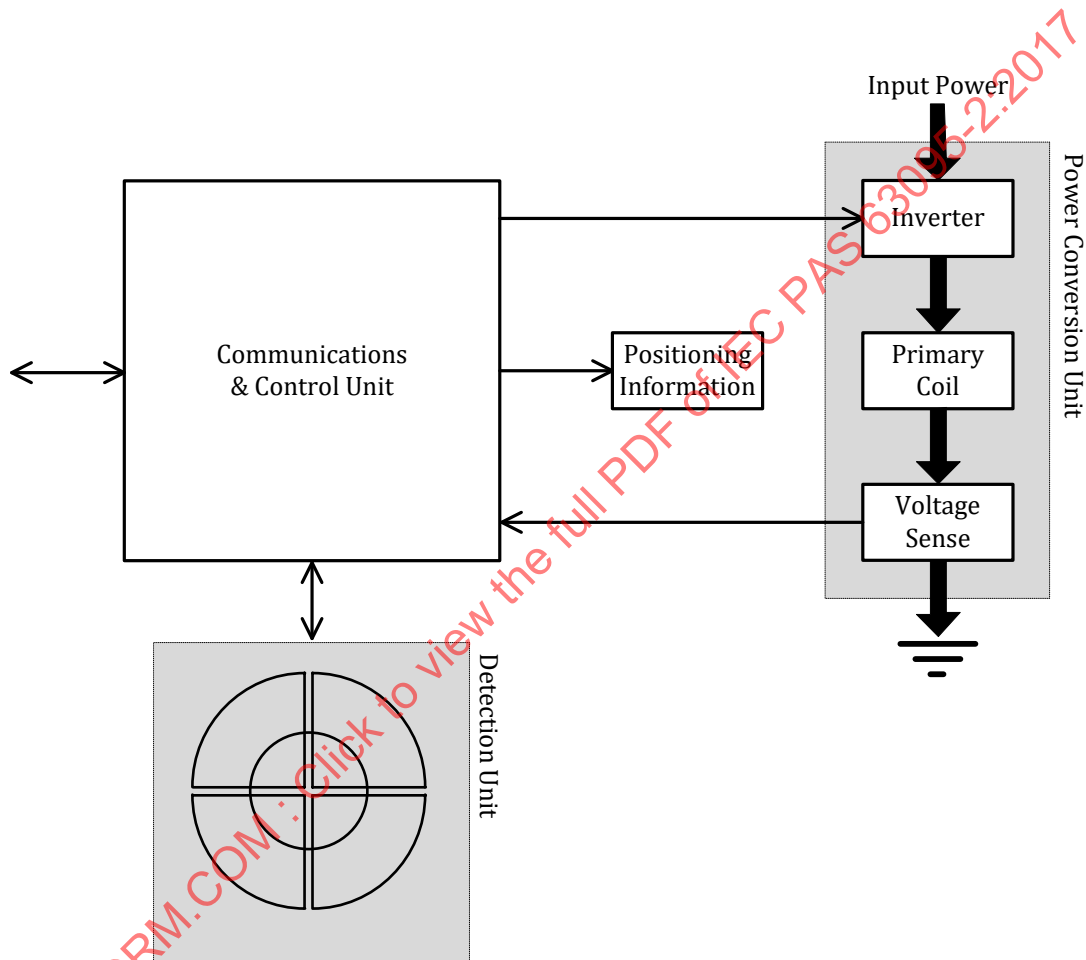
Table 40. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	1	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	1	mA^{-1}ms
Integral term limit	M_i	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	200	mV

2.2.18 Power Transmitter design A18

Figure 61 illustrates the functional block diagram of this design, which consists of three major functional units, namely a Power Conversion Unit, a Detection Unit, and a Communications and Control Unit.

Figure 61. Functional block diagram of Power Transmitter design A18



The Power Conversion Unit on the right-hand side of Figure 61 and the Detection Unit of the bottom of Figure 61 comprise the analog parts of the design. The Power Conversion Unit is similar to the Power Conversion Unit of Power Transmitter design A7. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the voltage sense monitors the Primary Coil voltage.

The Communications and Control Unit on the left-hand side of Figure 61 comprises the digital logic part of the design. This unit is similar to the Communications and Control Unit of Power Transmitter design A7. The Communications and Control Unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input voltage of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

The Detection Unit determines the approximate location of objects and/or Power Receivers on the Interface Surface. This version of *Part 4: Reference Designs* does not specify a particular detection method. However, it is recommended that the Detection Unit exploits the resonance in the Power Receiver at the detection frequency f_d (see the *Power Receiver Design Requirements* section in *Parts 1 and 2: Interface Definitions*). The reason is that this approach minimizes movements of the Secondary Coil, because the Power Transmitter does not need to inform the user about objects that do not respond at this resonant frequency. *Parts 1 and 2: Interface Definitions* provides an example resonant detection method.

2.2.18.1 Mechanical details

Power Transmitter design A18 includes a single Primary Coil as defined in Section 2.2.18.1.1, Shielding as defined in Section 2.2.18.1.2, an Interface Surface as defined in Section 2.2.18.1.3, and an alignment aid as defined in Section 2.2.18.1.4.

2.2.18.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 80 strands of 0.08 mm diameter, or equivalent. As shown in Figure 62, the Primary Coil has a circular shape and consists of a single layer. Table 41 lists the dimensions of the Primary Coil.

Figure 62. Primary Coil of Power Transmitter design A18

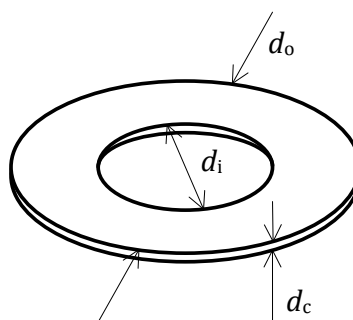


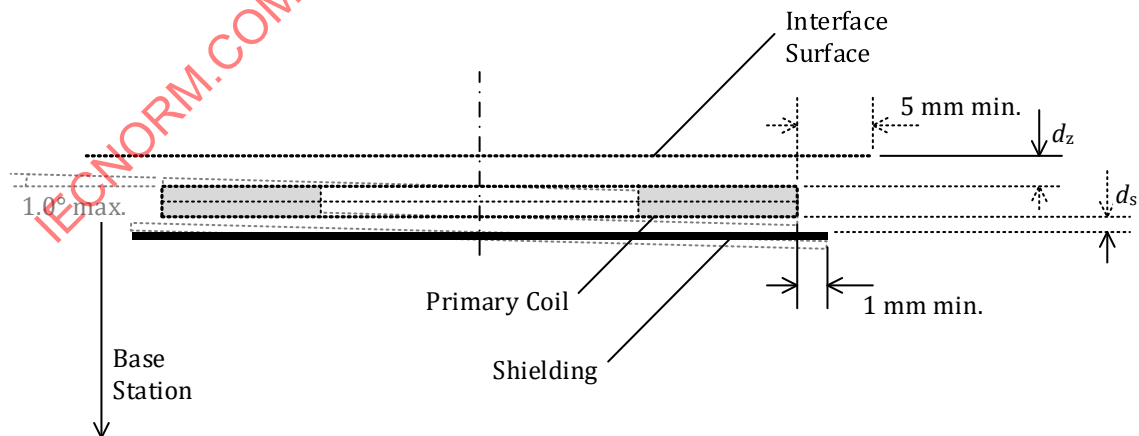
Table 41. Primary Coil parameters of Power Transmitter design A18

Parameter	Symbol	Value
Outer diameter	d_o	$39^{\pm 2}$ mm
Inner diameter	d_i	$12^{\pm 0.2}$ mm
Thickness	d_c	$1.5^{\pm 0.2}$ mm
Number of turns per layer	N	20
Number of layers	–	1

2.2.18.1.2 Shielding

As shown in Figure 63, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 1 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 0.60 mm and is placed below the Primary Coil at a distance of at most $d_s = 0.5$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- KNZWAB – Panasonic
- KNZWAC – Panasonic
- FK2 – TDK Corporation
- FK5 – TDK Corporation
- PF600F – FDK Corporation

Figure 63. Primary Coil assembly of Power Transmitter design A18

2.2.18.1.3 Interface Surface

As shown in Figure 63, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.0^{+1.5}_{-0}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5mm beyond the outer diameter of the Primary Coil.

2.2.18.1.4 Alignment aid

The alignment aid consists of a visual, audible or tactile indication, which helps a user to guide a Power Receiver into the Active Area of the Interface Surface by giving directional or distance feedback.

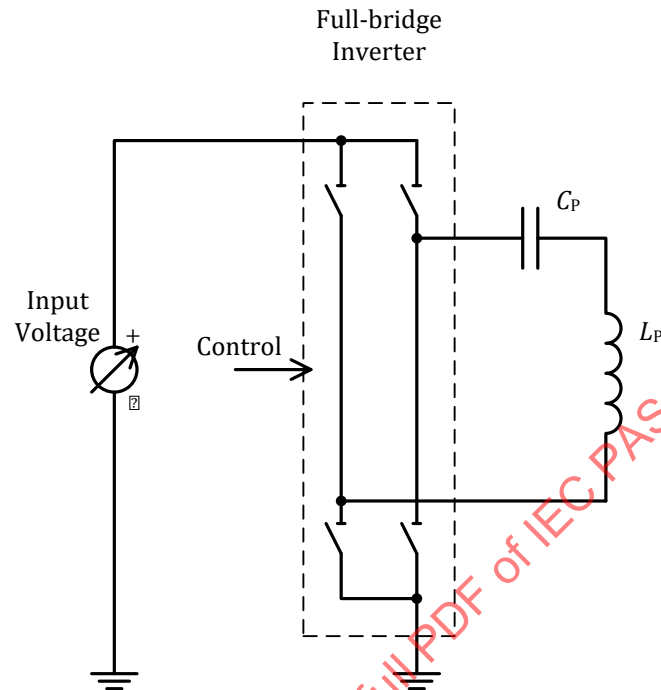
2.2.18.2 Electrical details

As shown in Figure 64, Power Transmitter design A18 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. At an Operating Frequency range between 105 kHz and 140 kHz, the assembly of Primary Coil and Shielding has a self inductance $L_p = 13.6^{\pm 10\%}$ μH . The value of the series capacitance is $C_p = 180^{\pm 5\%}$ nF.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A18 uses the input voltage to the full-bridge inverter to control the amount of power that is transferred. For this purpose, the input voltage range is 3...12 V, where a lower input voltage results in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type A18 Power Transmitter shall be able to control the input voltage with a resolution of 50 mV or better.

When a type A18 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial input voltage of 6.5 V. It is recommended that the Power Transmitter uses an Operating Frequency of 140 kHz when first applying the Power Signal. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may reapply the Power Signal multiple times at other—consecutively lower—Operating Frequencies within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 64. Electrical diagram (outline) of Power Transmitter design A18

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(t)}$ introduced in the definition of that algorithm represents the input voltage to the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type A18 Power Transmitter shall determine the amplitude of the Primary Cell voltage—which is equal to the Primary Coil voltage—with a resolution of 5 mV or better. Finally, Table 42 provides the values of several parameters, which are used in the PID algorithm.

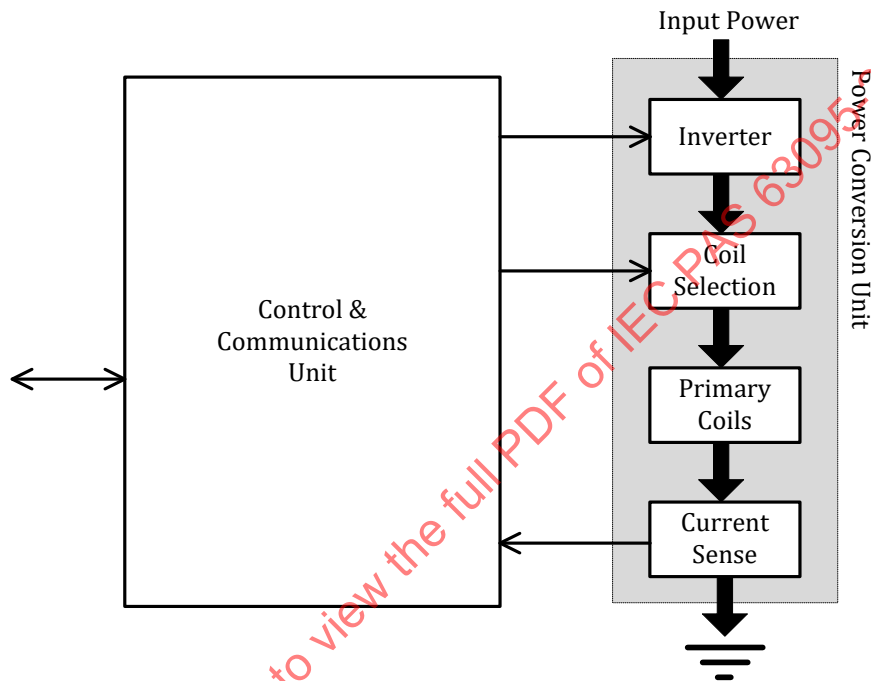
Table 42. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	–0.5	mV

2.2.19 Power Transmitter design A19

Figure 65 illustrates the functional block diagram of this design, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 65. Functional block diagram of Power Transmitter design A19



The Power Conversion Unit on the right-hand side of Figure 65 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from two partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the Primary Coils. Selection of the Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using any of the Primary Coils. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 65 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.19.1 Mechanical details

Power Transmitter design A19 includes two Primary Coils as defined in Section 2.2.19.1.1, Shielding as defined in Section 2.2.19.1.2, and an Interface Surface as defined in Section 2.2.19.1.3.

2.2.19.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of no. 20 AWG (0.81 mm diameter) type 2 litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 66, the Primary Coil has a rectangular shape and consists of a single layer. Table 43 lists the dimensions of the Primary Coil.

Figure 66. Primary Coil of Power Transmitter design A19

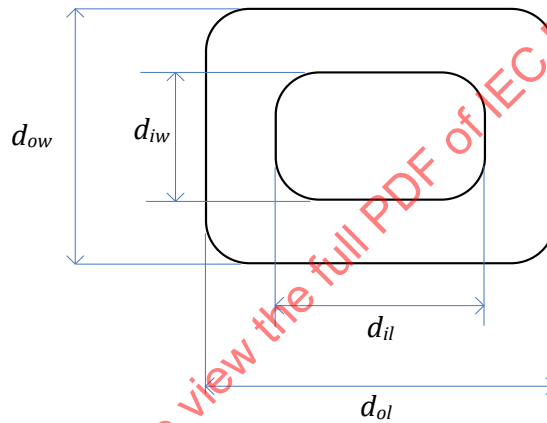
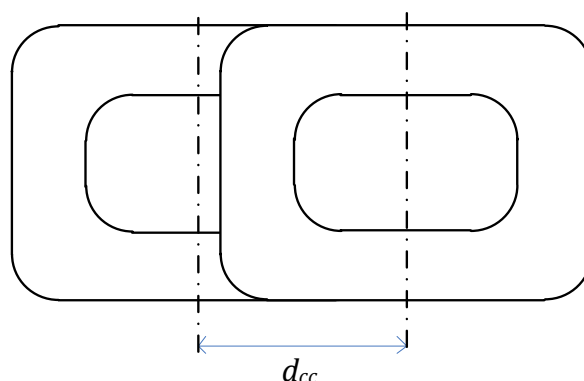


Table 43. Primary Coil parameters of Power Transmitter design A19

Parameter	Symbol	Value
Outer length	d_{ol}	$51.5^{+0.5}$ mm
Inner length	d_{il}	$29.5^{+0.5}$ mm
Outer width	d_{ow}	$43.3^{+0.5}$ mm
Inner width	d_{iw}	$21.3^{+0.5}$ mm
Thickness	d_c	$1.1^{+0.5}$ mm
Number of turns per layer	N	12 turns
Number of layers	–	1

Power Transmitter design A19 contains two overlapping Primary Coils, with coinciding long axes. The distance between the Primary Coil centers is $d_{cc} = 27^{+4}$ mm. See Figure 67.

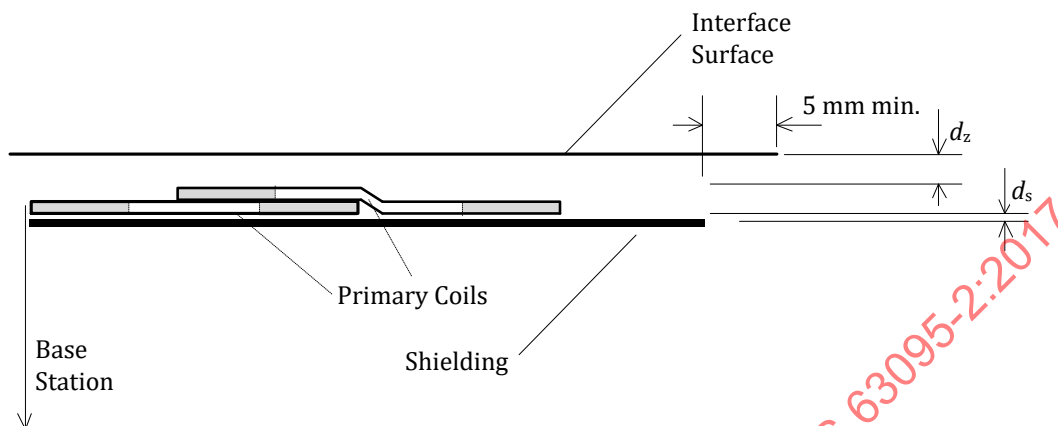
Figure 67. Primary Coils of Power Transmitter design A19

2.2.19.1.2 Shielding

As shown in Figure 68, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least the outer dimensions of the Primary Coils, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 44 — Fair Rite Corporation.
- Material 28 — Steward, Inc.
- CMG22G — Ceramic Magnetics, Inc.
- Kolektor 22G — Kolektor.
- LeaderTech SB28B2100-1 — LeaderTech Inc.
- TopFlux “A” — TopFlux.
- TopFlux “B” — TopFlux.
- ACME K081 — Acme Electronics.
- L7H — TDK Corporation.
- PE22 — TDK Corporation.
- FK2 — TDK Corporation.

Figure 68. Primary Coil assembly of Power Transmitter design A19



2.2.19.1.3 Interface Surface

As shown in Figure 68, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.25}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer dimensions of the Primary Coils.

2.2.19.1.4 Inter coil separation

If the Base Station contains multiple type A19 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 49.2^{+4} mm.

2.2.19.2 Electrical details

As shown in Figure 69, Power Transmitter design A19 uses a half-bridge inverter to drive an individual Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coils and Shielding has a self inductance $L_p = 12.2^{+10\%}$ μH for coils closest to the Interface Surface and inductance $L_p = 12.5^{+10\%}$ μH for coils furthest from the Interface Surface. The value of the series capacitance is $C_p = 0.138^{+5\%}$ μF for coils closest to the Interface Surface and $C_p = 0.136^{+5\%}$ μF for coils furthest from the Interface Surface. The input voltage to the half-bridge inverter is $12^{+5\%}$ V.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A19 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the half-bridge inverter is $f_{op} = 115 \dots 205$ kHz with a duty cycle of 50%; and its duty cycle range is 10...50% at an Operating Frequency of 205 kHz. A higher Operating Frequency or lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the amount of power that is transferred, a type A6 Power Transmitter shall control the Operating Frequency with a resolution of

- $0.01 \times f_{op} - 0.7$ kHz, for f_{op} in the 115...175 kHz range;
- $0.015 \times f_{op} - 1.58$ kHz, for f_{op} in the 175...205 kHz range;

or better. In addition, a type A19 Power Transmitter shall control the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A19 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial Operating Frequency of 175 kHz (and a duty cycle of 50%).

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency or the duty cycle. In order to guarantee sufficiently accurate power control, a type A19 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 44, Table 45, and Table 46 provide the values of several parameters, which are used in the PID algorithm.

Figure 69. Electrical diagram (outline) of Power Transmitter design A19

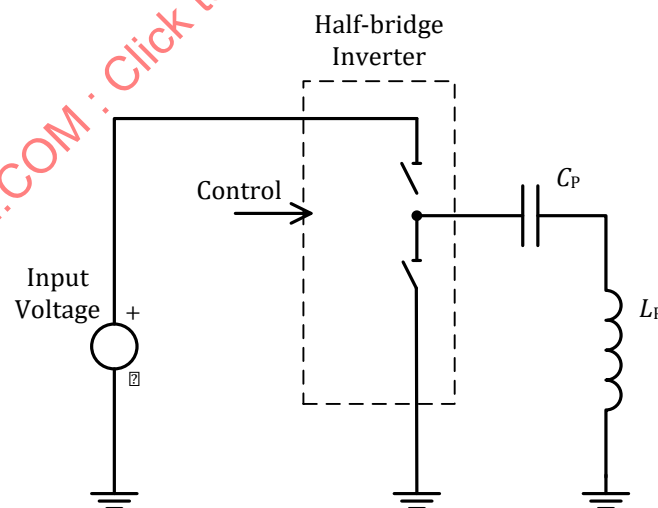


Table 44. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.

Table 45. Operating Frequency dependent scaling factor

Frequency Range [kHz]	Scaling Factor S_v [Hz]
115...140	1.5
140...160	2
160...180	3
180...205	5

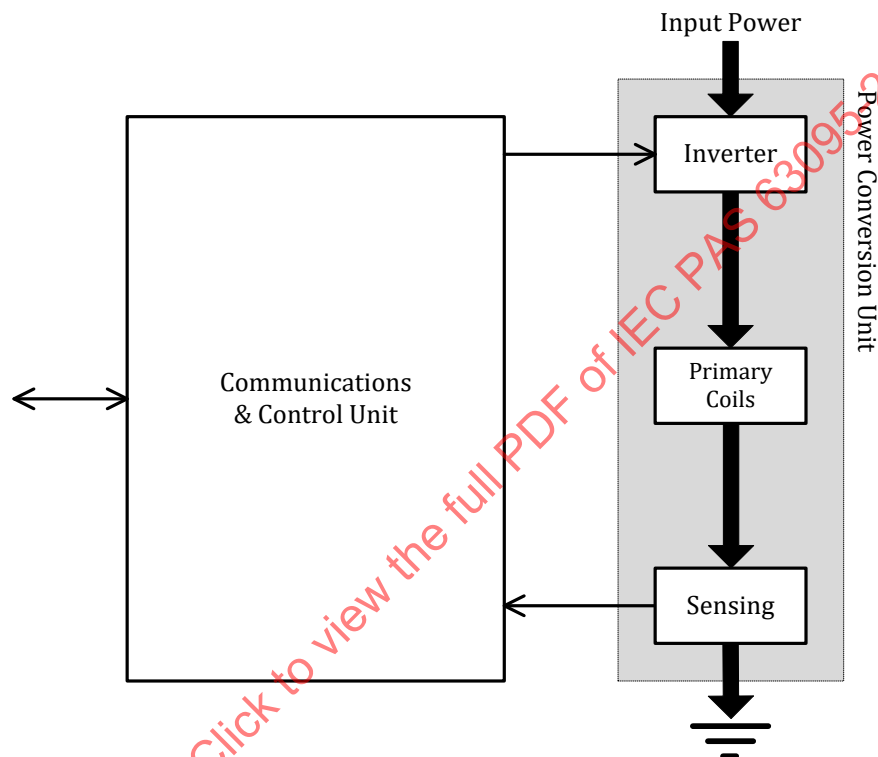
Table 46. PID parameters for duty cycle control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	–0.01	%

2.2.20 Power Transmitter design A20

Figure 70 illustrates the functional block diagram of Power Transmitter design A20, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 70. Functional block diagram of Power Transmitter design A20



The Power Conversion Unit on the right-hand side of Figure 70 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the voltage and current sense monitors the Primary Coil voltage and current.

The Communications and Control Unit on the left-hand side of Figure 70 comprises the digital logic part of the design. The unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input power and frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.20.1 Mechanical details

Power Transmitter design A20 includes one Primary Coil as defined in Section 2.2.20.1.1, Shielding as defined in Section 2.2.20.1.2, and an Interface Surface as defined in Section 2.2.20.1.3.

2.2.20.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 71, a Primary Coil has a racetrack-like shape and consists of a single layer. Table 47 lists the dimensions of a Primary Coil.

Figure 71. Primary Coil of Power Transmitter design A20

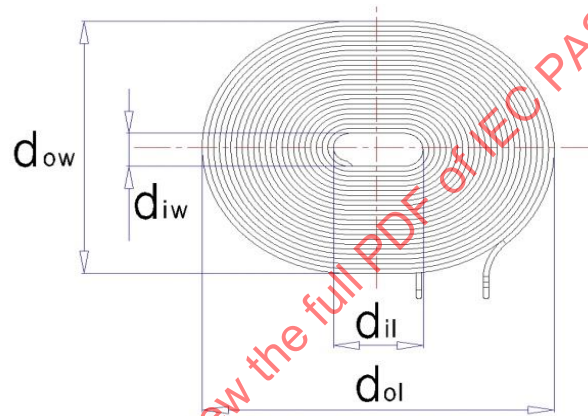


Table 47. Primary Coil parameters of Power Transmitter design A20

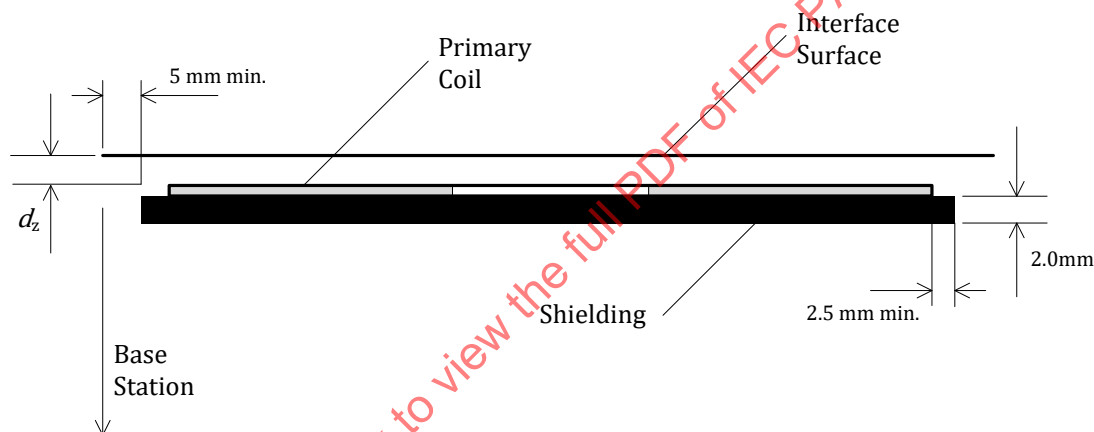
Parameter	Symbol	Value
Outer length	d_{ol}	$65.5^{+0.5}$ mm
Inner length	d_{il}	$16.5^{+0.5}$ mm
Outer width	d_{ow}	$57.1^{+0.5}$ mm
Inner width	d_{iw}	$4.5^{+0.5}$ mm
Thickness	d_c	$1.3^{+0.15}$ mm
Number of turns per layer	N	22
Number of layers	–	1

2.2.20.1.2 Shielding

As shown in Figure 72, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The top face of the Shielding block is aligned with the top face of the Primary Coil, such that the Shielding surrounds the Primary Coil on all sides except for the top face. In addition, the Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coil, and has a thickness of at least 2.0 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Mn-Zn-Ferrite Dust Core — any supplier
- Ni-Zn-Ferrite Core — any supplier

Figure 72. Primary Coil assembly of Power Transmitter design A20



2.2.20.1.3 Interface Surface

As shown in Figure 72, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 3.0^{+0.5}_{-0.5}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.20.1.4 Separation between multiple Power transmitters

If the Base Station contains multiple type A20 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least $65.0^{+0.5}_{-0.5}$ mm.

2.2.20.2 Electrical details

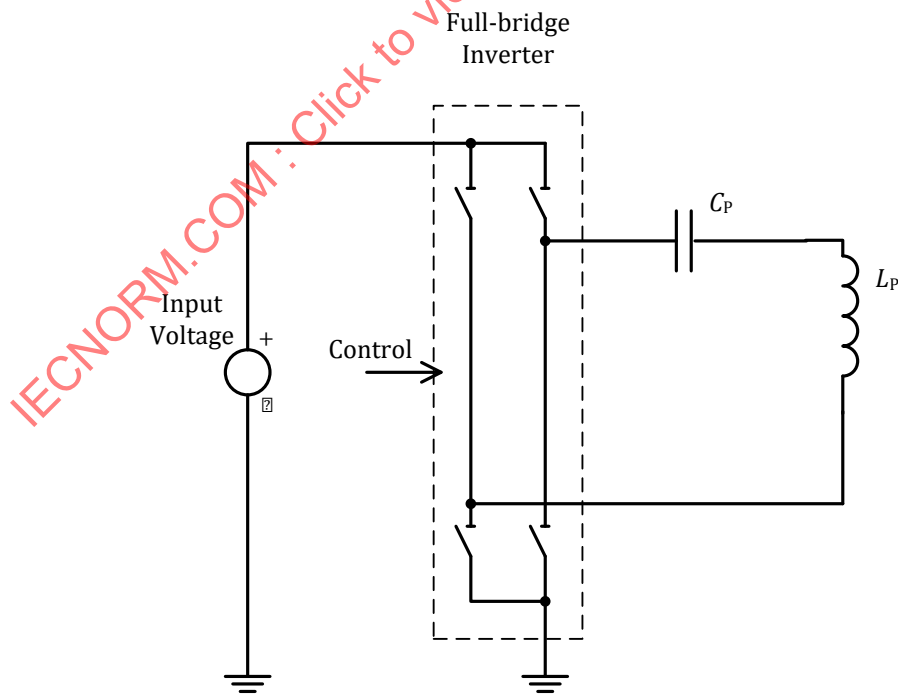
As shown in Figure 73, Power Transmitter design A20 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range Specified below, the assembly of Primary Coil and Shielding has a self inductance $L_P = 24^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_P = 148^{\pm 5\%} \text{nF}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A20 uses the input voltage to the full-bridge inverter to control the amount of power transferred. For this purpose, the input voltage has a range $2.5^{\pm 0.5} \dots 11.5^{\pm 0.5} \text{ V}$, with a resolution of 10mV or better; a higher input voltage results in more power transferred. The Operating Frequency range is $f_{\text{op}} = 87 \dots 110 \text{ kHz}$.

When a type A20 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an Operating Frequency of 98 kHz, and an input voltage of $5.5^{\pm 2.0} \text{ V}$. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may reapply the Power Signal multiple times at consecutively lower-Operating Frequencies within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 73. Electrical diagram (outline) of Power Transmitter design A20



Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents Operating Frequency as well as the input voltage to the full-bridge inverter. It is recommended that control of the power occurs primarily by means of adjustments to the Operating Frequency, and that voltage adjustments are made only at the boundaries of the Operating Frequency range. In order to guarantee sufficiently accurate power control, a type A20 Power Transmitter shall determine the amplitude of the Primary Coil current with a resolution of 5 mA or better. Finally, Table 48 and Table 49 provide the values of several parameters, which are used in the PID algorithm.

Table 48. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA ⁻¹
Integral gain	K_i	0	mA ⁻¹ ms ⁻¹
Derivative gain	K_d	0	mA ⁻¹ ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

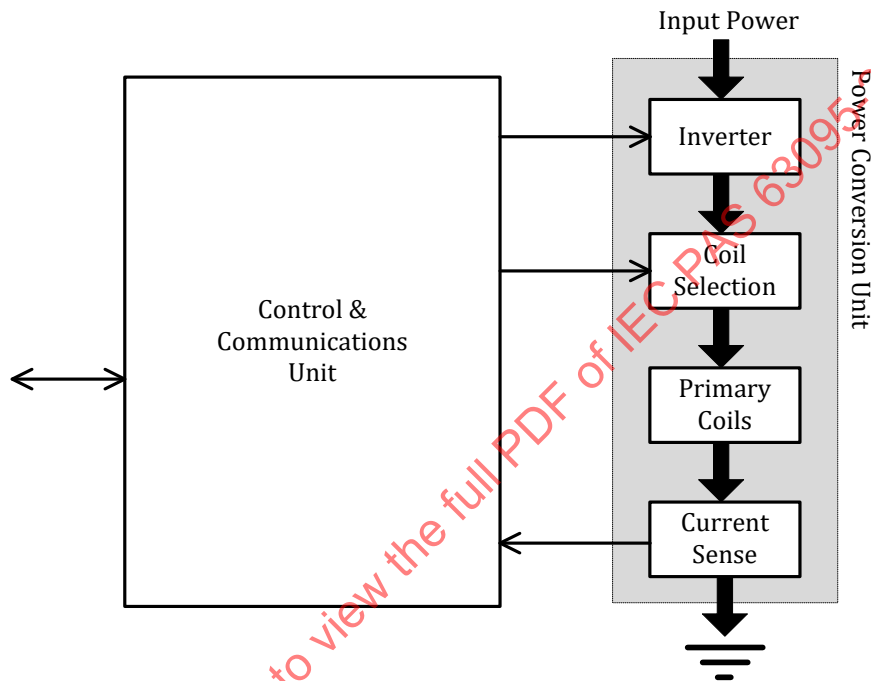
Table 49. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA ⁻¹
Integral gain	K_i	0	mA ⁻¹ ms ⁻¹
Derivative gain	K_d	0	mA ⁻¹ ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	–0.5	mV

2.2.21 Power Transmitter design A21

Figure 74 illustrates the functional block diagram of this Power Transmitter design A21, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 74. Functional block diagram of Power Transmitter design A21



The Power Conversion Unit on the right-hand side of Figure 74 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from at least three partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the Primary Coils. Selection of the Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using any of the Primary Coils. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 74 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.21.1 Mechanical details

Power Transmitter design A21 includes one or more Primary Coils as defined in Section 2.2.21.1.1, Shielding as defined in Section 2.2.21.1.2, an Interface Surface as defined in Section 2.2.21.1.3.

2.2.21.1.1 Primary Coil

The Primary Coil consists of at least one PCB coil. Figure 75 shows a view of a single Primary Coil. Table 50 lists the dimensions of the Primary Coil.

Figure 75. Primary Coil of Power Transmitter design A21

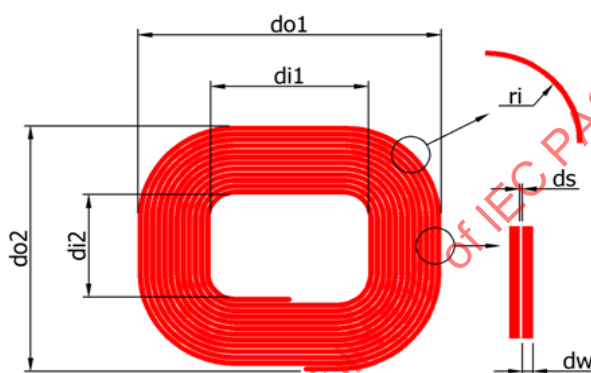


Table 50. Primary Coil parameters of Power Transmitter design A21

Parameter	Symbol	Value
Outer length	d_{o1}	$53.4^{+0.7}$ mm
Inner length	d_{i1}	$27.5^{+0.7}$ mm
Outer width	d_{o2}	$45.8^{+0.7}$ mm
Inner width	d_{i2}	$19.5^{+0.75}$ mm
4-layer PCB		
Track width	d_w	$0.82^{+0.2}$ mm
Track width plus spacing	$d_w + d_s$	$1.08^{+0.2}$ mm
Corner rounding*	r_i	$16.7^{+1.0}$ mm
Number of turns	N	12
5...8 layer PCB		
Track width	d_w	$0.55^{+0.15}$ mm
Track width plus spacing	$d_w + d_s$	$1.1^{+0.15}$ mm
Corner rounding*	r_i	$13.1^{+1.31}$ mm
Number of turns	N	12 ± 0.25

* Outermost winding only

Power Transmitter design A21 contains at least one Primary Coil. Odd numbered coils are placed alongside each other with a displacement of d_{h2} between their centers. Even numbered coils are placed orthogonal to the odd numbered coils with a displacement of d_{h1} mm between their centers. See Figure 76.

Figure 76. Primary Coils of Power Transmitter design A21

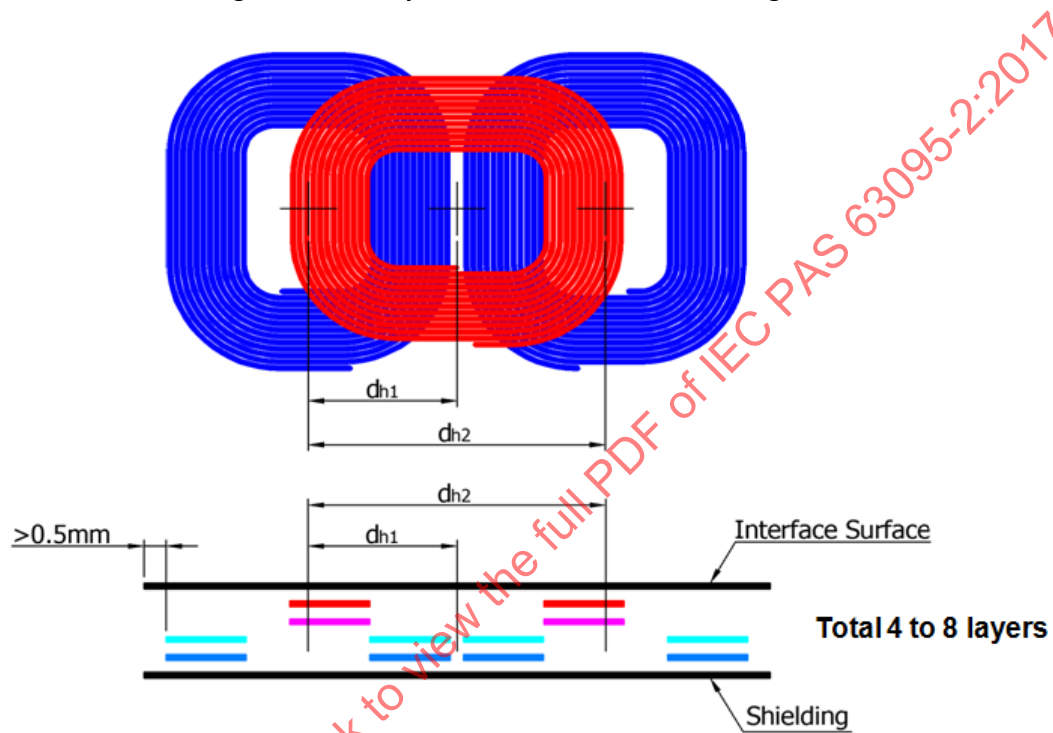


Figure 77. Primary Coils of Power Transmitter design A21

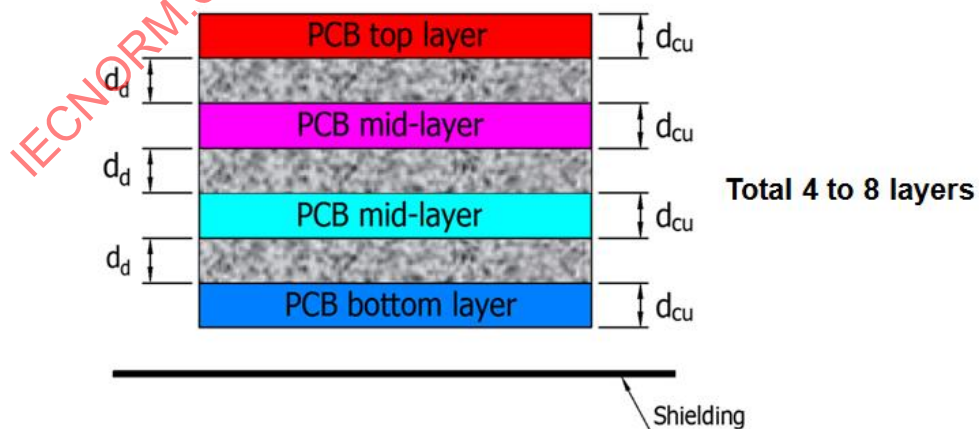


Table 51. Primary Coil parameters of Power Transmitter design A21

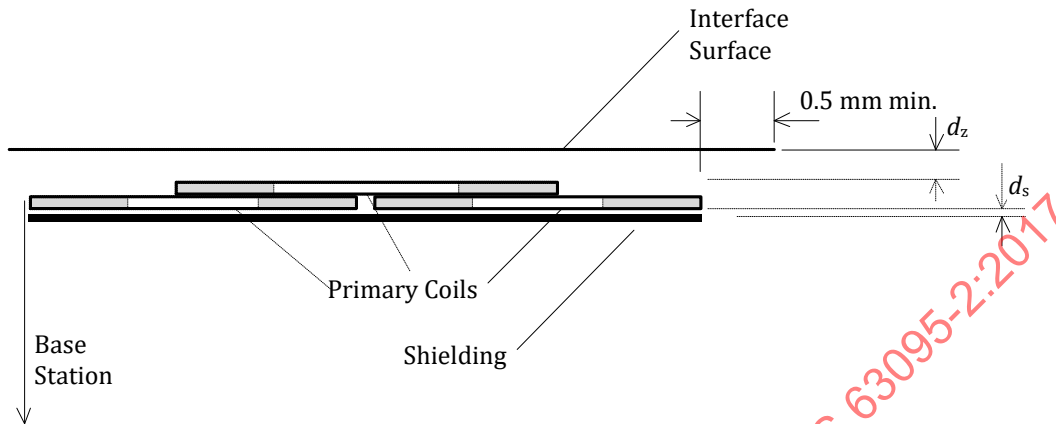
Parameter	Symbol	Value
4-layer PCB		
Center-to-center distance	d_{h1}	$23.8^{+1.0}$ mm
Center-to-center distance	d_{h2}	$47.52^{+2.0}$ mm
PCB copper thickness	d_{Cu}	$0.105^{+0.015}$ mm
Dielectric thickness	d_d	$0.375^{+0.063}$ mm
5...8 layer PCB		
Center-to-center distance	d_{h1}	$23.76^{+1.5}$ mm
Center-to-center distance	d_{h2}	47.52^{+3} mm
PCB copper thickness	d_{Cu}	$0.105^{+0.0161}$ mm
Dielectric thickness	d_d	$0.125^{+0.0254}$ mm

2.2.21.1.2 Shielding

As shown in Figure 78, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least the outer dimensions of the Primary Coils, has a thickness of at least 0.8 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- FK2 (TDK) – (Ni-Zn)
- FK5 (TDK) – (Ni-Zn)
- L7H (TDK) – (Ni-Zn)
- PE22 (TDK) – (Mn-Zn)
- P41 (ACME) – (Mn-Zn)
- K081 (ACME) – (Ni-Zn)

Figure 78. Primary Coil assembly of Power Transmitter design A21



2.2.21.1.3 Interface Surface

As shown in Figure 78, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.75^{+1}_{-1}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 0.5 mm beyond the outer dimensions of the Primary Coils.

2.2.21.1.4 Inter coil separation

If the Base Station contains multiple type A21 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 49.2^{+4}_{-4} mm.

2.2.21.2 Electrical details

As shown in Figure 79, Power Transmitter design A21 uses a half-bridge inverter to drive an individual Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coils and Shielding has a self inductance $L_p = 11.5^{+10\%}_{-10\%}$ μH for coils closest to the Interface Surface and inductance $L_p = 12.5^{+10\%}_{-10\%}$ μH for coils furthest from the Interface Surface. The value of the series capacitance is $C_p = 0.147^{+5\%}_{-5\%}$ μF for coils closest to the Interface Surface and $C_p = 0.136^{+5\%}_{-5\%}$ μF for coils furthest from the Interface Surface. The input voltage to the half-bridge inverter is $12^{+5\%}_{-5\%}$ V.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A21 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the half-bridge inverter is $f_{op} = 115 \dots 205$ kHz with a duty cycle of 50%; and its duty cycle range is 10...50% at an Operating Frequency of 205 kHz. A higher Operating Frequency or lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the amount of power that is transferred, a type A21 Power Transmitter shall control the Operating Frequency with a resolution of

- $0.01 \times f_{op} - 0.7$ kHz, for f_{op} in the 115...175 kHz range;
- $0.015 \times f_{op} - 1.58$ kHz, for f_{op} in the 175...205 kHz range;

or better. In addition, a type A21 Power Transmitter shall control the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A21 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial Operating Frequency of 175 kHz (and a duty cycle of 50%).

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency or the duty cycle. In order to guarantee sufficiently accurate power control, a type A21 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 52, Table 53, and Table 54 provide the values of several parameters, which are used in the PID algorithm.

Figure 79. Electrical diagram (outline) of Power Transmitter design A21

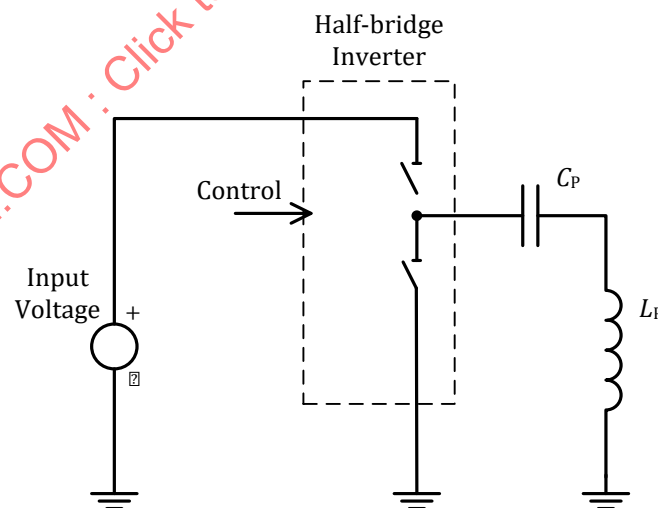


Table 52. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.

Table 53. Operating Frequency dependent scaling factor

Frequency Range [kHz]	Scaling Factor S_v [Hz]
115...140	1.5
140...160	2
160...180	3
180...205	5

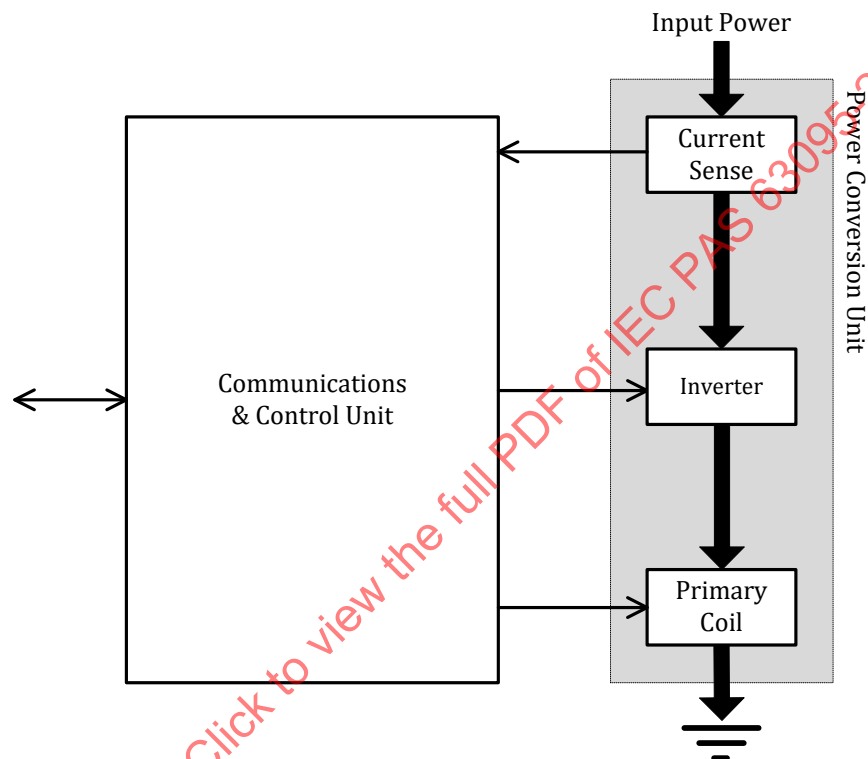
Table 54. PID parameters for duty cycle control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-0.01	%

2.2.22 Power Transmitter design A22

Figure 80 illustrates the functional block diagram of Power Transmitter design A22, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 80. Functional block diagram of Power Transmitter design A22



The Power Conversion Unit on the right-hand side of Figure 80 comprises the analog parts of the design. The voltage and current sense monitors the input voltage and current. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor.

The Communications and Control Unit on the left-hand side of Figure 80 comprises the digital logic part of the design. The unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input power and frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.22.1 Mechanical details

Power Transmitter design A22 includes one Primary Coil as defined in Section 2.2.22.1.1, Shielding as defined in Section 2.2.22.1.2, and an Interface Surface as defined in Section 2.2.22.1.3.

2.2.22.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 81, a Primary Coil has a racetrack-like shape and consists of a single layer. Table 55 lists the dimensions of a Primary Coil.

Figure 81. Primary Coil of Power Transmitter design A22

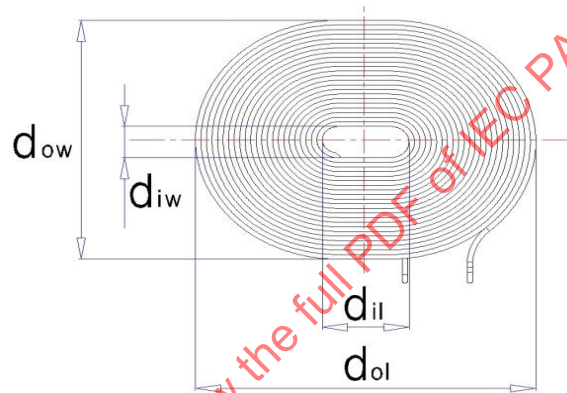


Table 55. Primary Coil parameters of Power Transmitter design A22

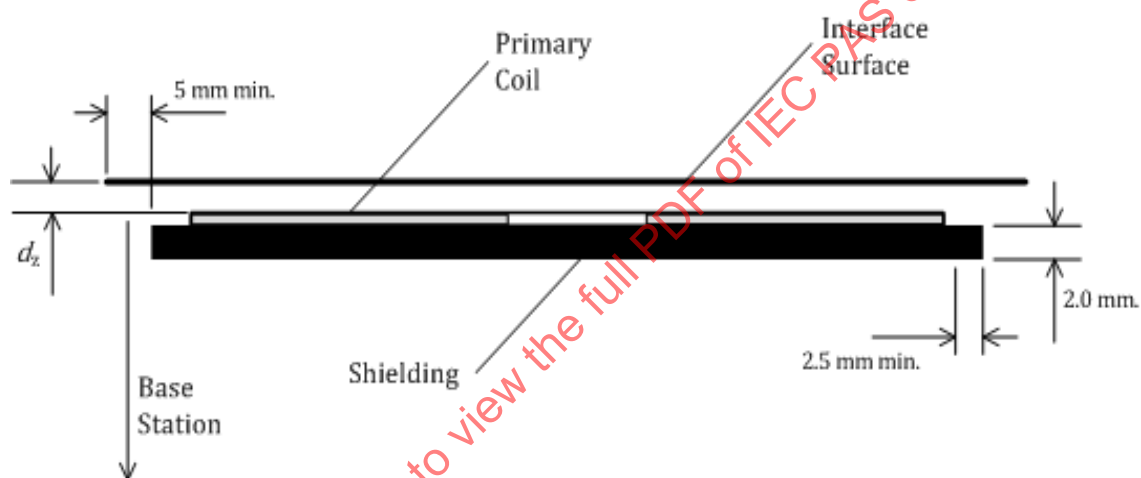
Parameter	Symbol	Value
Outer length	d_{ol}	$65.5^{+0.5}$ mm
Inner length	d_{il}	$16.5^{+0.5}$ mm
Outer width	d_{ow}	$57.1^{+0.5}$ mm
Inner width	d_{iw}	$4.5^{+0.5}$ mm
Thickness	d_c	$1.3^{+0.15}$ mm
Number of turns per layer	N	22
Number of layers	–	1

2.2.22.1.2 Shielding

As shown in Figure 82, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding may surround the Primary Coil on all sides except for the top face. In addition, the Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coil, and has a thickness of at least 2.0 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Mn-Zn-Ferrite Core – any supplier
- Sendust-Ferrite Core – any supplier

Figure 82. Primary Coil assembly of Power Transmitter design A22



2.2.22.1.3 Interface Surface

As shown in Figure 82, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.5 \pm 1.0$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.22.1.4 Separation between multiple Power transmitters

If the Base Station contains multiple type A22 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 66 mm.

2.2.22.2 Electrical details

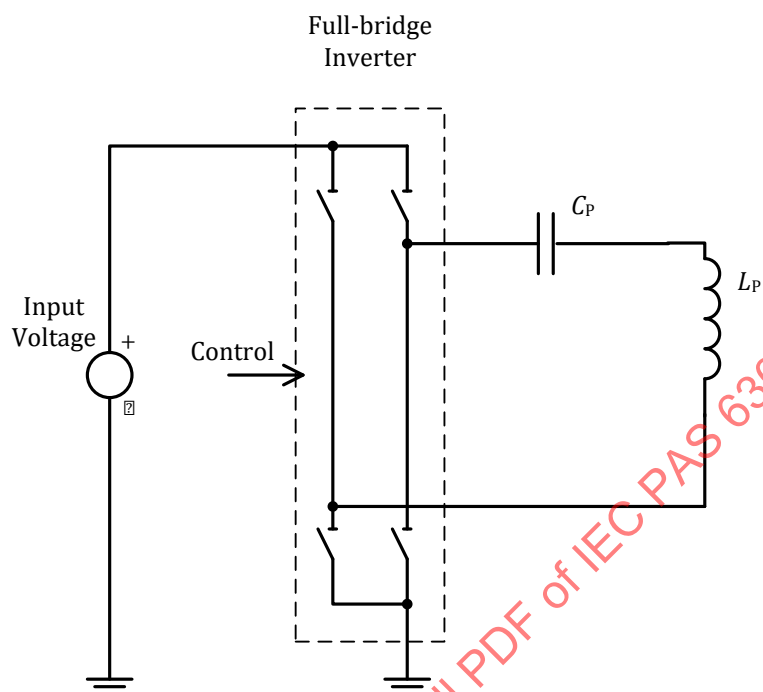
As shown in Figure 83, Power Transmitter design A22 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range Specified below, the assembly of Primary Coil and Shielding has a self inductance $L_p = 19.0^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_p = 122^{\pm 10\%} \text{nF}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A22 uses the input voltage to the full-bridge inverter as well as its Operating Frequency and duty cycle to control the amount of power transferred. For this purpose, the input voltage range is 2 ... 12 V, with a resolution of 10 mV or better; the Operating Frequency range is 110 ... 205 kHz; and the duty cycle range is 2 ... 50%.

When a type A22 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an Operating Frequency of $125^{\pm 10} \text{kHz}$, and an input voltage of 3.5 ... 7.5 V. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may re-apply the power signal multiple times at consecutively higher input voltage to the full-bridge inverter within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable v_i introduced in the definition of that algorithm represents the input voltage to the full-bridge inverter, Operating Frequency and duty cycle. It is recommended that control of the power occurs primarily by means of adjustments to the input voltage. In order to guarantee sufficiently accurate power control, a type A22 Power Transmitter shall determine the amplitude of the Primary Coil current with a resolution of 5 mA or better. Finally, Table 56, Table 57, and Table 58 provide the values of several parameters, which are used in the PID algorithm.

Figure 83. Electrical diagram (outline) of Power Transmitter design A22**Table 56. PID parameters for voltage control**

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA-1
Integral gain	K_i	0	mA-1ms-1
Derivative gain	K_d	0	mA-1ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	-0.5	mV

Table 57. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

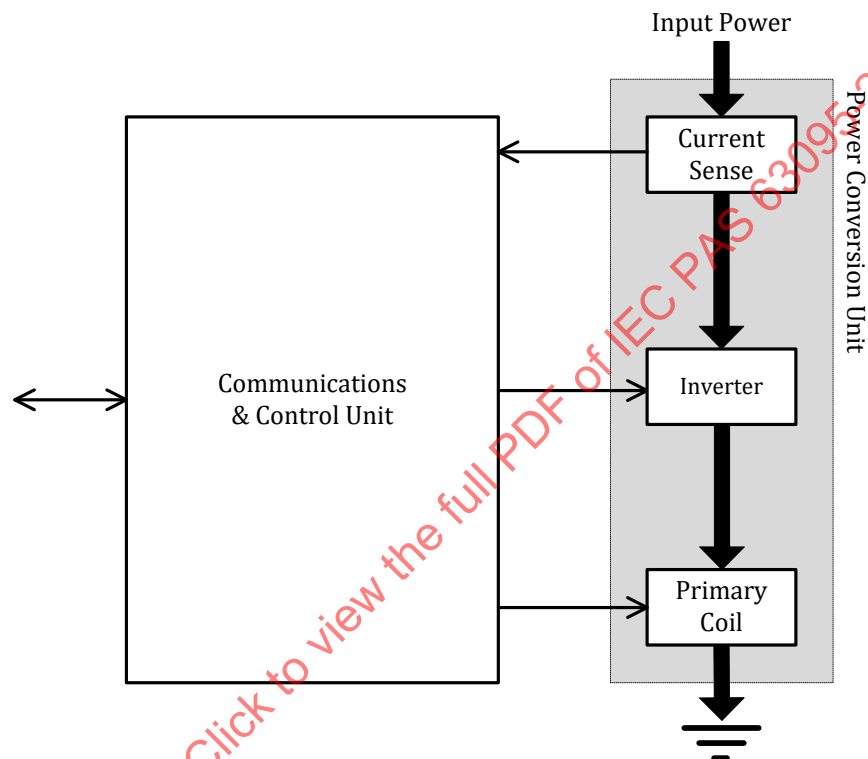
Table 58. PID parameters for duty control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-0.1	°

2.2.23 Power Transmitter design A23

Figure 84 illustrates the functional block diagram of Power Transmitter design A23, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 84. Functional block diagram of Power Transmitter design A23



The Power Conversion Unit on the right-hand side of Figure 84 comprises the analog parts of the design. The voltage and current sense monitors the input voltage and current. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor.

The Communications and Control Unit on the left-hand side of Figure 84 comprises the digital logic part of the design. The unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input power and frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.23.1 Mechanical details

Power Transmitter design A23 includes one Primary Coil as defined in Section 2.2.23.1.1, Shielding as defined in Section 2.2.23.1.2, and an Interface Surface as defined in Section 2.2.23.1.3.

2.2.23.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 85, a Primary Coil has a racetrack-like shape and consists of a single layer. Table 59 lists the dimensions of a Primary Coil.

Figure 85. Primary Coil of Power Transmitter design A23

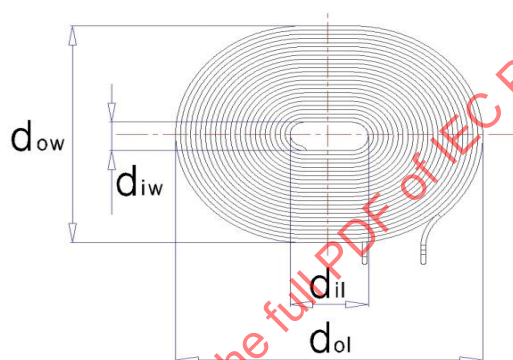


Table 59. Primary Coil parameters of Power Transmitter design A23

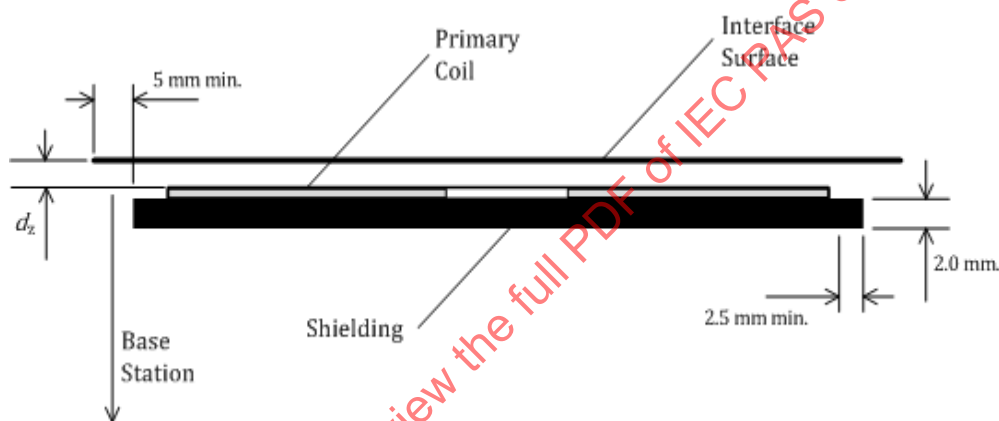
Parameter	Symbol	Value
Outer length	d_{ol}	$65.5^{±0.5}$ mm
Inner length	d_{il}	$16.5^{±0.5}$ mm
Outer width	d_{ow}	$57.1^{±0.5}$ mm
Inner width	d_{iw}	$4.5^{±0.5}$ mm
Thickness	d_c	$1.3^{±0.15}$ mm
Number of turns per layer	N	22
Number of layers	–	1

2.2.23.1.2 Shielding

As shown in Figure 86, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding may surround the Primary Coil on all sides except for the top face. In addition, the Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coil, and has a thickness of at least 2.0 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Mn-Zn-Ferrite Core – any supplier
- Sendust-Ferrite Core – any supplier

Figure 86. Primary Coil assembly of Power Transmitter design A23



2.2.23.1.3 Interface Surface

As shown in Figure 86, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.5 \pm 1.0$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.23.1.4 Separation between multiple Power transmitters

If the Base Station contains multiple type A23 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 66 mm.

2.2.23.2 Electrical details

As shown in Figure 87, Power Transmitter design A23 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range Specified below, the assembly of Primary Coil and Shielding has a self inductance $L_p = 19.0^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_p = 168^{\pm 10\%} \text{nF}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A23 uses the input voltage to the full-bridge inverter as well as its Operating Frequency and duty cycle to control the amount of power transferred. For this purpose, the input voltage range is 2 ... 12 V, with a resolution of 10 mV or better; the Operating Frequency range is 101...115 kHz; and the duty cycle range is 2 ... 50%.

When a type A23 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an Operating Frequency of $108^{\pm 5} \text{kHz}$, and an input voltage of 3.5 ... 7.5 V. If the Power Transmitter does not to receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may re-apply the power signal multiple times at consecutively higher input voltage to the full-bridge inverter within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable v_i introduced in the definition of that algorithm represents the input voltage to the full-bridge inverter, Operating Frequency and duty cycle. It is recommended that control of the power occurs primarily by means of adjustments to the input voltage. In order to guarantee sufficiently accurate power control, a type A23 Power Transmitter shall determine the amplitude of the Primary Coil current with a resolution of 5 mA or better. Finally, Table 60, Table 61, and Table 62 provide the values of several parameters, which are used in the PID algorithm.

Figure 87. Electrical diagram (outline) of Power Transmitter design A23

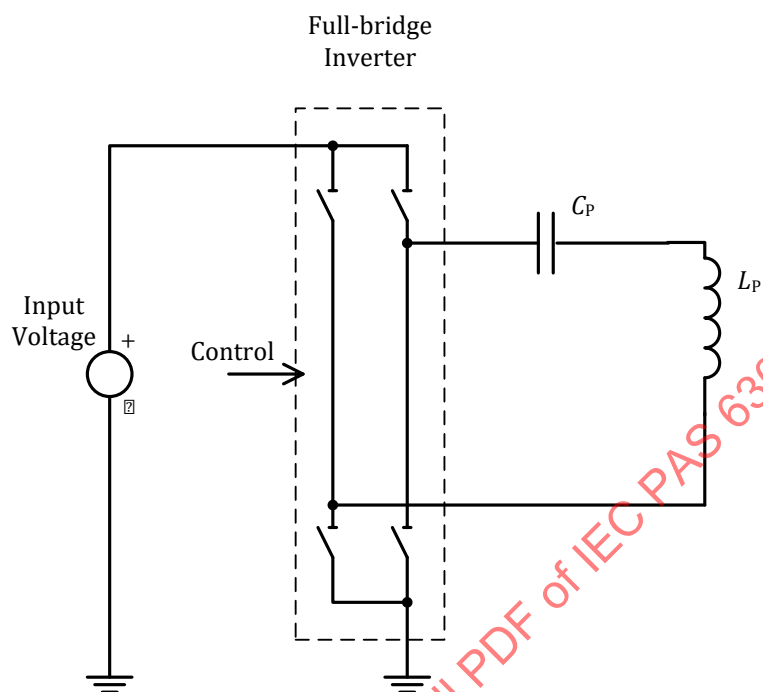


Table 60. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA-1
Integral gain	K_i	0	mA-1ms-1
Derivative gain	K_d	0	mA-1ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	1,500	N.A.
Scaling factor	S_v	-0.5	mV

Table 61. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

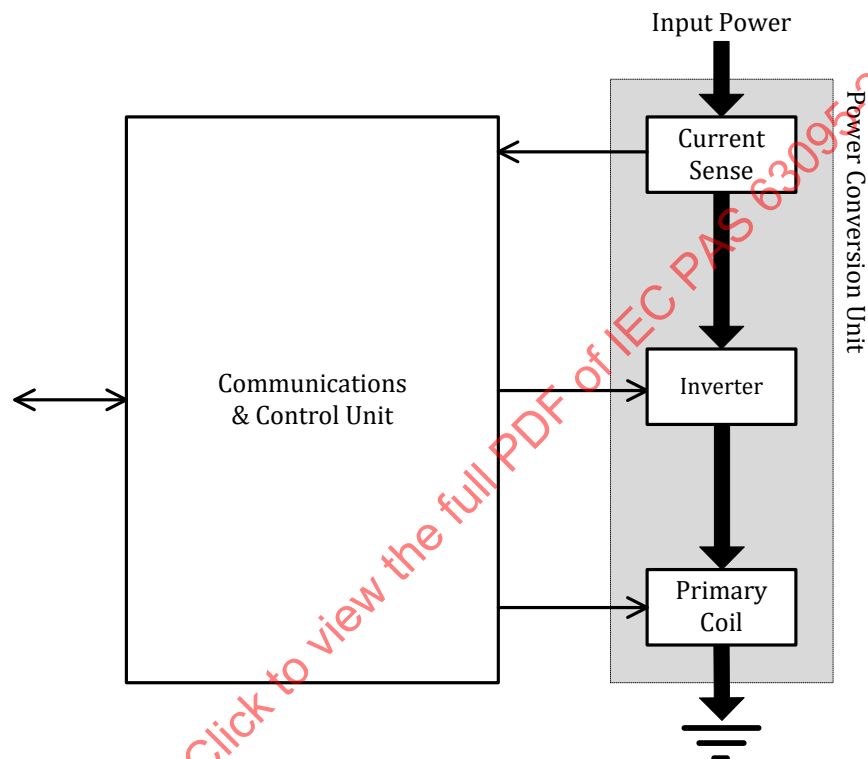
Table 62. PID parameters for duty control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-0.1	°

2.2.24 Power Transmitter design A24

Figure 88 illustrates the functional block diagram of Power Transmitter design A24, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 88. Functional block diagram of Power Transmitter design A24



The Power Conversion Unit on the right-hand side of Figure 88 comprises the analog parts of the design. The voltage and current sense monitors the input voltage and current. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor.

The Communications and Control Unit on the left-hand side of Figure 88 comprises the digital logic part of the design. The unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input power and frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.24.1 Mechanical details

Power Transmitter design A24 includes one Primary Coil as defined in Section 2.2.24.1.1, Shielding as defined in Section 2.4.3.1.2, and an Interface Surface as defined in Section 2.2.24.1.3.

2.2.24.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 105 strands of 0.08 mm diameter, or equivalent. As shown in Figure 89, a Primary Coil has a circular shape and consists of a single layer. Table 63 lists the dimensions of a Primary Coil.

Figure 89. Primary Coil of Power Transmitter design A24

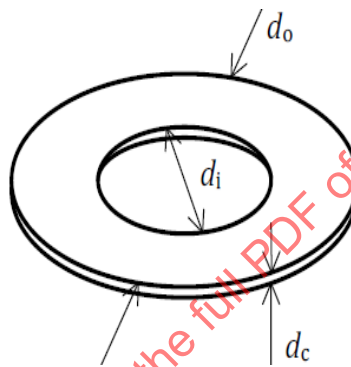


Table 63. Primary Coil parameters of Power Transmitter design A24

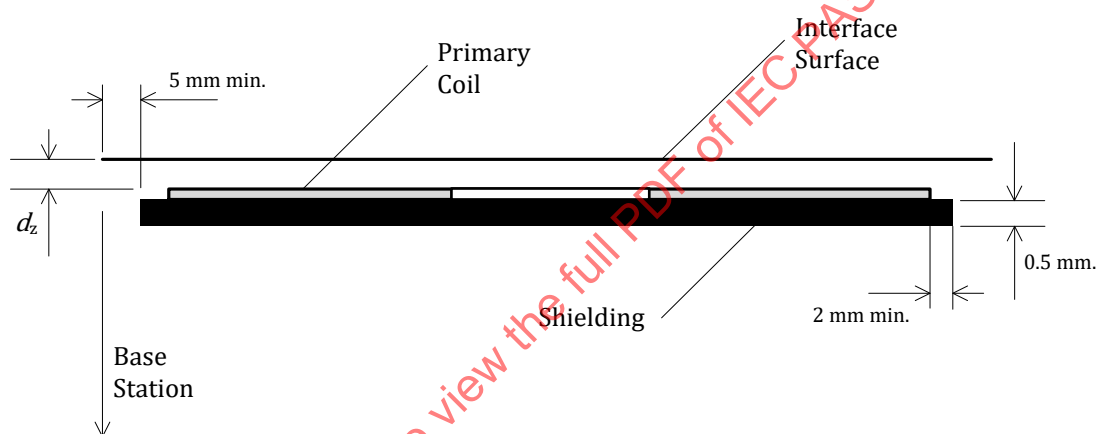
Parameter	Symbol	Value
Outer diameter	d_o	$44.0^{\pm 1.5}$ mm
Inner diameter	d_i	$22.5^{\pm 1.0}$ mm
Thickness	d_c	$1.3^{\pm 0.15}$ mm
Number of turns per layer	N	9
Number of layers	–	1

2.2.24.1.2 Shielding

As shown in Figure 90, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. In addition, the Shielding extends to at least 2.0 mm beyond the outer edge of the Primary Coil, and has a thickness of at least 0.5 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Ni-Mn-Ferrite Core – any supplier.
- Mn-Zn-Ferrite Core – any supplier.
- Sendust-Ferrite Core – any supplier.

Figure 90. Primary Coil assembly of Power Transmitter design A24



2.2.24.1.3 Interface Surface

As shown in Figure 90, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 3.0 \pm 0.5$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.24.1.4 Separation between multiple Power transmitters

If the Base Station contains multiple type A24 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 50 mm.

2.2.24.2 Electrical details

As shown in Figure 91, Power Transmitter design A24 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range Specified below, the assembly of Primary Coil and Shielding has a self inductance $L_p = 6.1^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_p = 400^{\pm 10\%} \text{ nF}$. The input voltage to the full-bridge is $5.0^{\pm 5\%} \text{ V}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A24 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power transferred. For this purpose, the Operating Frequency range is $f_{op} = 110 \dots 205 \text{ kHz}$, and the duty cycle range is $2 \dots 50\%$. A higher Operating Frequency and lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurately adjustment of the power that is transferred, a type A24 Power Transmitter shall be able to control the Operating Frequency with a resolution of 0.1 kHz or better.

When a type A24 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an Operating Frequency of $155^{\pm 15} \text{ kHz}$, and a duty cycle of $30^{\pm 10}\%$. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power transmitter may re-apply the power signal multiple times at consecutively Operating Frequencies within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the full-bridge inverter, Operating Frequency and duty cycle. It is recommended that control of the power occurs primarily by means of adjustments to the duty cycle. In order to guarantee sufficiently accurate power control, a type A24 Power Transmitter shall determine the amplitude of the Primary Coil current with a resolution of 5 mA or better. Finally, Table 64 and Table 65 provide the values of several parameters, which are used in the PID algorithm.

Figure 91. Electrical diagram (outline) of Power Transmitter design A24

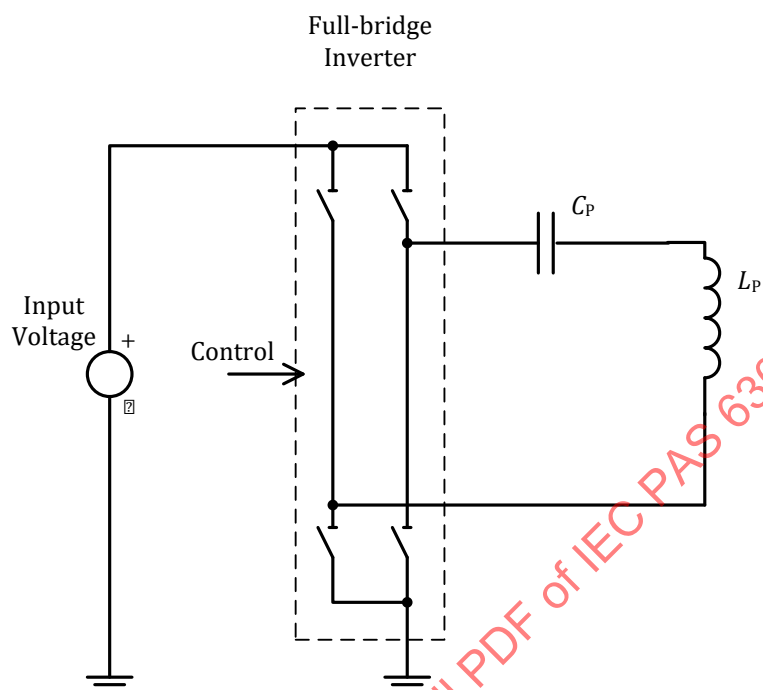


Table 64. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

Table 65. PID parameters for duty cycle control

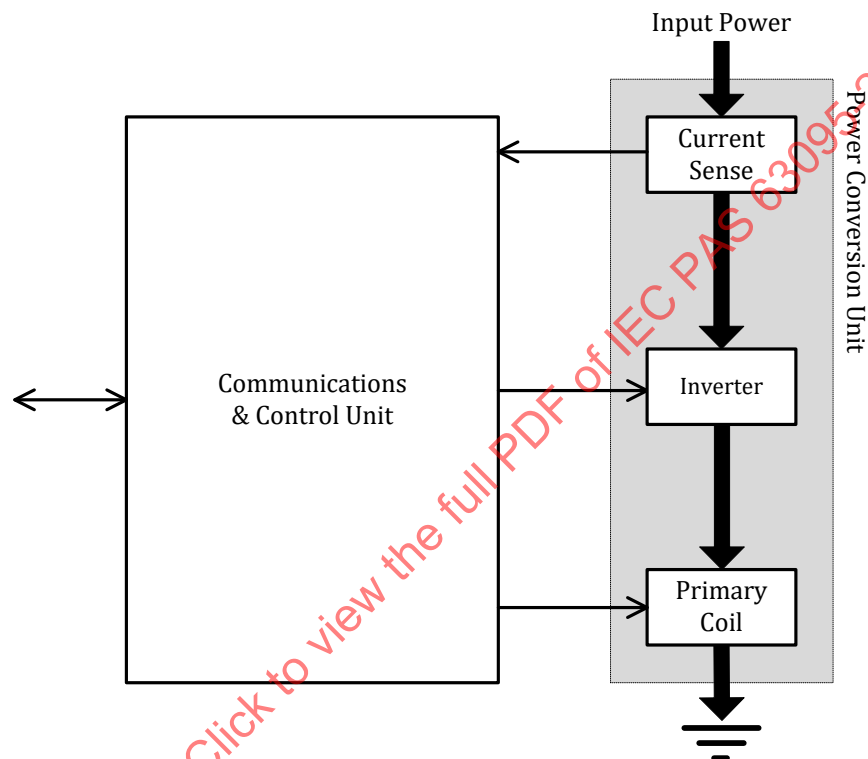
Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-0.1	$^{\circ}$

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2.2.25 Power Transmitter design A25

Figure 92 illustrates the functional block diagram of Power Transmitter design A25, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 92. Functional block diagram of Power Transmitter design A25



The Power Conversion Unit on the right-hand side of Figure 92 comprises the analog parts of the design. The voltage and current sense monitors the input voltage and current. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor.

The Communications and Control Unit on the left-hand side of Figure 92 comprises the digital logic part of the design. The unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input power and frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.25.1 Mechanical details

Power Transmitter design A25 includes one Primary Coil as defined in Section 2.2.25.1.1, Shielding as defined in Section 2.2.25.1.2, and an Interface Surface as defined in Section 2.2.25.1.3.

2.2.25.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 93, a Primary Coil has a racetrack-like shape and consists of a single layer. Table 66 lists the dimensions of a Primary Coil.

Figure 93. Primary Coil of Power Transmitter design A25

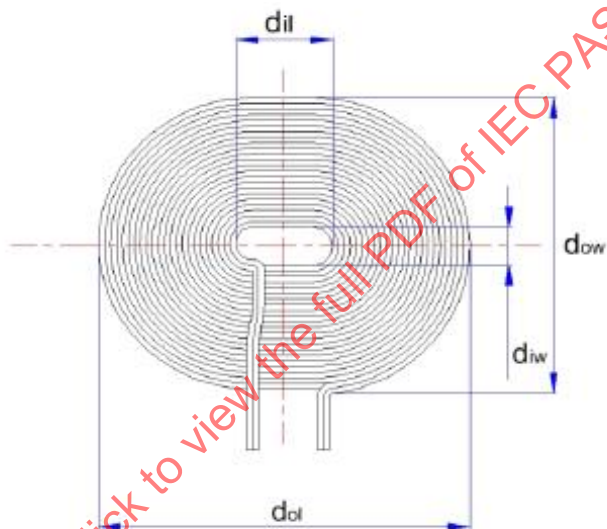


Table 66. Primary Coil parameters of Power Transmitter design A25

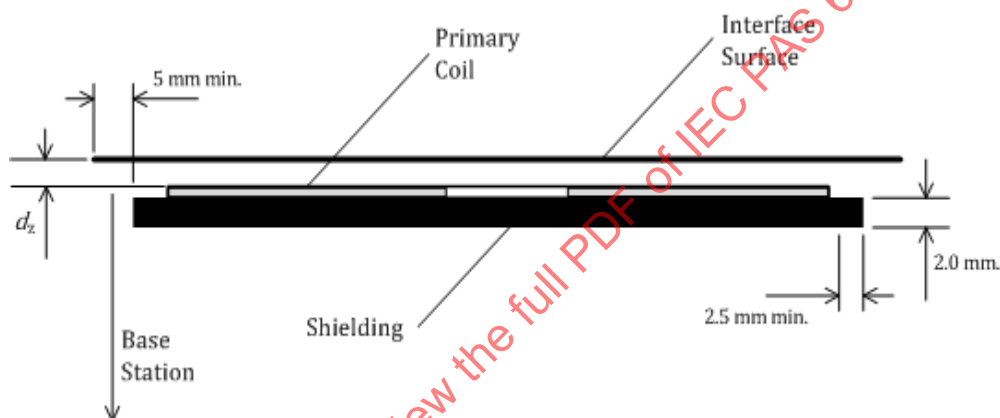
Parameter	Symbol	Value
Outer length	d_{ol}	$65.7^{+1.5}$ mm
Inner length	d_{il}	$16.3^{+1.0}$ mm
Outer width	d_{ow}	$59.2^{+1.5}$ mm
Inner width	d_{iw}	$5.1^{+1.0}$ mm
Thickness	d_c	$1.3^{+0.15}$ mm
Number of turns per layer	N	11 (bifilar turns)
Number of layers	–	1

2.2.25.1.2 Shielding

As shown in Figure 94, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. In addition, the Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coil, and has a thickness of at least 2.0 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Ni-Mn-Ferrite Core – any supplier.
- Mn-Zn-Ferrite Core – any supplier.
- Sendust-Ferrite Core – any supplier.

Figure 94. Primary Coil assembly of Power Transmitter design A25



2.2.25.1.3 Interface Surface

As shown in Figure 94, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.5^{+1.0}_{-0}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.25.1.4 Separation between multiple Power transmitters

If the Base Station contains multiple type A25 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 67.2 mm.

2.2.25.2 Electrical details

As shown in Figure 95, Power Transmitter design A25 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range Specified below, the assembly of Primary Coil and Shielding has a self inductance $L_p = 6.1^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_p = 400^{\pm 10\%} \text{nF}$. The input voltage to the full-bridge is $5.0^{\pm 5.0\%} \text{V}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A25 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power transferred. For this purpose, the Operating Frequency range is $f_{op} = 110 \dots 205 \text{ kHz}$, and the duty cycle range is $2 \dots 50\%$. A higher Operating Frequency and lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurately adjustment of the power that is transferred, a type A25 Power Transmitter shall be able to control the Operating Frequency with a resolution of 0.1kHz or better.

When a type A25 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an Operating Frequency of $155^{\pm 15} \text{ kHz}$, and a duty cycle of $30^{\pm 10}\%$. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may re-apply the power signal multiple times at consecutively lower Operating Frequencies within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the full-bridge inverter, Operating Frequency and duty cycle. It is recommended that control of the power occurs primarily by means of adjustments to the duty cycle. In order to guarantee sufficiently accurate power control, a type A25 Power Transmitter shall determine the amplitude of the Primary Coil current with a resolution of 5 mA or better. Finally, Table 67 and Table 68 provide the values of several parameters, which are used in the PID algorithm.

Figure 95. Electrical diagram (outline) of Power Transmitter design A25

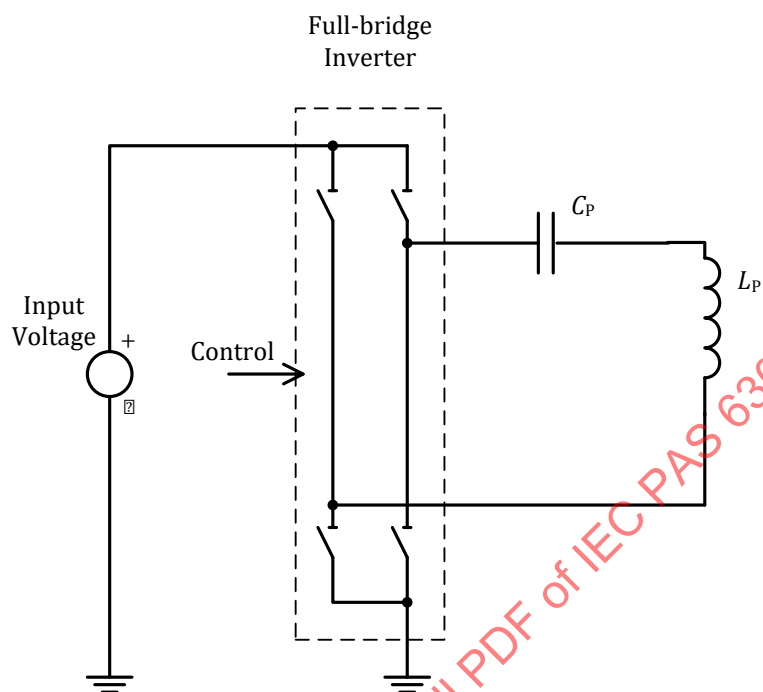


Table 67. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

Table 68. PID parameters for duty cycle control

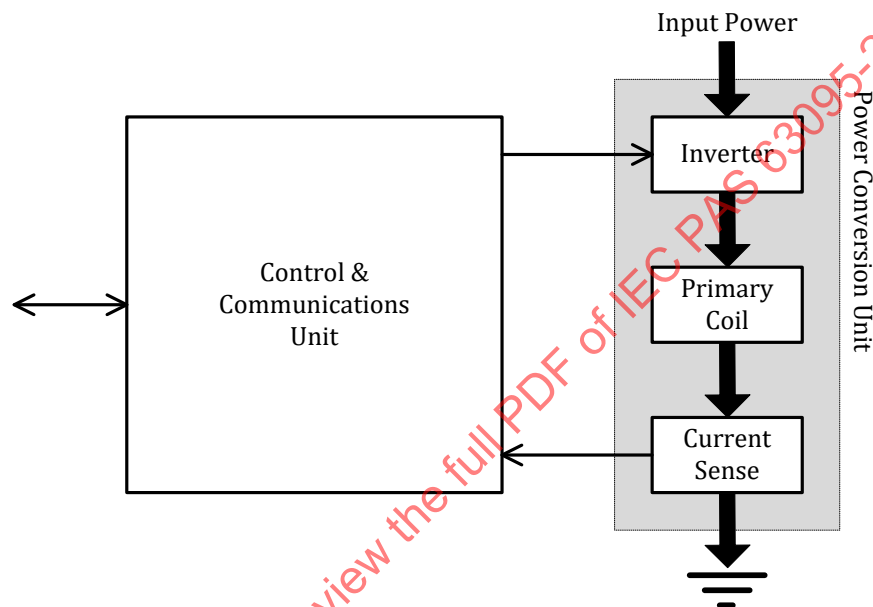
Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-0.1	$^{\circ}$

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2.2.26 Power Transmitter design A26

Figure 96 illustrates the functional block diagram of Power Transmitter design A26, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 96. Functional block diagram of Power Transmitter design A26



The Power Conversion Unit on the right-hand side of Figure 96 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 96 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.26.1 Mechanical details

Power Transmitter design A26 includes a single Primary Coil as defined in Section 2.2.26.1.1, Shielding as defined in Section 2.2.26.1.2, an Interface Surface as defined in Section 2.2.26.1.3, and an alignment aid as defined in Section 2.2.26.1.4.

2.2.26.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 97, the Primary Coil has a triangular shape and consists of a single layer. Table 69 lists the dimensions of the Primary Coil.

Figure 97. Primary Coil of Power Transmitter design A26

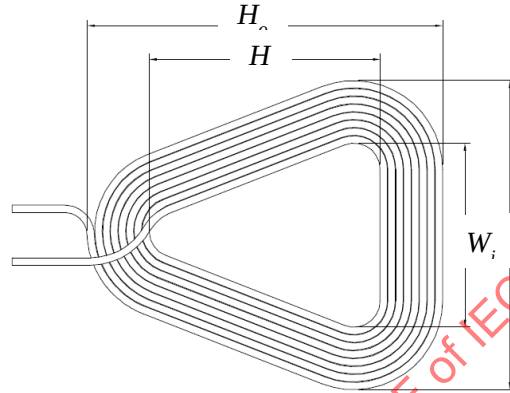


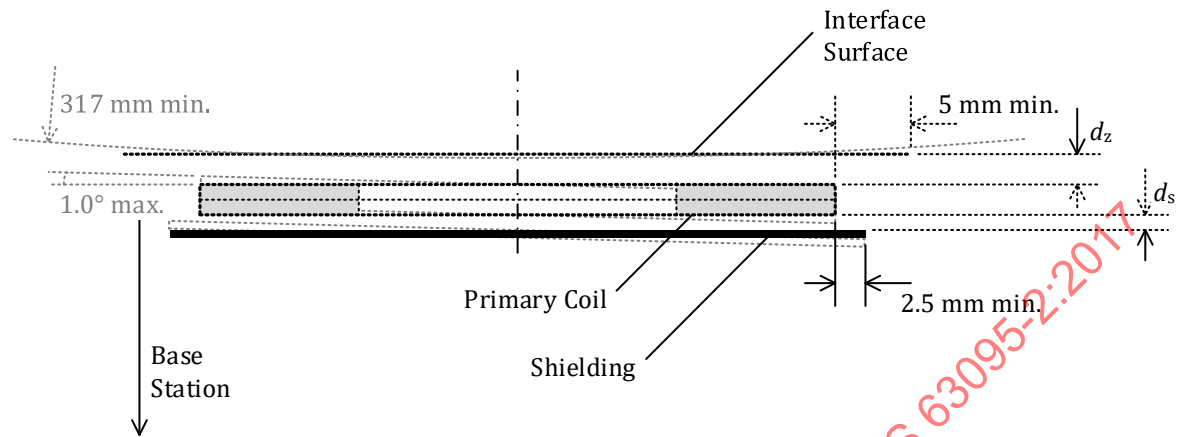
Table 69. Primary Coil parameters of Power Transmitter design A26

Parameter	Symbol	Value
Outer height	H_o	52 ± 0.5 mm
Inner height	H_i	34 ± 0.5 mm
Outer width	W_o	46 ± 0.5 mm
Inner width	W_i	28 ± 0.5 mm
Thickness	d_c	1.1 ± 0.3 mm
Number of turns per layer	N	8
Number of layers	–	1

2.2.26.1.2 Shielding

As shown in Figure 98, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2.5 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 0.7 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to the following materials:

- Mn-Zn ferrite (any supplier).

Figure 98. Primary Coil assembly of Power Transmitter design A26

2.2.26.1.3 Interface Surface

As shown in Figure 98, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.5}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

NOTE This Primary-Coil-to-Interface-Surface distance implies that the tilt angle between the Primary Coil and a flat Interface Surface is at most 1.0°. Alternatively, in case of a non-flat Interface Surface, this Primary-Coil-to-Interface-Surface distance implies a radius of curvature of the Interface Surface of at least 317 mm, centered on the Primary Coil. See Figure 98.

2.2.26.1.4 Alignment aid

The user manual of the Base Station containing a type A26 Power Transmitter shall have information about the location of its Active Area(s).

For the best user experience, it is recommended to employ at least one user feedback mechanism during Mobile Device positioning to help alignment.

NOTE Examples of Base Station alignment aids to assist the user positioning of the Mobile Device include:

- A marked Interface Surface to indicate the location of the Active Area(s)—e.g. by means of the logo or other visual marking, lighting, etc.
- A visual feedback display—e.g. by means of illuminating an LED to indicate proper alignment.
- An audible or haptic feedback mechanism.

2.2.26.1.5 Inter coil separation

If the Base Station contains multiple type A26 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall not overlap.

2.2.26.2 Electrical details

As shown in Figure 99, Power Transmitter design A26 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coil, Shielding, and magnet has a self inductance $L_p = 6.3^{\pm 10\%} \mu\text{H}$. The value of the series capacitance is $C_p = 0.4^{\pm 5\%} \mu\text{F}$. The input voltage to the full-bridge inverter is $5^{\pm 5\%} \text{ V}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A26 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the full-bridge inverter is $f_{op} = 110 \dots 205 \text{ kHz}$ with a duty cycle of 50%; and its duty cycle range is 10...50% at an Operating Frequency of 205 kHz. A higher Operating Frequency or lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the amount of power that is transferred, a type A26 Power Transmitter shall control the Operating Frequency with a resolution of

- $0.01 \times f_{op} - 0.7 \text{ kHz}$, for f_{op} in the 110...175 kHz range;
- $0.015 \times f_{op} - 1.58 \text{ kHz}$, for f_{op} in the 175...205 kHz range;

or better. In addition, a type A26 Power Transmitter shall control the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A26 Power Transmitter first applies a Power Signal (see *Parts 1 and 2: Interface Definitions*), it shall use an initial Operating Frequency of 175 kHz (and a duty cycle of 50%).

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency or the duty cycle. In order to guarantee sufficiently accurate power control, a type A16 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 70, Table 71, and Table 72 provide the values of several parameters, which are used in the PID algorithm.

Figure 99. Electrical diagram (outline) of Power Transmitter design A26

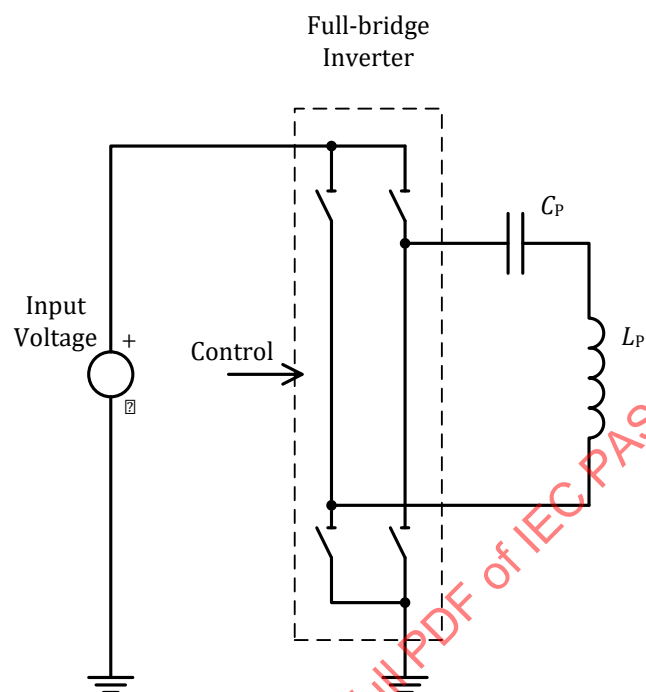


Table 70. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.

Table 71. Operating Frequency dependent scaling factor

Frequency Range [kHz]	Scaling Factor S_v [Hz]
110...140	1.5
140...160	2
160...180	3
180...205	5

Table 72. PID parameters for duty cycle control

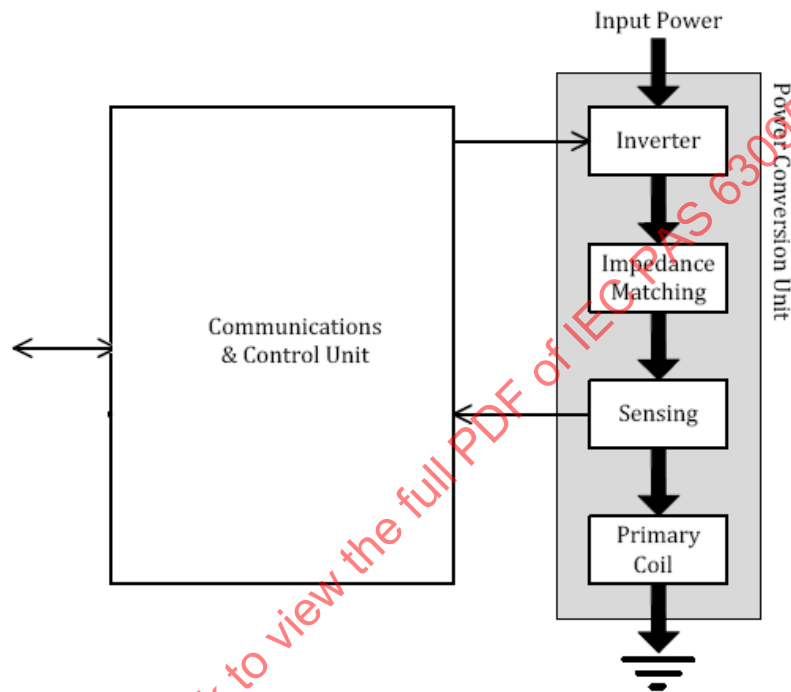
Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	–0.01	%

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2.2.27 Power Transmitter design A27

Figure 100 illustrates the functional block diagram of Power Transmitter design A27, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 100. Functional block diagram of Power Transmitter design A27



The Power Conversion Unit on the right-hand side of Figure 100 comprises the analog parts of the design. The impedance matching network forms a resonant circuit with the Primary Coil. The sensing circuits monitor (amongst others) the Primary Coil current and voltage, and the inverter converts the DC input to an AC waveform that drives the Primary Coil.

The Communications and Control Unit on the left-hand side of Figure 100 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the inverter to control the amount of power provided to the Power Receiver. The Communications and Control Unit also interfaces with the other subsystems of the Base Station, e.g. for user interface purposes.

2.2.27.1 Mechanical details

Power Transmitter design A27 includes a Primary Coil array as defined in Section 2.2.27.1.1, Shielding as defined in Section 2.2.27.1.2, and an Interface Surface as defined in Section 2.2.27.1.3.

2.2.27.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of 17 AWG (1.15 mm diameter) type 2 ftz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 101, the Primary Coil has a circular shape and consists of one layer. Table 73 lists the dimensions of the Primary Coil.

Figure 101. Primary Coil of Power Transmitter design A27

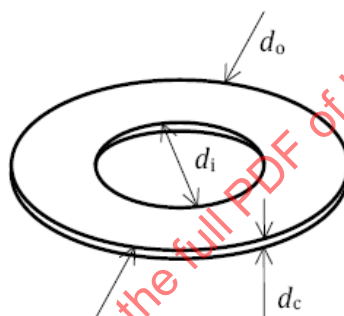


Table 73. Primary Coil parameters of Power Transmitter design A27

Parameter	Symbol	Value
Outer diameter	d_o	$60.0^{+3.0}_{-0.0}$ mm
Inner diameter	d_i	$20.5^{+0.5}$ mm
Number of turns	N	18
Thickness	d_c	$1.2^{+0.2}$ mm
Number of layers	-	1

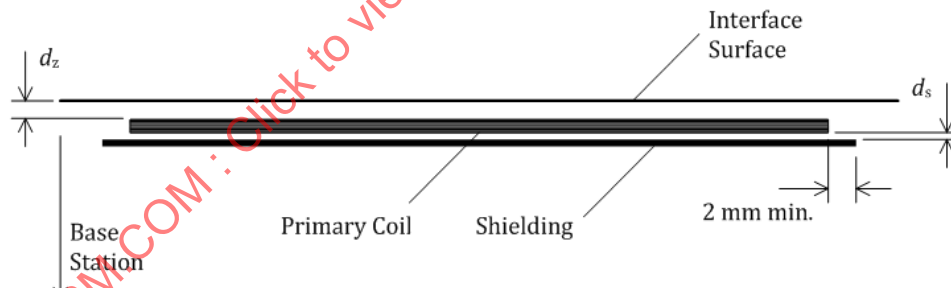
2.2.27.1.2 Shielding

As shown in Figure 102, Transmitter design A27 employs Shielding to protect the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2 mm beyond the outer edges of the Primary Coil array, and is placed at a distance of at most $d_s = 0.5$ mm below the Primary Coil array.

The Shielding consists of soft magnetic material that has a thickness of at least 0.5 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 78 — Fair Rite Corporation.
- 3C94 — Ferroxcube.
- N87 — Epcos AG.
- PC44 — TDK Corp.
- FK2 — TDK Corp (at least 0.8mm thickness).
- 68 — EMICORE Corp.
- M79 — EMICORE Corp.

Figure 102. Primary Coil array assembly of Power Transmitter design A27



2.2.27.1.3 Interface Surface

As shown in Figure 102, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.5}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface extends at least 5 mm beyond the outer edges of the Primary Coil array.

2.2.27.1.4 Alignment aid

The user manual of the Base Station containing a type A27 Power Transmitter shall have information about the location of its Active Area(s).

For the best user experience, it is recommended to employ at least one user feedback mechanism during Mobile Device positioning to help alignment.

NOTE Examples of Base Station alignment aids to assist the user positioning of the Mobile Device include:

- A marked Interface Surface to indicate the location of the Active Area(s)—e.g. by means of the logo or other visual marking, lighting, etc.
- A visual feedback display—e.g. by means of illuminating an LED to indicate proper alignment.
- An audible or haptic feedback mechanism.

2.2.27.1.5 Inter coil separation

If the Base Station contains multiple type A27 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 70 mm.

2.2.27.2 Electrical details

As shown in Figure 103, Power Transmitter design A27 uses a full-bridge inverter to drive the resonant network including filter inductor, a Primary Coil with a series and parallel capacitance. Within the Operating Frequency range $f_{op} = 110 \dots 120$ kHz, the assembly of Primary Coil and Shielding has an inductance of $24.0^{+10\%}_{-10\%}$ μ H. The inductance and capacitances in the impedance matching circuit are, respectively, $L_m = 8.2^{+20\%}_{-20\%}$ μ H, $C_{ser} = 100^{+5\%}_{-5\%}$ nF and $C_{par} = 100^{+5\%}_{-5\%}$ nF. The input voltage to the full-bridge inverter is $12^{+5\%}_{-5\%}$ V.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100V pk-pk.

Power Transmitter design A27 uses the phase difference between the control signals to two halves of the full-bridge inverter to control the amount of power that is transferred, see Figure 104. For this purpose, the range of the phase difference α is $0 \dots 180^\circ$ —with a larger phase difference resulting in a lower power transfer. In order to achieve a sufficient accurate adjustment of the power that is transferred, a type A27 Power Transmitter shall be able to control the phase difference with a resolution of 0.42° or better. When a type A27 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial phase difference of 120° .

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the phase difference between the two halves of the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type A27 Transmitter shall determine the amplitude of the current into the Primary Coil with a resolution of 7 mA or better. Finally, Table 74 provides the values of several parameters, which are used in the PID algorithm.

Figure 103. Electrical diagram (outline) of Power Transmitter design A27

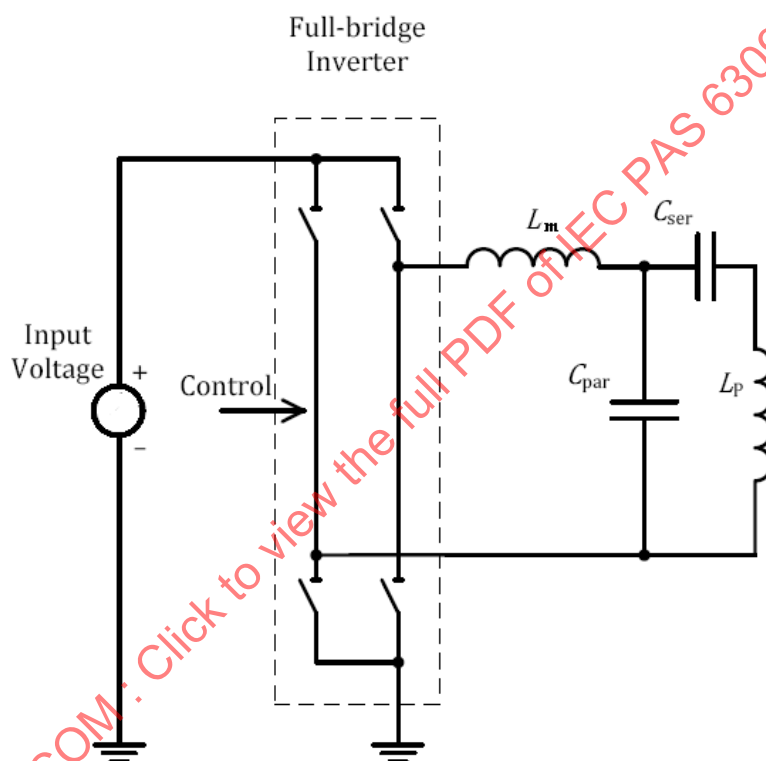


Figure 104. Control signals to the inverter

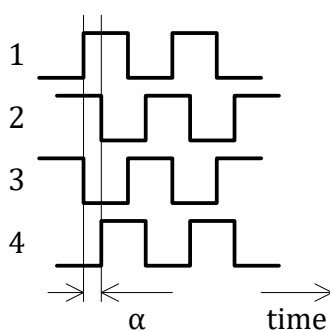


Table 74. Control parameters for power control

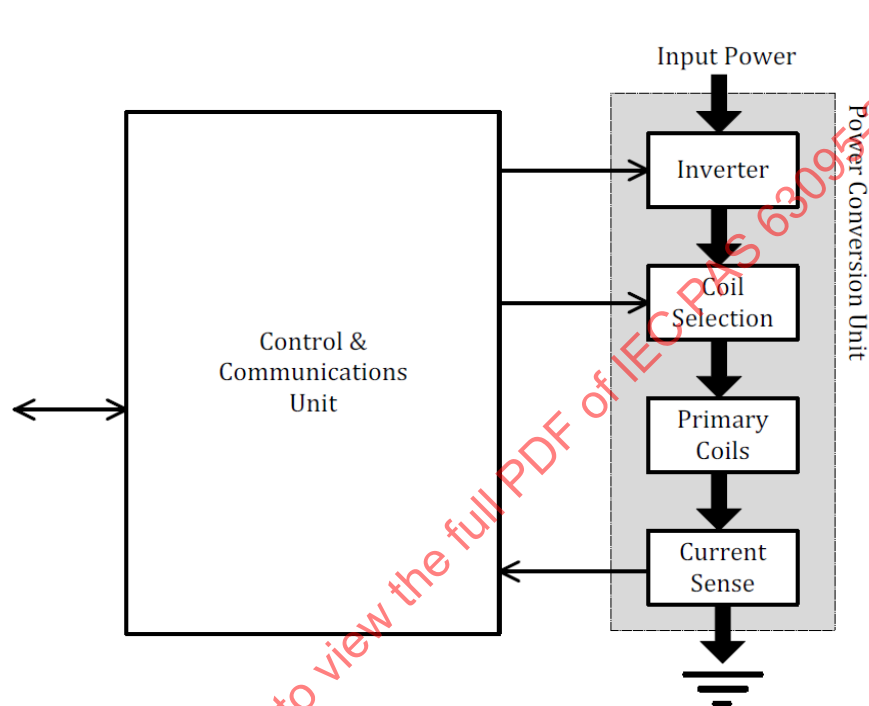
Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	2,000	N.A.
Scaling factor	S_v	0.01	°

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2.2.28 Power Transmitter design A28

Figure 105 illustrates the functional block diagram of this Power Transmitter design A28, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 105. Functional block diagram of Power Transmitter design A28



The Power Conversion Unit on the right-hand side of Figure 105 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from three partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the Primary Coils. Selection of the appropriate Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using anyone of the Primary Coils. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 105 comprises both analog circuit and digital logic. This unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.28.1 Mechanical details

Power Transmitter design A28 includes one or more Primary Coils as defined in Section 2.2.28.1.1, Shielding as defined in Section 2.2.28.1.2, and Interface Surface as defined in Section 2.2.28.1.3.

2.2.28.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of no. 17 AWG (1.15 mm diameter) type 2 litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 106, the Primary Coil has a rectangular shape and consists of a single layer. Table 75 lists the dimensions of the Primary Coil.

Figure 106. Primary Coil of Power Transmitter design A28

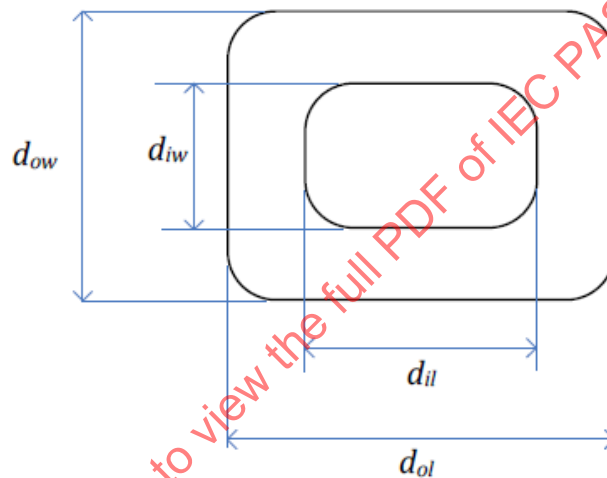
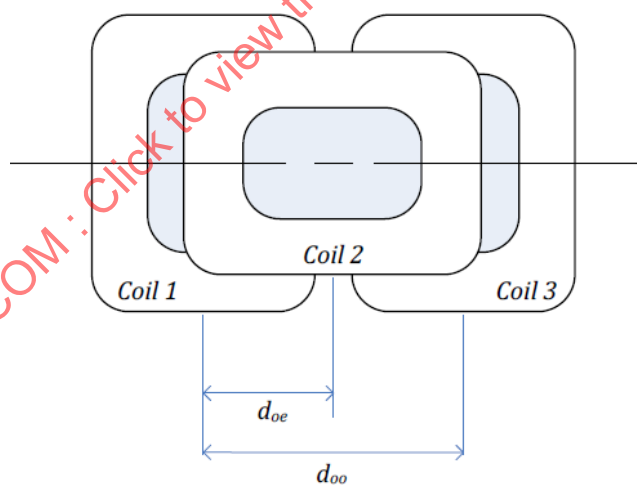


Table 75. Primary Coil parameters of Power Transmitter design A28

Parameter	Symbol	Value
Outer length	d_{ol}	$47.5^{+1.0}$ mm
Inner length	d_{il}	$28.0^{+1.0}$ mm
Outer width	d_{ow}	$39.5^{+1.0}$ mm
Inner width	d_{iw}	$19.5^{+1.0}$ mm
Thickness	d_c	$1.5^{+0.5}$ mm
Number of turns per layer	N	9
Number of layers	–	1

Power Transmitter design A28 contains one or more Primary Coils. Power Transmitter design A28 contains at least one Primary Coil. Odd numbered coils are placed alongside each other with a displacement of $d_{oo} = 49.2^{+4}$ mm between their centers. Even numbered coils are placed orthogonal to the odd numbered coils with a displacement of $d_{oe} = 24.6^{+2}$ mm between their centers. See Figure 107.

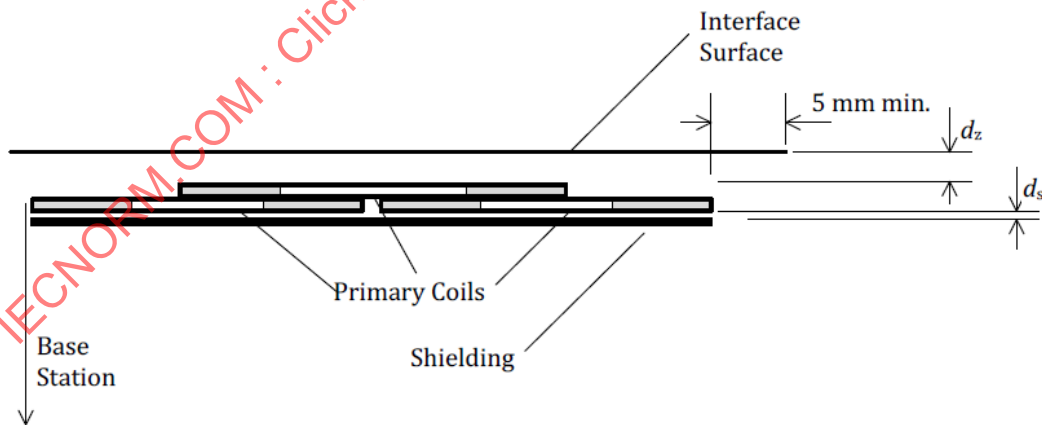
Figure 107. Primary Coils of Power Transmitter design A28

2.2.28.1.2 Shielding

As shown in Figure 108, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coils. The Shielding extends to at least the outer dimensions of the Primary Coils, has a thickness of at least 0.5 mm, and is placed below the Primary Coils at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 44 — Fair Rite Corporation.
- Material 28 — Steward, Inc.
- CMG22G — Ceramic Magnetics, Inc.
- Kolektor 22G — Kolektor.
- LeaderTech SB28B2100-1 — LeaderTech Inc.
- TopFlux “A” — TopFlux.
- TopFlux “B” — TopFlux.
- ACME K081 — Acme Electronics.
- L7H — TDK Corporation.
- PE22 — TDK Corporation.
- FK2 — TDK Corporation.

Figure 108. Primary Coil assembly of Power Transmitter design A28



2.2.28.1.3 Interface Surface

As shown in Figure 108, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.25}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer dimensions of the Primary Coils.

2.2.28.1.4 Inter coil separation

If the Base Station contains multiple type A28 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least $49.2^{\pm 4}$ mm.

2.2.28.2 Electrical details

As shown in Figure 109, Power Transmitter design A28 uses a full-bridge inverter to drive an individual Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coils and Shielding has a self inductance $6.4^{\pm 10\%}$ μ H for coils closest to the Interface Surface and inductance $6.9^{\pm 10\%}$ μ H for coils furthest from the Interface Surface. The value of the series capacitance is $400^{\pm 5\%}$ nF for coils closest to the Interface Surface and $357^{\pm 5\%}$ nF for coils furthest from the Interface Surface. The input voltage to the full-bridge inverter is $5^{\pm 5\%}$ V.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A28 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power that is transferred. For this purpose, the Operating Frequency range of the full-bridge inverter is $f_{op} = 115 \dots 205$ kHz with a duty cycle of 50%; and its duty cycle range is 10...50% at an Operating Frequency of 205 kHz. A higher Operating Frequency or lower duty cycle result in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the amount of power that is transferred, a type A28 Power Transmitter shall control the Operating Frequency with a resolution of

- $0.01 \times f_{op} - 0.7$ kHz, for f_{op} in the 115...175 kHz range;
- $0.015 \times f_{op} - 1.58$ kHz, for f_{op} in the 175...205 kHz range;

or better. In addition, a type A28 Power Transmitter shall control the duty cycle of the Power Signal with a resolution of 0.1% or better.

When a type A28 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial Operating Frequency of 175 kHz (and a duty cycle of 50%).

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency or the duty cycle. In order to guarantee sufficiently accurate power control, a type A28 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 76, Table 77, and Table 78 provide the values of several parameters, which are used in the PID algorithm.

Figure 109. Electrical diagram (outline) of Power Transmitter design A28

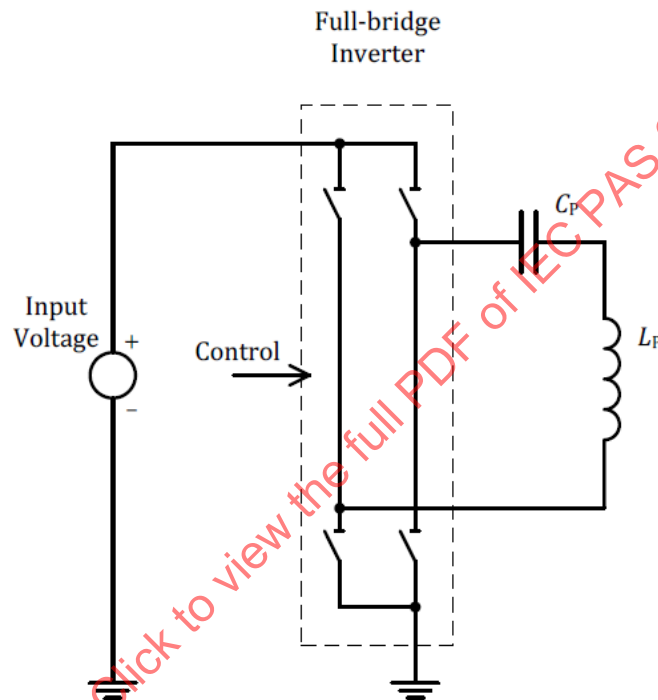


Table 76. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.

Table 77. Operating Frequency dependent scaling factor

Frequency Range [kHz]	Scaling Factor S_v [Hz]
115...140	1.5
140...160	2
160...180	3
180...205	5

Table 78. PID parameters for duty cycle control

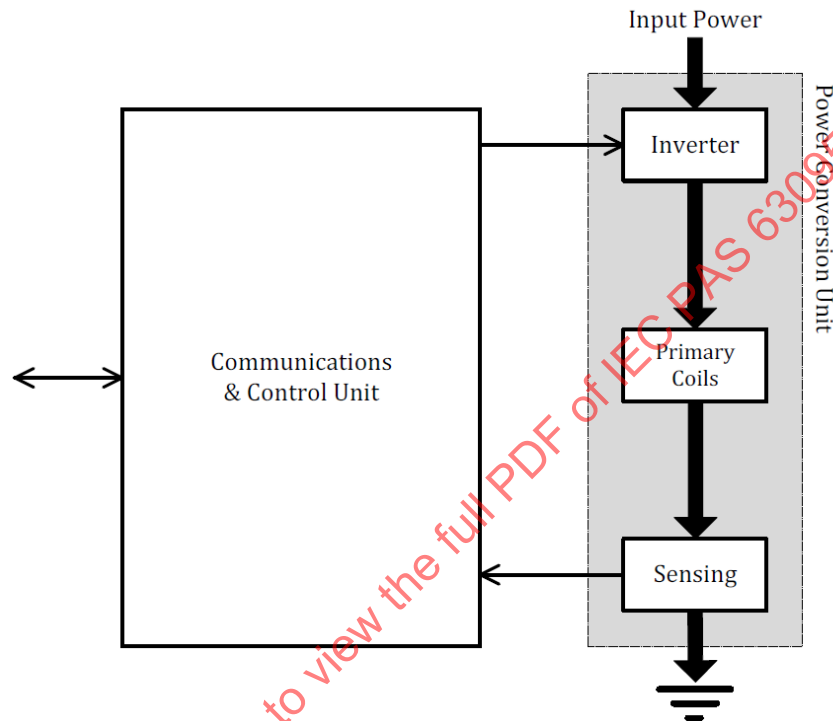
Parameter	Symbol	Value	Unit
Proportional gain	K_p	10	mA^{-1}
Integral gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	–0.01	%

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2.2.29 Power Transmitter design A29

Figure 110 illustrates the functional block diagram of Power Transmitter Design A29.

Figure 110. Functional block diagram of Power Transmitter A29



The Power Conversion Unit on the right-hand side of Figure 110 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the voltage and current sense monitors the Primary Coil voltage and current.

The Communications and Control Unit on the left-hand side of Figure 110 comprises the digital logic part of the design. The unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input power and frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.29.1 Mechanical details

Power Transmitter design A29 includes a Primary Coil array as defined in Section 2.2.29.1.1, Shielding as defined in Section 2.2.29.1.2, and an Interface Surface as defined in Section 2.2.29.1.3.

2.2.29.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire with nylon spinning having 180 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 111 the Primary Coil has a circular shape and consists of two layers with a total of 13 turns. Table 79 lists the dimensions of the Primary Coil.

Figure 111. Primary Coil of Power Transmitter A29

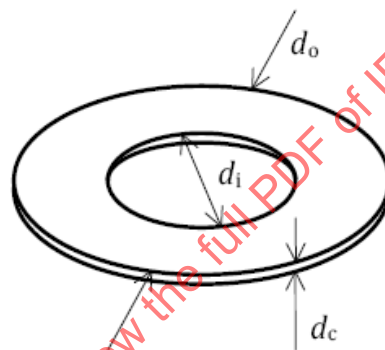


Table 79. Primary Coil parameters of Power Transmitter design A29

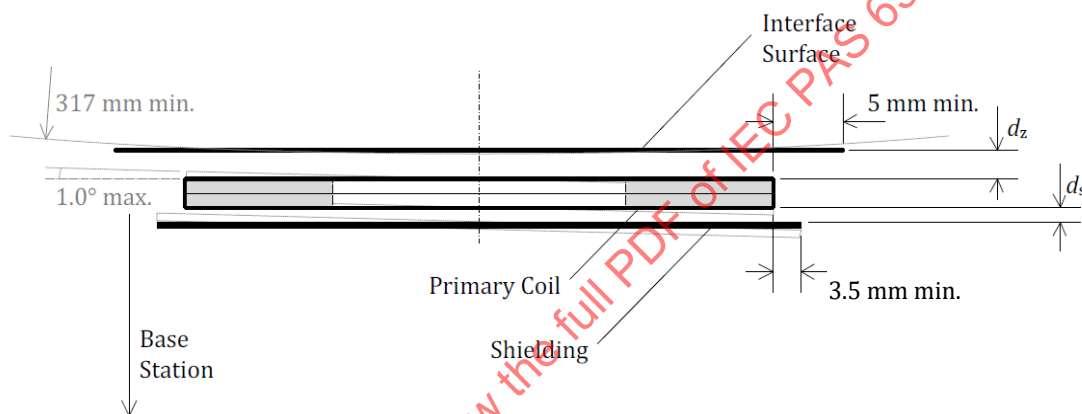
Parameter	Symbol	Value
Outer diameter	d_o	41^{+2} mm
Inner diameter	d_i	$21^{+0.5}$ mm
Thickness	d_c	$3^{+0.5}$ mm
Numbers of turns per layer	N	6.5
Number of layers	–	2

2.2.29.1.2 Shielding

As shown in Figure 112, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 3.5 mm beyond the outer diameter of the Primary Coil, has a thickness of at least 2.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Ni-Zn ferrite (ACME)

Figure 112. Primary Coil assembly of Power Transmitter design A29



2.2.29.1.3 Interface Surface

As shown in Figure 112, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.5^{+0.5}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

NOTE This Primary-Coil-to-Interface-Surface distance implies that the tilt angle between the Primary Coil and a flat Interface Surface is at most 1.0° . Alternatively, in case of a non-flat Interface Surface, this Primary-Coil-to-Interface-Surface distance implies a radius of curvature of the Interface Surface of at least 317 mm, centered on the Primary Coil. See Figure 112.

2.2.29.1.4 Alignment Aid

The user manual of the Base Station containing a type A29 Power Transmitter shall have information about the location of its Active Area(s).

For the best user experience, it is recommended to employ at least one user feedback mechanism during Mobile Device positioning to help alignment.

NOTE Examples of Base Station alignment aids to assist the user positioning of the Mobile Device include:

- A marked Interface Surface to indicate the location of the Active Area(s)—e.g. by means of the logo or other visual marking, lighting, etc.
- A visual feedback display—e.g. by means of illuminating an LED to indicate proper alignment.
- An audible or haptic feedback mechanism.

2.2.29.1.4.1 Inter coil separation

If the Base Station contains multiple type A29 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 70 mm.

2.2.29.2 Electrical Details

As shown in Figure 113, Power Transmitter design A29 uses a full-bridge inverter to drive the resonant network with a primary Coil with a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coil and Shielding, has a self inductance $L_p = 10^{\pm 10\%}$ μH . The value of the total series capacitance $C_p = 247^{\pm 5\%}$ nF, where the individual series capacitances may have any value less than the sum.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A29 uses the input voltage to the inverter to control the amount of power transferred. For this purpose, the input voltage has a range $1^{\pm 5\%} \dots 12^{\pm 5\%}$ V, with a resolution of 40 mV or better; a higher input voltage results in more power transferred. The Operating Frequency is $130^{\pm 3\%}$ kHz with a duty cycle of 50%.

When a type A29 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an Operating Frequency of 130 kHz and a recommended input voltage of 4 V.

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage. Finally, Table 80 provides the values of several parameters, which are used in the PID algorithm.

Figure 113. Electrical diagram (outline) Primary Coil of Power Transmitter design A29

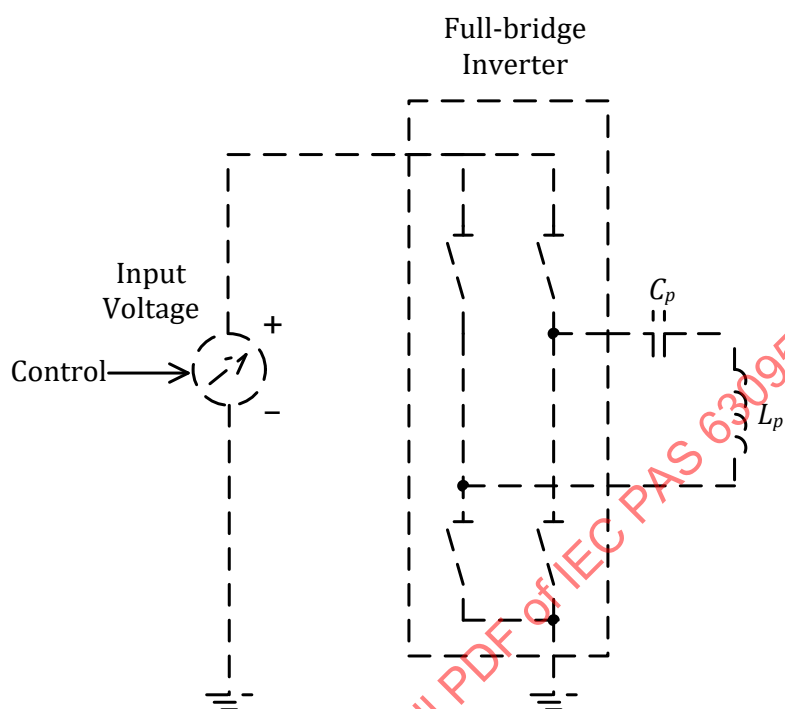


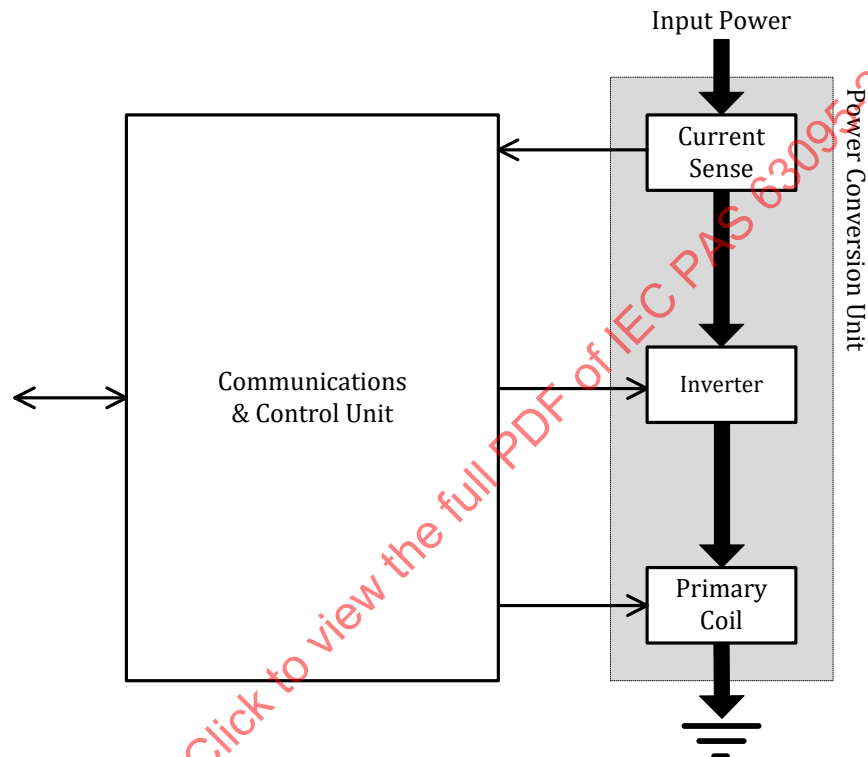
Table 80. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional Gain	K_p	10	mA^{-1}
Integral Gain	K_i	0.05	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative Gain	K_d	0	$\text{mA}^{-1}\text{ms}^{-1}$
Integral Term Limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	0.01	%

2.2.30 Power Transmitter design A30

Figure 114 illustrates the functional block diagram of the Power Transmitter design A30, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 114. Functional block diagram of Power Transmitter design A30



The Power Conversion Unit on the right-hand side of Figure 114 comprises the analog parts of the design. The voltage and current sense monitors the System voltage and current. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor.

The Communications and Control Unit on the left-hand side of Figure 114 comprises the digital logic part of the design. The unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input power and frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.30.1 Mechanical details

Power Transmitter design A30 includes one Primary Coil as defined in Section 2.2.30.1.1, Shielding as defined in Section 2.2.30.1.2, and an Interface Surface as defined in Section 2.2.30.1.3.

2.2.30.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 115, a Primary Coil has a racetrack-like shape and consists of a single layer. Table 81 lists the dimensions of a Primary Coil.

Figure 115. Primary Coil of Power Transmitter design A30

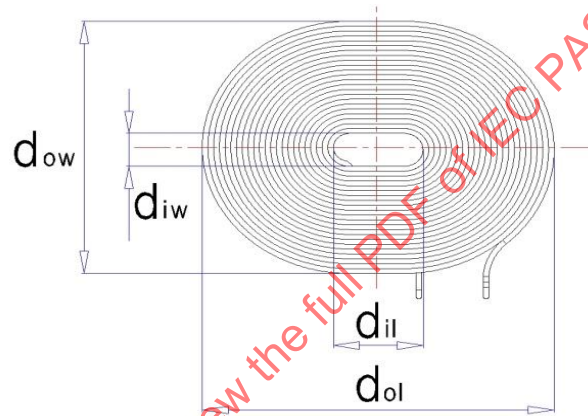


Table 81. Primary Coil parameters of Power Transmitter design A30

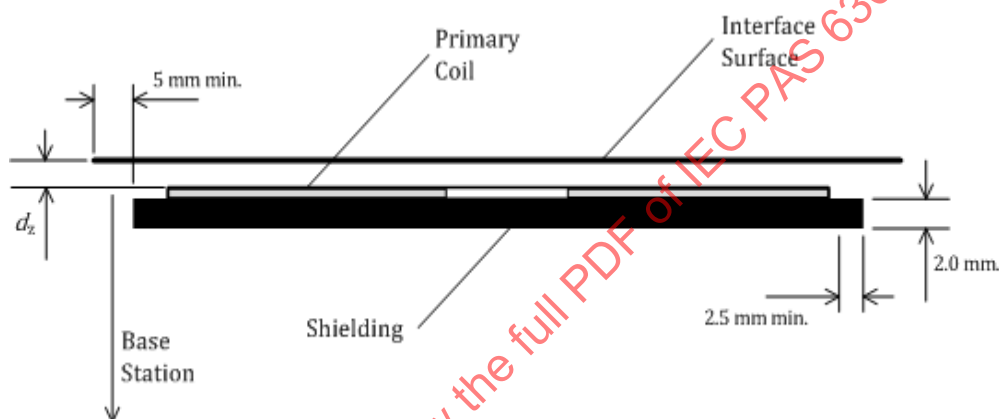
Parameter	Symbol	Value
Outer length	d_{ol}	$65.5^{+0.5}$ mm
Inner length	d_{il}	$16.5^{+0.5}$ mm
Outer width	d_{ow}	$57.1^{+0.5}$ mm
Inner width	d_{iw}	$4.5^{+0.5}$ mm
Thickness	d_c	$1.3^{+0.15}$ mm
Number of turns per layer	N	22
Number of layers	–	1

2.2.30.1.2 Shielding

As shown in Figure 116, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coil, and has a thickness of at least 2.0 mm. The version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Ni-Mn-Ferrite Core – any supplier
- Mn-Zn-Ferrite Core – any supplier

Figure 116. Primary Coil assembly of Power Transmitter design A30



2.2.30.1.3 Interface Surface

As shown in Figure 116, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 5^{+1.0}_{-0}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer diameter of the Primary Coil.

2.2.30.1.4 Separation between multiple Power transmitters

If the Base Station contains multiple type A30 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 80 mm.

2.2.30.2 Electrical details

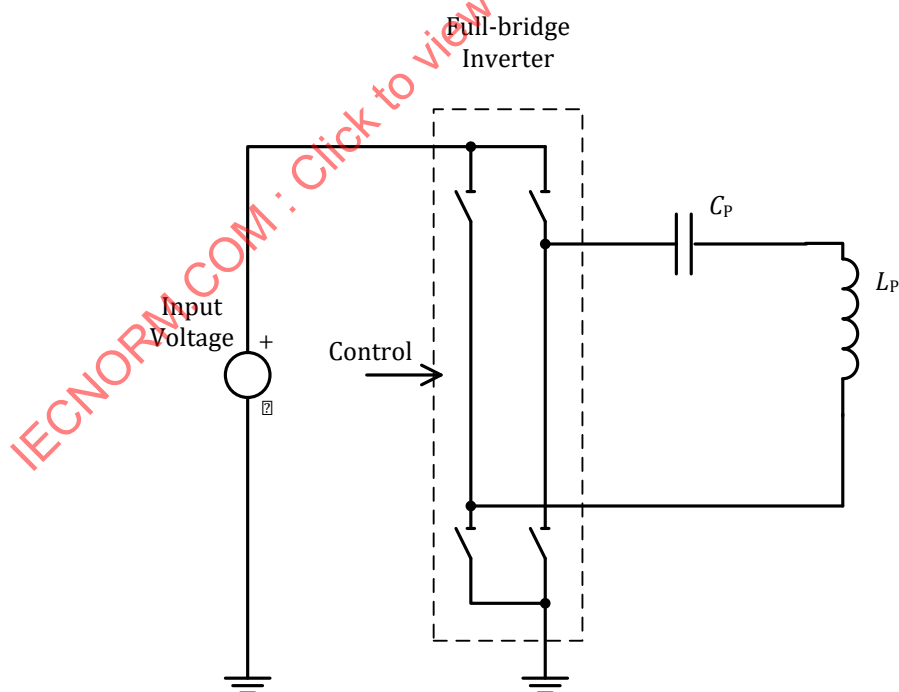
As shown in Figure 117, Power Transmitter design A30 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range Specified below, the assembly of Primary Coil and Shielding has a self inductance $L_p = 24.0^{\pm 10\%} \mu\text{H}$. The input voltage to the full-bridge inverter is $12^{\pm 5\%} \text{ V}$. The value of the series capacitance is $C_p = 100^{\pm 10\%} \text{ nF}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A30 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power transferred. For this purpose, The Operating Frequency range is $f_{op} = 110 \dots 205 \text{ kHz}$, and the duty cycle range of 2...50%.

When a type A30 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an Operating Frequency of $130^{\pm 10} \text{ kHz}$, and a duty cycle of $25^{\pm 15\%}$. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may re-apply the Power Signal multiple times at consecutively higher duty cycle to the full-bridge inverter within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 117. Electrical diagram (outline) of Power Transmitter design A30



Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency to the full-bridge inverter and duty cycle. It is recommended that control of the power occurs primarily by means of adjustments to the Operating Frequency and that duty cycle adjustments are made according to the amount of current. In order to guarantee sufficiently accurate power control, a type A30 Power Transmitter shall determine the amplitude of the Primary Coil current with a resolution of 5 mA or better. Finally, Table 82 and Table 83 provide the value of several parameters, which are used in the PID algorithm.

Table 82. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

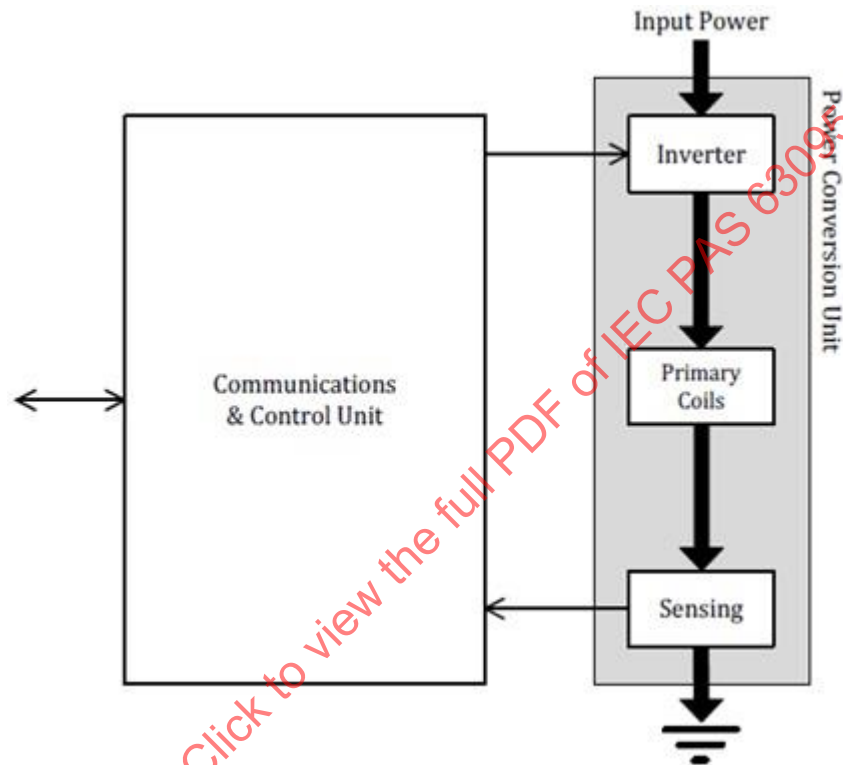
Table 83. PID parameters for duty cycle control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-0.1	°

2.2.31 Power Transmitter design A31

Figure 118 illustrates the functional block diagram of Power Transmitter design A31, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 118. Functional block diagram of Power Transmitter design A31



The Power Conversion Unit on the right-hand side of Figure 118 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the Primary Coil plus a series capacitor. Finally, the voltage and current sense monitors the Primary Coil voltage and current.

The Communications and Control Unit on the left-hand side of Figure 118 comprises the digital logic part of the design. The unit receives and decodes messages from the Power Receiver, executes the relevant power control algorithms and protocols, and drives the input power and frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.31.1 Mechanical details

Power Transmitter design A31 includes one Primary Coil as defined in Section 2.2.31.1.1, Shielding as defined in Section 2.2.31.1.2, and an Interface Surface as defined in Section 2.2.31.1.3.

2.2.31.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of litz wire having 115 strands of 0.08 mm diameter, or equivalent. As shown in Figure 119, a Primary Coil has a racetrack-like shape and consists of a single layer. Table 84 lists the dimensions of a Primary Coil.

Figure 119. Primary Coil of Power Transmitter design A31

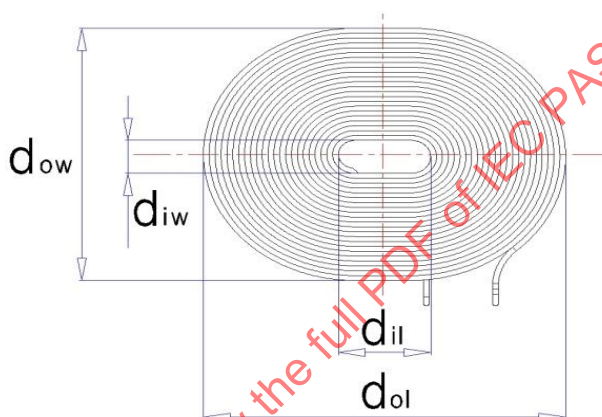


Table 84. Primary Coil parameters of Power Transmitter design A31

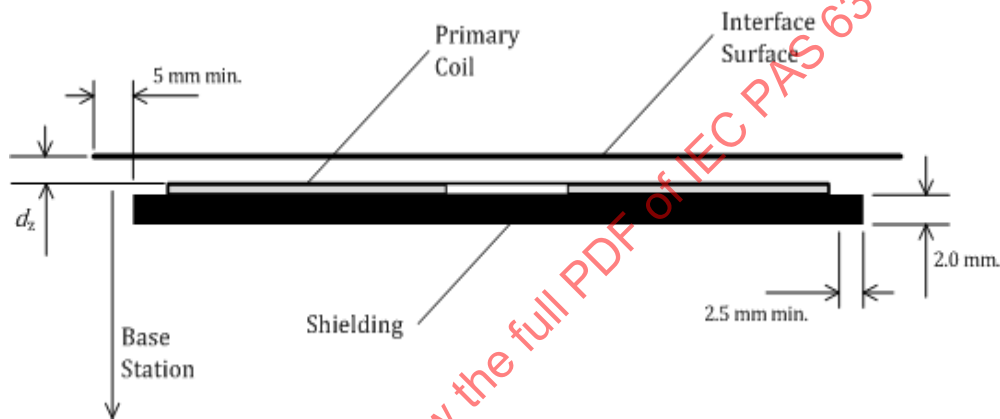
Parameter	Symbol	Value
Outer length	d_{ol}	$65.5^{±0.5}$ mm
Inner length	d_{il}	$16.5^{±0.5}$ mm
Outer width	d_{ow}	$57.1^{±0.5}$ mm
Inner width	d_{iw}	$4.5^{±0.5}$ mm
Thickness	d_c	$1.3^{±0.15}$ mm
Number of turns per layer	N	22
Number of layers	–	1

2.2.31.1.2 Shielding

As shown in Figure 120, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least 2.5 mm beyond the outer edge of the Primary Coil, and has a thickness of at least 2.0 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Mn-Zn-Ferrite Core - any supplier
- Ni-Zn Ferrite Core – any supplier

Figure 120. Primary Coil assembly of Power Transmitter design A31



2.2.31.1.3 Interface Surface

As shown in Figure 120, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 3.0^{+0.5}_{-0.5}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5.0 mm beyond the outer diameter of the Primary Coil.

2.2.31.1.4 Separation between multiple Power transmitters

If the Base Station contains multiple type A31 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 71.0 mm.

2.2.31.2 Electrical details

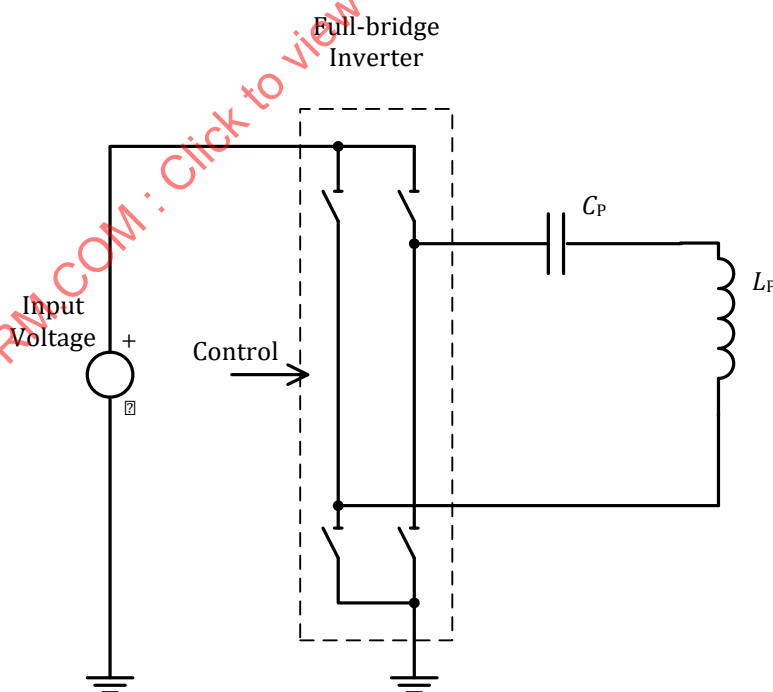
As shown in Figure 121, Power Transmitter design A31 uses a full-bridge inverter to drive the Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coil and Shielding has a self inductance $L_P = 24^{\pm 10\%} \mu\text{H}$. The input voltage to the full-bridge inverter is $12^{\pm 5\%} \text{ V}$. The value of the series capacitance is $C_P = 148^{\pm 5\%} \text{ nF}$.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels up to 100 V pk-pk.

Power Transmitter design A31 uses the Operating Frequency and duty cycle of the Power Signal in order to control the amount of power transferred. For this purpose, the Operating Frequency is $f_{op} = 87 \dots 110 \text{ kHz}$ and the duty cycle range of 2...50%.

When a type A31 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), the Power Transmitter shall use an Operating Frequency of $98^{\pm 10.0} \text{ kHz}$, and a duty cycle of $25^{\pm 10.0}\%$. If the Power Transmitter does not receive a Signal Strength Packet from the Power Receiver, the Power Transmitter shall remove the Power Signal as defined in *Parts 1 and 2: Interface Definitions*. The Power Transmitter may reapply the Power Signal multiple times at consecutively higher duty cycles to the full bridge inverter within the range specified above, until the Power Transmitter receives a Signal Strength Packet containing an appropriate Signal Strength Value.

Figure 121. Electrical diagram (outline) of Power Transmitter design A31



Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the Operating Frequency as well as the duty cycle to the full-bridge inverter. It is recommended that control of the power occurs primarily by means of adjustments to the Operating Frequency, and that duty cycle adjustments are made according to the amount of current. In order to guarantee sufficiently accurate power control, a type A31 Power Transmitter shall determine the amplitude of the Primary Coil current with a resolution of 5 mA or better. Finally, Table 85 and Table 86 provide the values of several parameters, which are used in the PID algorithm.

Table 85. PID parameters for Operating Frequency control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA ⁻¹
Integral gain	K_i	0	mA ⁻¹ ms ⁻¹
Derivative gain	K_d	0	mA ⁻¹ ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	1.0	Hz

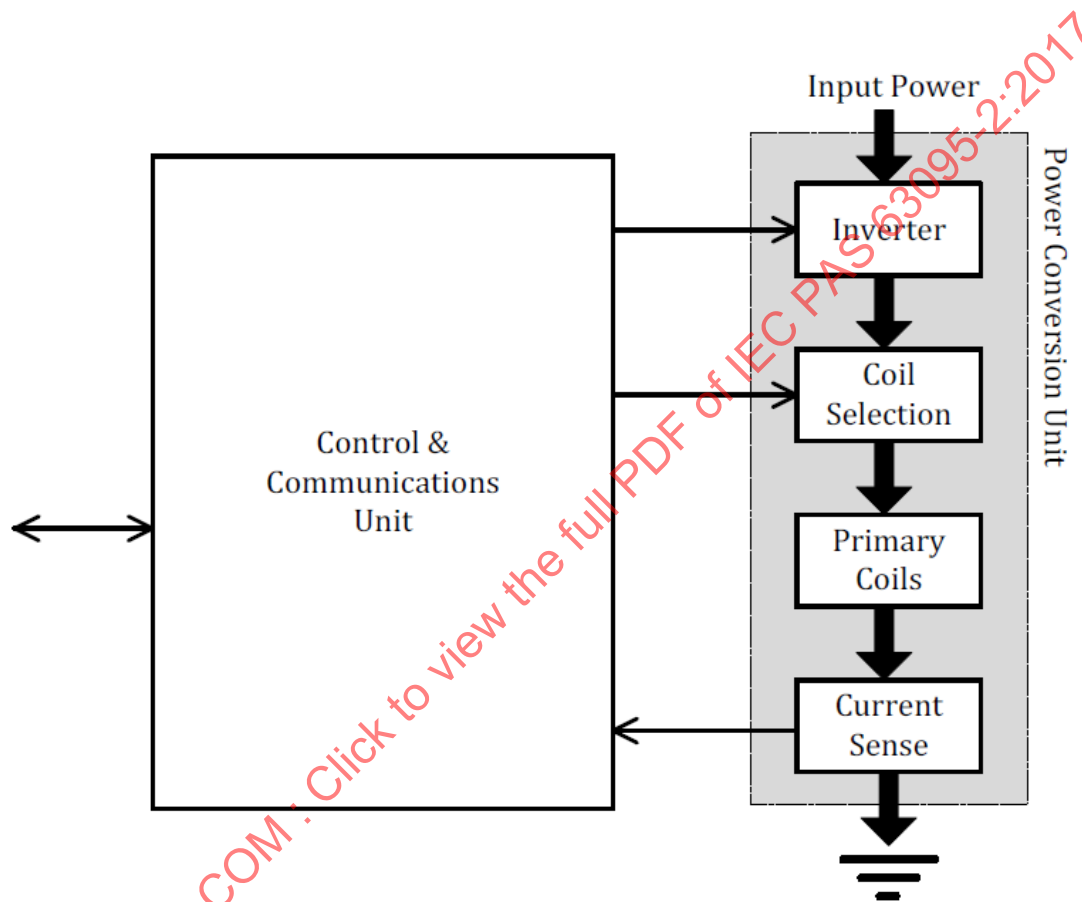
Table 86. PID parameters for duty control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA ⁻¹
Integral gain	K_i	0	mA ⁻¹ ms ⁻¹
Derivative gain	K_d	0	mA ⁻¹ ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	–0.1	°

2.2.32 Power Transmitter design A32

Figure 122 illustrates the functional block diagram of Power Transmitter design A32, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 122. Functional block diagram of Power Transmitter design A32



The Power Conversion Unit on the right-hand side of Figure 122 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from a linear array of partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the Primary Coils. Selection of the Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using any of the Primary Coils. Note that the array may consist of a single Primary Coil only, in which case the selection is trivial. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 122 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.32.1 Mechanical details

Power Transmitter design A32 includes one Primary Coil as defined in Section 2.2.32.1.1, Shielding as defined in Section 2.2.32.1.2, and an Interface Surface as defined in Section 2.2.32.1.3.

2.2.32.1.1 Primary coil

The Primary Coil consists of at least one PCB coil. Figure 115 shows a view of a single Primary Coil. Table 87 lists the dimensions of the Primary Coil.

Figure 123. Primary Coil of Power Transmitter design A32

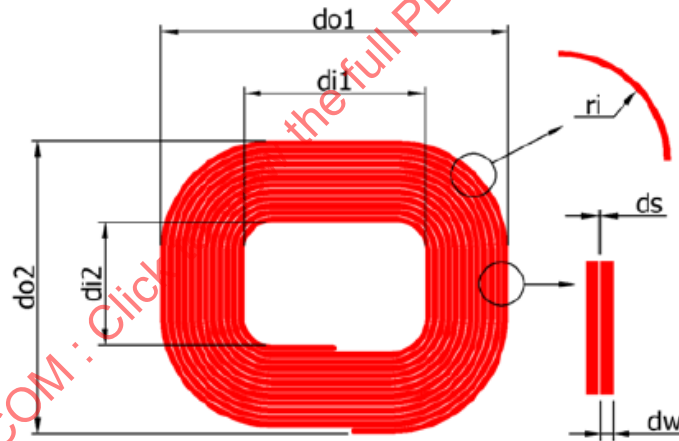


Table 87. Primary Coil parameters of Power Transmitter design A32

Parameter	Symbol	Value
Outer length	d_{o1}	$53.4^{±0.7}$ mm
Inner length	d_{i1}	$27.5^{±0.7}$ mm
Outer width	d_{o2}	$45.8^{±0.7}$ mm
Inner width	d_{i2}	$19.5^{±0.75}$ mm
4- layer PCB		
Track width	d_w	$0.82^{±0.2}$ mm
Track width plus spacing	$d_w + d_s$	$1.08^{±0.2}$ mm
Corner rounding*	r_i	$16.7^{±1.0}$ mm
Number of turns	N	$12^{±0.25}$
5...8 layer PCB		
Track width	d_w	$0.55^{±0.15}$ mm
Track width plus spacing	$d_w + d_s$	$1.1^{±0.15}$ mm
Corner rounding*	r_i	$13.1^{±1.31}$ mm
Number of turns	N	$12^{±0.25}$

Power Transmitter design A32 contains at least one Primary Coil. Odd numbered coils are placed alongside each other with a displacement of d_{h2} between their centers. Even numbered coils are placed orthogonal to the odd numbered coils with a displacement of d_{h1} mm between their centers. See Figure 124.

Figure 124. Primary Coils of Power Transmitter design A32

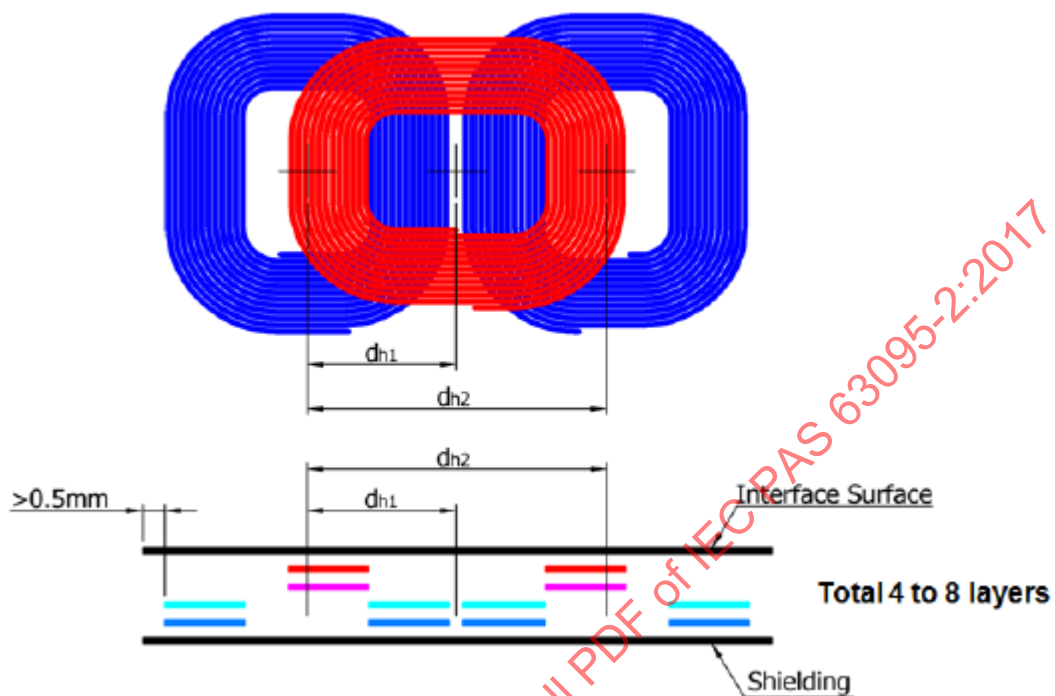


Figure 125. Primary Coils of Power Transmitter design A32

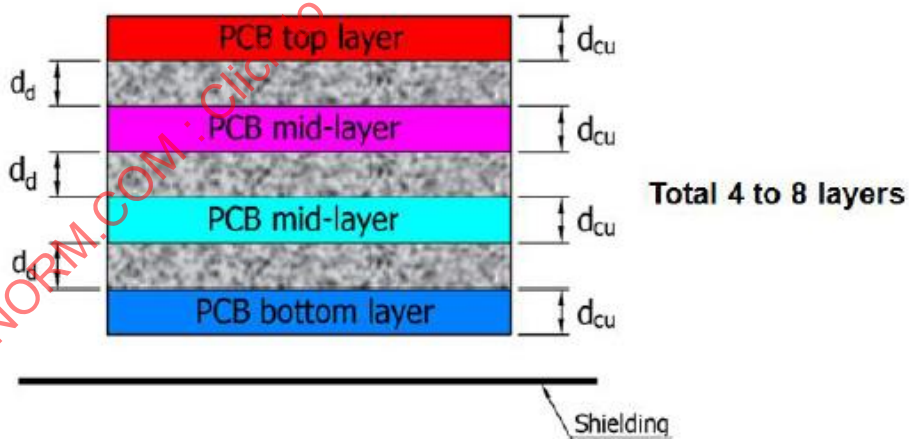


Table 88. Primary Coil parameters of Power Transmitter design A32

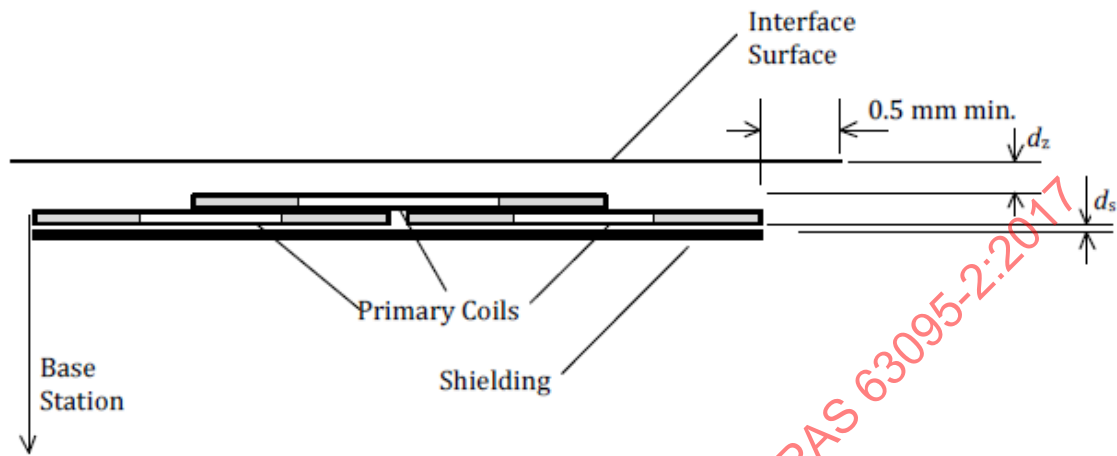
Parameter	Symbol	Value
4- layer PCB		
Center-to-center distance	d_{h1}	23.8 $\pm$ 1.0 mm
Center-to-center distance	d_{h2}	47.52 $\pm$ 2.0 mm
PCB copper thickness	d_{Cu}	0.105 $\pm$ 0.015 mm
Dielectric thickness	d_d	0.375 $\pm$ 0.063 mm
5...8 layer PCB		
Center-to-center distance	d_{h1}	23.76 $\pm$ 1.5 mm
Center-to-center distance	d_{h2}	47.52 $\pm$ 3.0 mm
PCB copper thickness	d_{Cu}	0.105 $\pm$ 0.0161 mm
Dielectric thickness	d_d	0.125 $\pm$ 0.0254 mm

2.2.32.1.2 Shielding

As shown in Figure 126, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least the outer dimensions of the Primary Coils, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $ds = 1.0$ mm. The version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Ni-Mn-Ferrite Core – any supplier
- Mn-Zn-Ferrite Core – any supplier
- Ni-Zn- Ferrite Core – any supplier

Figure 126. Primary Coil assembly of Power Transmitter design A32



2.2.32.1.3 Interface Surface

As shown in Figure 126, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 2.75 \pm 1$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 0.5 mm beyond the outer dimensions of the Primary Coils.

2.2.32.1.4 Separation between multiple Power transmitters

If the Base Station contains multiple type A32 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least 49.2 ± 4 mm.

2.2.32.2 Electrical details

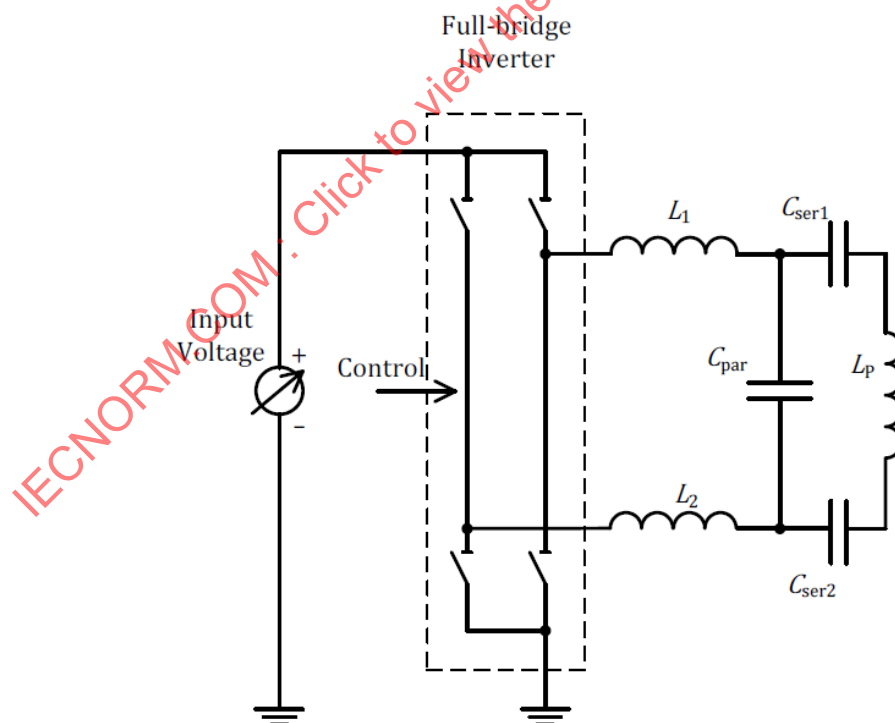
As shown in Figure 117, Power Transmitter design A32 uses a full-bridge inverter to drive an individual Primary Coil and a series capacitance. Within the Operating Frequency range Specified below, the assembly of Primary Coil and Shielding has a self-inductance $L_p = 11.5^{\pm 10\%}$ μH for coils closest to the interface surface, and inductance $L_p = 12.5^{\pm 10\%}$ μH for coils furthest from the Interface Surface. The value of inductances L_1 and L_2 is $1^{\pm 20\%}$ μH . The value of the total series capacitance is $1/C_{\text{ser1}} + 1/C_{\text{ser2}} = 1/200^{\pm 10\%}$ 1/nF. The value of the parallel capacitance is $C_{\text{par}} = 400^{\pm 10\%}$ nF.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk. Power

Power Transmitter design A32 uses the input voltage of the inverter to control the amount of power that is transferred. For this purpose, the input voltage has a range of 1...12 V, with a resolution of 10 mV or better. The Operating Frequency is $f_{\text{op}} = 105 \dots 115$ kHz, with a duty cycle of 50%.

When a type A32 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial voltage of 3.5 ± 0.5 V for a bottom Primary Coil, and 3.0 ± 0.5 V for a top Primary Coil, and a recommended Operating Frequency of 110 kHz.

Figure 127. Electrical diagram (outline) of Power Transmitter design A32



Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the inverter. In order to guarantee sufficiently accurate power control, a type A32 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 89 provides the values of several parameters, which are used in the PID algorithm.

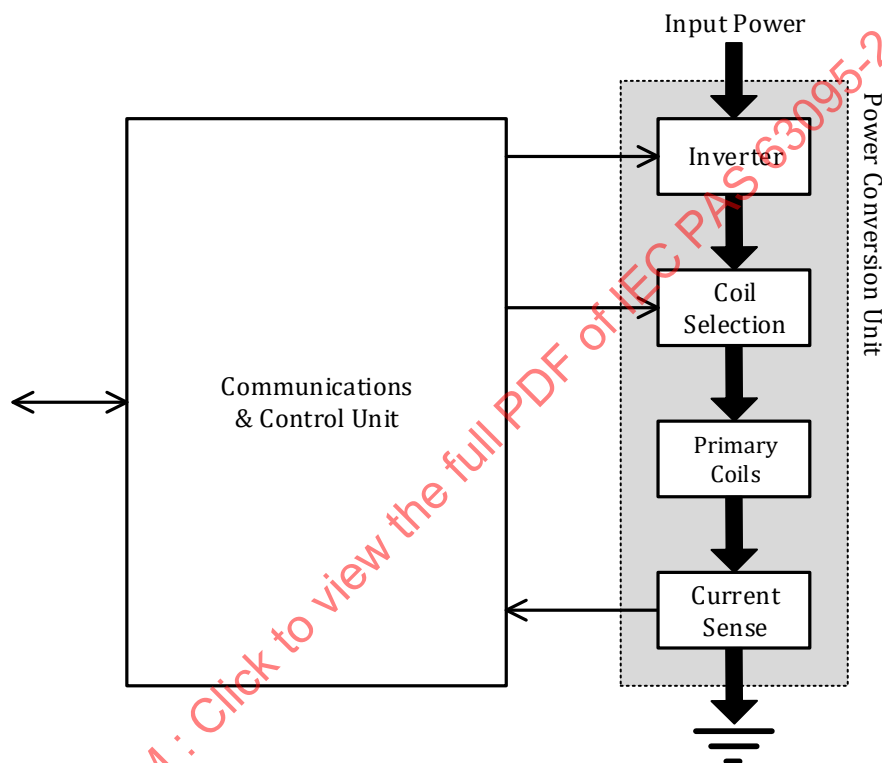
Table 89. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	0.03	mA-1
Integral gain	K_i	0.01	mA-1ms-1
Derivative gain	K_d	0	mA-1ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-1	mV

2.2.33 Power Transmitter design A33

Power Transmitter design A33 enables Free Positioning of Power Receiver. Figure 128 illustrates the functional block diagram of this Power Transmitter design A33, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 128. Functional block diagram of Power Transmitter design A33



The Power Conversion Unit on the right-hand side of Figure 128 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from a linear array of partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the Primary Coils. Selection of the Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using any of the Primary Coils. Note that the array may consist of a single Primary Coil only, in which case the selection is trivial. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 128 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.33.1 Mechanical details

Power Transmitter design A33 includes one or more Primary Coils as defined in Section 2.2.33.1.1, Shielding as defined in Section 2.2.33.1.2, an Interface Surface as defined in Section 2.2.33.1.3.

2.2.33.1.1 Primary coil

The Primary Coil consists of at least one PCB coil. Figure 129 shows a view of a single Primary Coil. Table 90 lists the dimensions of the Primary Coil.

Figure 129. Primary Coil of Power Transmitter design A33

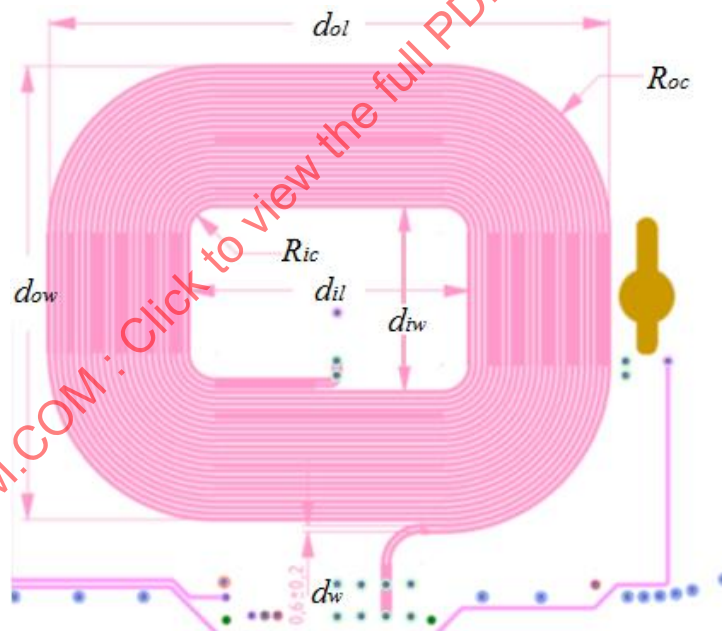


Table 90. Primary Coil parameters of Power Transmitter design A33

Parameter	Symbol	Value
Outer length	d_{ol}	$55.5^{±0.2}$ mm
Inner length	d_{il}	$27.9^{±0.2}$ mm
Outer width	d_{ow}	$44.8^{±0.2}$ mm
Inner width	d_{iw}	$18.4^{±0.2}$ mm
Track width	d_w	$0.6^{±0.2}$ mm
Outer Corner rounding*	R_{oc}	$16.5^{±0.2}$ mm
Inner Corner rounding**	R_{ic}	$2.7^{±0.2}$ mm
Number of turns	N	12

* outermost winding only

** innermost winding only

Power Transmitter design A33 contains at least one Primary Coil. Odd numbered coils are placed alongside each other with a displacement of d_{oo} between their centers. Even numbered coils are placed orthogonal to the odd numbered coils with a displacement of d_{oe} between their centers. See Figure 130 and Figure 131. Table 91 lists the dimensions of the Primary Coils.

Figure 130. Three Primary Coils of Power Transmitter design A33

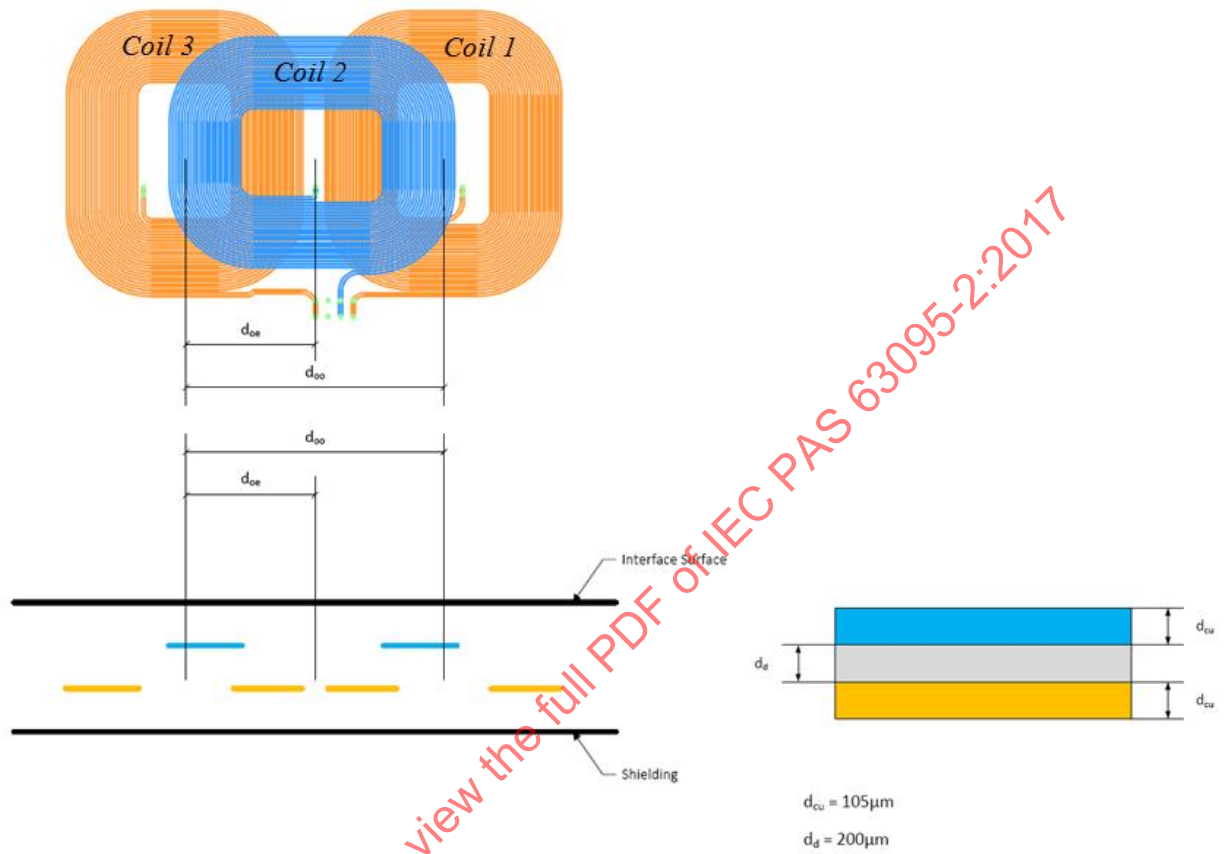
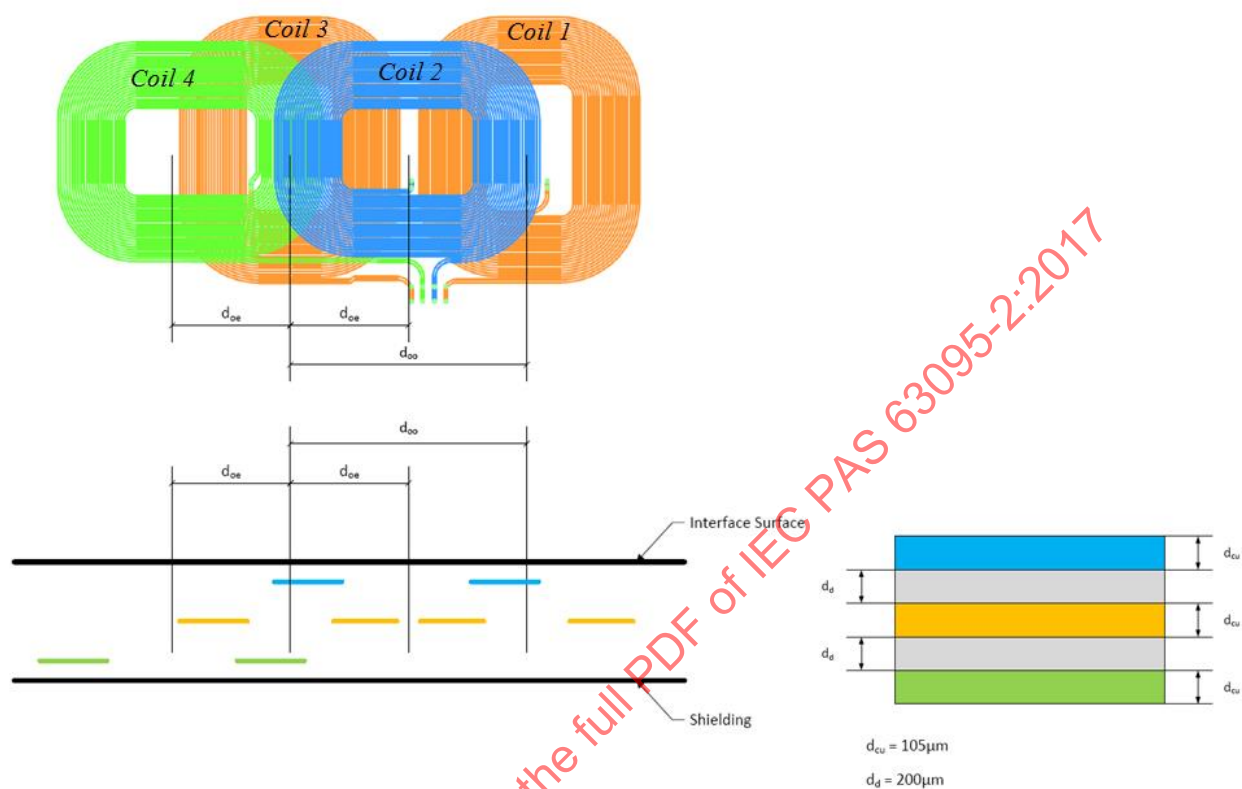
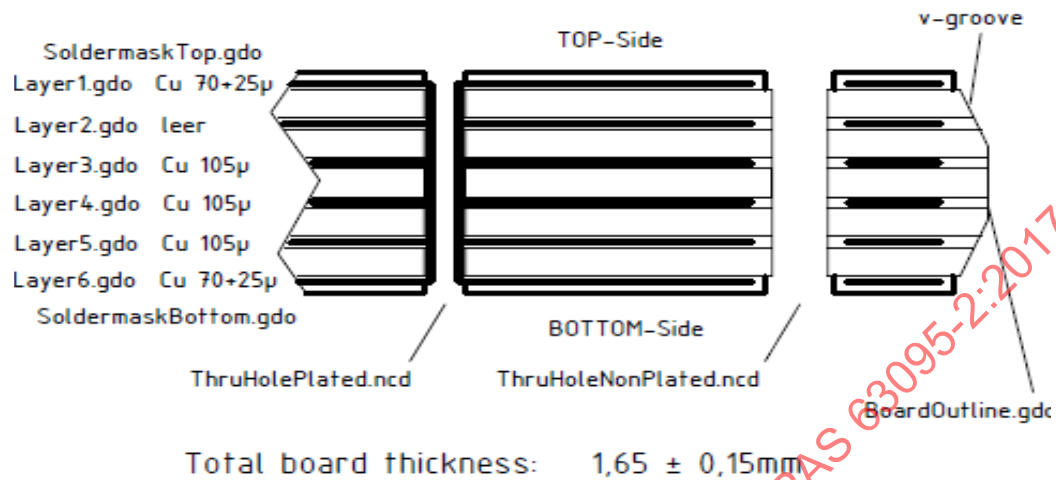


Figure 131. Four Primary Coils of Power Transmitter design A33**Table 91. Primary Coil parameters of Power Transmitter design A33**

Parameter	Symbol	Value
Center-to-center distance	d_{oo}	$49.2^{+0.2} \text{ mm}$
Center-to-center distance	d_{oe}	$24.6^{+0.2} \text{ mm}$
PCB copper thickness	d_{cu}	$105 \mu\text{m}$
Dielectric thickness	d_d	$200 \mu\text{m}$

Figure 132 shows the layered structure of the Primary Coils array. Note: 1 coil configuration uses 1 metal layer, 2 and 3 coils configuration uses 2 metal layers, 4 coils and more coils configuration use 3 metal layers.

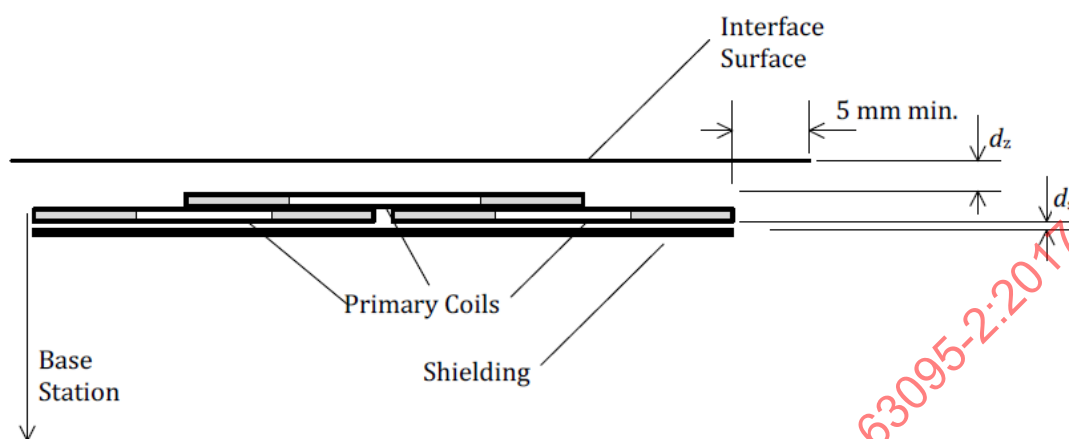
Figure 132. Layered structure of the Primary Coils of Power Transmitter design A33



2.2.33.1.2 Shielding

As shown in Figure 133, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least the outer dimensions of the Primary Coils, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 44 — Fair Rite Corporation.
- Material 28 — Steward, Inc.
- CMG22G — Ceramic Magnetics, Inc.
- Kolektor 22G — Kolektor.
- LeaderTech SB28B2100-1 — LeaderTech Inc.
- TopFlux "A" — TopFlux.
- TopFlux "B" — TopFlux.
- ACME K081 — Acme Electronics.
- L7H — TDK Corporation.
- PE22 — TDK Corporation.
- FK2 — TDK Corporation.

Figure 133. Primary Coil assembly of Power Transmitter design A33

2.2.33.1.3 Interface Surface

As shown in Figure 133, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 3^{\pm 1}$ mm, across the top face of the Primary Coil. In the case of a single Primary Coil, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 4.5^{\pm 1}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer dimensions of the Primary Coils.

2.2.33.1.4 Inter coil separation

If the Base Station contains multiple type A33 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least $49.2^{\pm 4}$ mm.

2.2.33.2 Electrical details

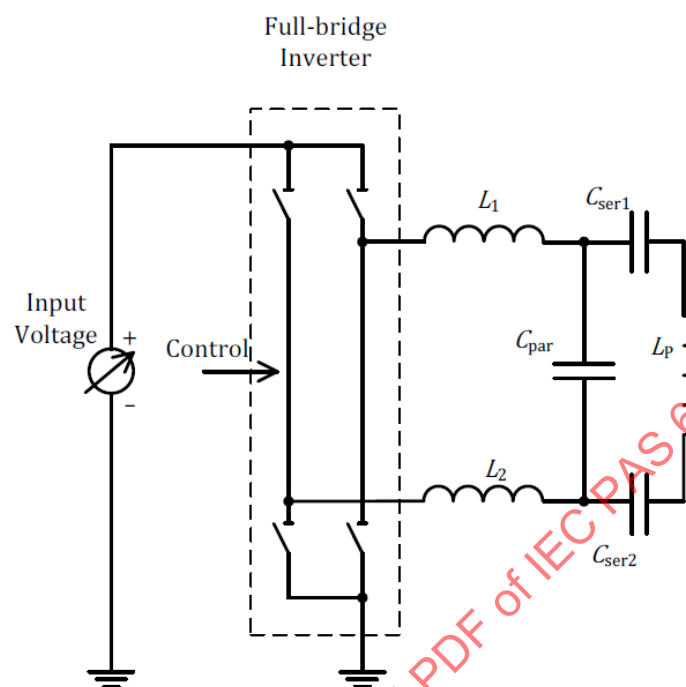
As shown in Figure 134, Power Transmitter design A33 uses a full-bridge inverter to drive an individual Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coils and Shielding has a self inductance $L_p = 11.5^{\pm 10\%}$ μH for coils closest to the Interface Surface and inductance $L_p = 12.5^{\pm 10\%}$ μH for coils furthest from the Interface Surface. The value of inductances L_1 and L_2 is $1^{\pm 20\%}$ μH . The value of the total series capacitance is $1/C_{\text{ser1}} + 1/C_{\text{ser2}} = 1/200^{\pm 10\%}$ 1/nF, where the individual series capacitances may have any value less than the sum. The value of the parallel capacitance is $C_{\text{par}} = 400^{\pm 10\%}$ nF.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A33 uses the input voltage of the inverter to control the amount of power that is transferred. For this purpose, the input voltage has a range of 1...9V, with a resolution of 10mV or better. The Operating Frequency is $f_{\text{op}} = 120\text{...}130$ kHz, with a duty cycle of 50%.

When a type A33 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial voltage of $4^{\pm 5\%}$ V, and a recommended Operating Frequency of 125 kHz.

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the inverter. In order to guarantee sufficiently accurate power control, a type A33 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 nA or better. Finally, Table 92 provides the values of several parameters, which are used in the PID algorithm.

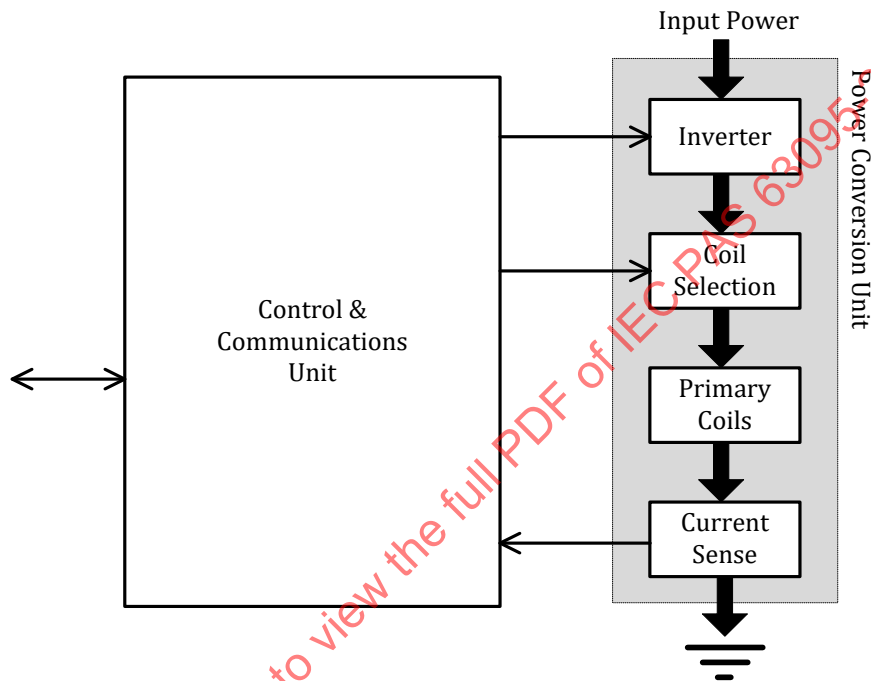
Figure 134. Electrical diagram (outline) of Power Transmitter design A33**Table 92. PID parameters for voltage control**

Parameter	Symbol	Value	Unit
Proportional gain	K_p	0.03	mA^{-1}
Integral gain	K_i	0.01	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-1	mV

2.2.34 Power Transmitter design A34

Figure 135 illustrates the functional block diagram of Power Transmitter design A34, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 135. Functional block diagram of Power Transmitter design A34



The Power Conversion Unit on the right-hand side of Figure 135 comprises the analog parts of the design. The inverter converts the DC input to an AC waveform that drives a resonant circuit, which consists of the selected Primary Coil plus a series capacitor. The selected Primary Coil is one from a linear array of partially overlapping Primary Coils, as appropriate for the position of the Power Receiver relative to the Primary Coils. Selection of the Primary Coil proceeds by the Power Transmitter attempting to establish communication with a Power Receiver using any of the Primary Coils. Note that the array may consist of a single Primary Coil only, in which case the selection is trivial. Finally, the current sense monitors the Primary Coil current.

The Communications and Control Unit on the left-hand side of Figure 135 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the Coil Selection block to connect the appropriate Primary Coil, executes the relevant power control algorithms and protocols, and drives the frequency of the AC waveform to control the power transfer. The Communications and Control Unit also interfaces with other subsystems of the Base Station, e.g. for user interface purposes.

2.2.34.1 Mechanical details

Power Transmitter design A34 includes one or more Primary Coils as defined in Section 2.2.34.1.1, Shielding as defined in Section 2.2.34.1.2, an Interface Surface as defined in Section 2.2.34.1.3.

2.2.34.1.1 Primary Coil

The Primary Coil is of the wire-wound type, and consists of no. 17 AWG (1.15 mm diameter) type 2 litz wire having 105 strands of no. 40 AWG (0.08 mm diameter), or equivalent. As shown in Figure 136, the Primary Coil has a rectangular shape and consists of a single layer. Table 93 lists the dimensions of the Primary Coil.

Figure 136. Primary Coil of Power Transmitter design A34

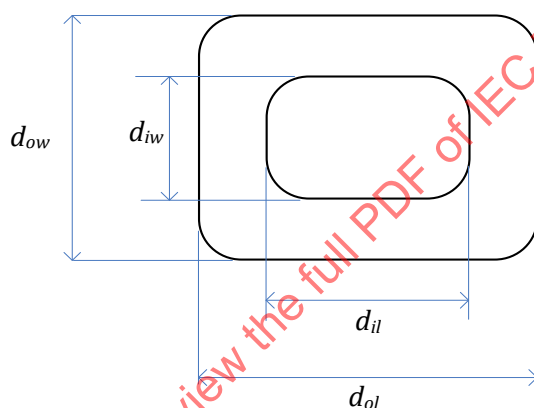
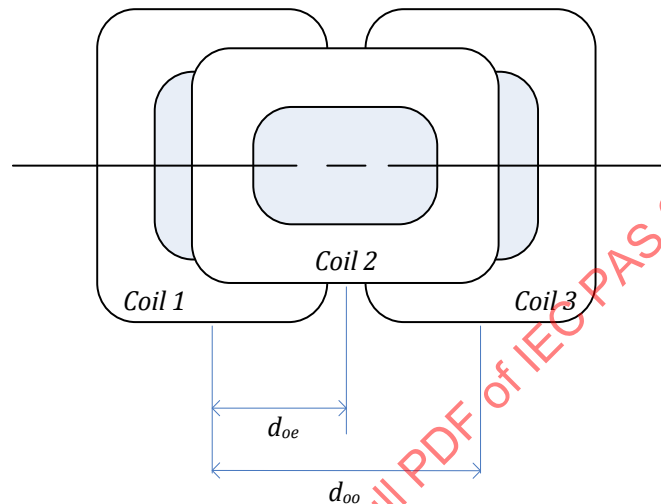


Table 93. Primary Coil parameters of Power Transmitter design A34

Parameter	Symbol	Value
Outer length	d_{ol}	$53.2^{+0.5}$ mm
Inner length	d_{il}	$27.5^{+0.5}$ mm
Outer width	d_{ow}	$45.2^{+0.5}$ mm
Inner width	d_{iw}	$19.5^{+0.5}$ mm
Thickness	d_c	$1.5^{+0.5}$ mm
Number of turns per layer	N	12 turns
Number of layers	–	1

Power Transmitter design A34 contains at least one Primary Coil. Odd numbered coils are placed alongside each other with a displacement of $d_{oo} = 49.2^{\pm 4}$ mm between their centers. Even numbered coils are placed orthogonal to the odd numbered coils with a displacement of $d_{oe} = 24.6^{\pm 2}$ mm between their centers. See Figure 137.

Figure 137. Primary Coils of Power Transmitter design A34



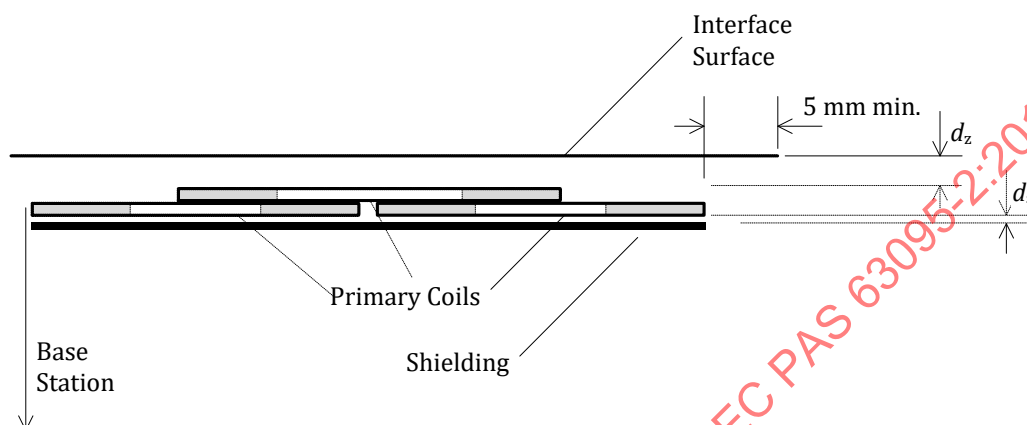
2.2.34.1.2 Shielding

As shown in Figure 138, soft-magnetic material protects the Base Station from the magnetic field that is generated in the Primary Coil. The Shielding extends to at least the outer dimensions of the Primary Coils, has a thickness of at least 0.5 mm, and is placed below the Primary Coil at a distance of at most $d_s = 1.0$ mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 44 — Fair Rite Corporation.
- Material 28 — Steward, Inc.
- CMG22G — Ceramic Magnetics, Inc.
- Kolektor 22G — Kolektor.
- LeaderTech SB28B2100-1 — LeaderTech Inc.
- TopFlux “A” — TopFlux.
- TopFlux “B” — TopFlux.
- ACME K081 — Acme Electronics.
- L7H — TDK Corporation.

- PE22 — TDK Corporation.
- FK2 — TDK Corporation.

Figure 138. Primary Coil assembly of Power Transmitter design A34



2.2.34.1.3 Interface Surface

As shown in Figure 138, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 3^{\pm 1}$ mm, across the top face of the Primary Coil. In the case of a single Primary Coil, the distance from the Primary Coil to the Interface Surface of the Base Station is $d_z = 4.5^{\pm 1}$ mm, across the top face of the Primary Coil. In addition, the Interface Surface of the Base Station extends at least 5 mm beyond the outer dimensions of the Primary Coils.

2.2.34.1.4 Inter coil separation

If the Base Station contains multiple type A34 Power Transmitters, the Primary Coils of any pair of those Power Transmitters shall have a center-to-center distance of at least $49.2^{\pm 4}$ mm.

2.2.34.2 Electrical details

As shown in Figure 139, Power Transmitter design A34 uses a half-bridge inverter to drive an individual Primary Coil and a series capacitance. Within the Operating Frequency range specified below, the assembly of Primary Coils and Shielding has a self inductance $L_p = 11.5^{\pm 10\%}$ μH for coils closest to the Interface Surface and inductance $L_p = 12.5^{\pm 10\%}$ μH for coils furthest from the Interface Surface. The value of inductance L is $3.3^{\pm 20\%}$ μH . The value of series capacitance is $C_{\text{ser}} = 168^{\pm 10\%}$ nF. The value of the parallel capacitance is $C_{\text{par}} = 400^{\pm 10\%}$ nF.

NOTE Near resonance, the voltage developed across the series capacitance can reach levels exceeding 100 V pk-pk.

Power Transmitter design A34 uses the input voltage of the inverter to control the amount of power that is transferred. For this purpose, the input voltage has a range of 2...24 V, with a resolution of 20 mV or better. The Operating Frequency is $f_{\text{op}} = 105 \dots 115$ kHz, with a duty cycle of 50%.

When a type A34 Power Transmitter first applies a Power Signal (Digital Ping; see *Parts 1 and 2: Interface Definitions*), it shall use an initial voltage of $7.0^{\pm 1.0}$ V for a bottom Primary Coil, and $6.0^{\pm 1.0}$ V for a top Primary Coil, and a recommended Operating Frequency of 110 kHz.

Control of the power transfer shall proceed using the PID algorithm, which is defined in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the inverter. In order to guarantee sufficiently accurate power control, a type A34 Power Transmitter shall determine the amplitude of the Primary Cell current—which is equal to the Primary Coil current—with a resolution of 7 mA or better. Finally, Table 94 provides the values of several parameters, which are used in the PID algorithm.

Figure 139. Electrical diagram (outline) of Power Transmitter design A34

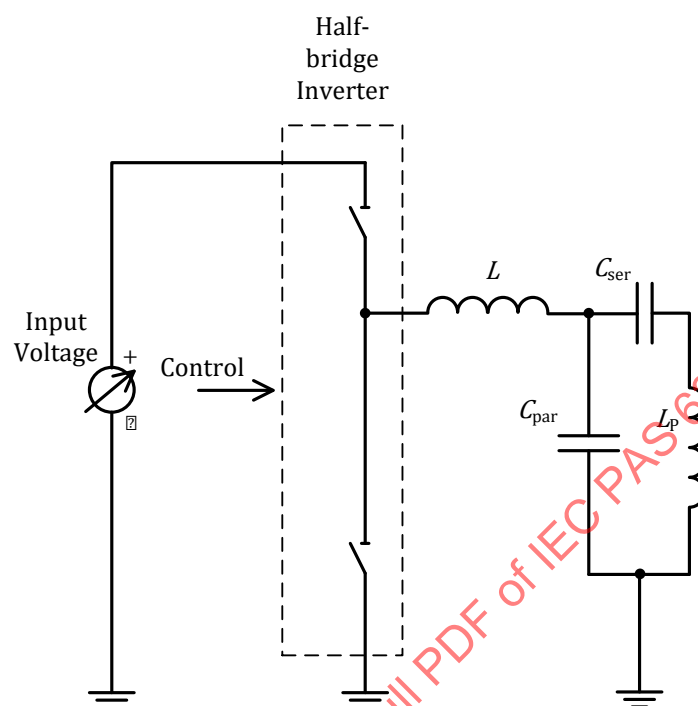


Table 94. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	0.03	mA-1
Integral gain	K_i	0.01	mA-1ms ⁻¹
Derivative gain	K_d	0	mA-1ms
Integral term limit	M_I	3,000	N.A.
PID output limit	M_{PID}	20,000	N.A.
Scaling factor	S_v	-2	mV

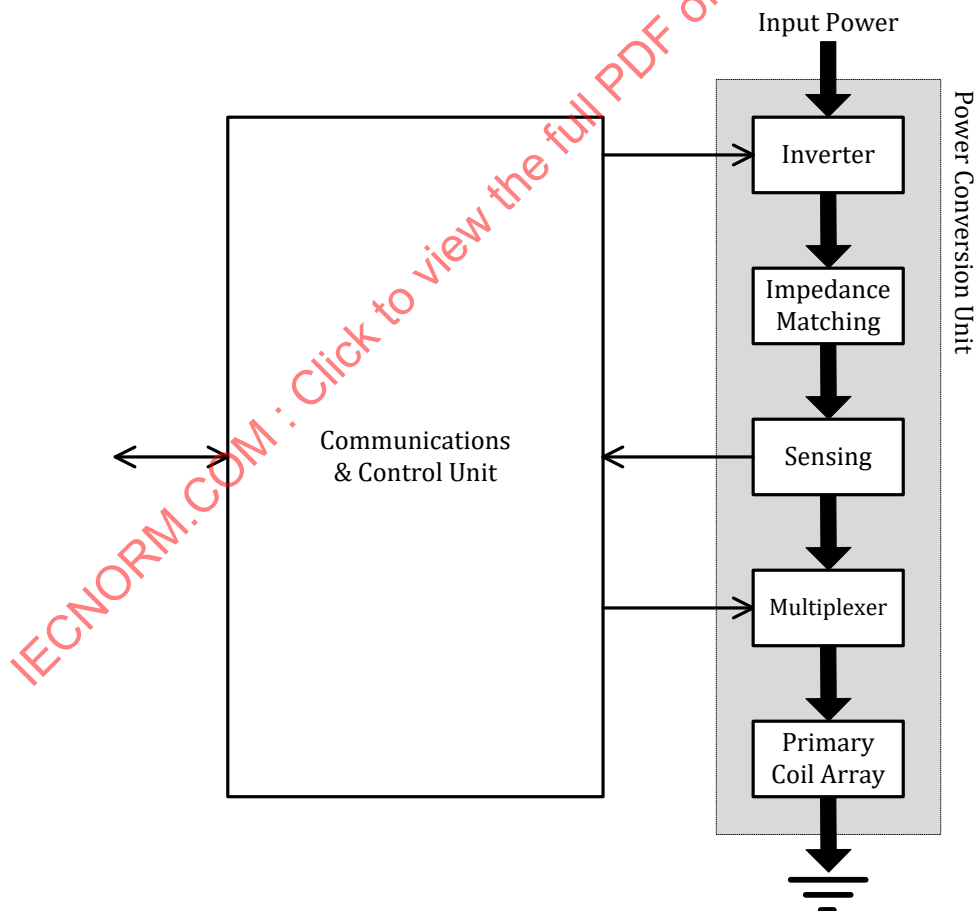
2.3 Baseline Power Profile designs that activate multiple Primary Coils simultaneously

This Section 2.2.34 defines all type B Power Transmitter designs in the Baseline Power Profile. In addition to the definitions in this section, each Power Transmitter design shall implement the relevant parts of the protocols and communications interface defined in *Parts 1 and 2: Interface Definitions*.

2.3.1 Power Transmitter design B1

Power Transmitter design B1 enables Free Positioning. Figure 140 illustrates the functional block diagram of this design, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 140. Functional block diagram of Power Transmitter design B1



The Power Conversion Unit on the right-hand side of Figure 140 comprises the analog parts of the design. The design uses an array of partly overlapping Primary Coils to provide for Free Positioning. Depending on the position of the Power Receiver, the multiplexer connects and/or disconnects the appropriate Primary Coils. The impedance matching network forms a resonant circuit with the parts of the Primary Coil array that are connected. The sensing circuits monitor (amongst others) the Primary Cell current and voltage, and the inverter converts the DC input to an AC waveform that drives the Primary Coil array.

The Communications and Control Unit on the left-hand side of Figure 140 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the multiplexer to connect the appropriate parts of the Primary Coil array, executes the relevant power control algorithms and protocols, and drives the frequency and input voltage to the inverter to control the amount of power provided to the Power Receiver. The Communications and Control Unit also interfaces with the other subsystems of the Base Station, e.g. for user interface purposes.

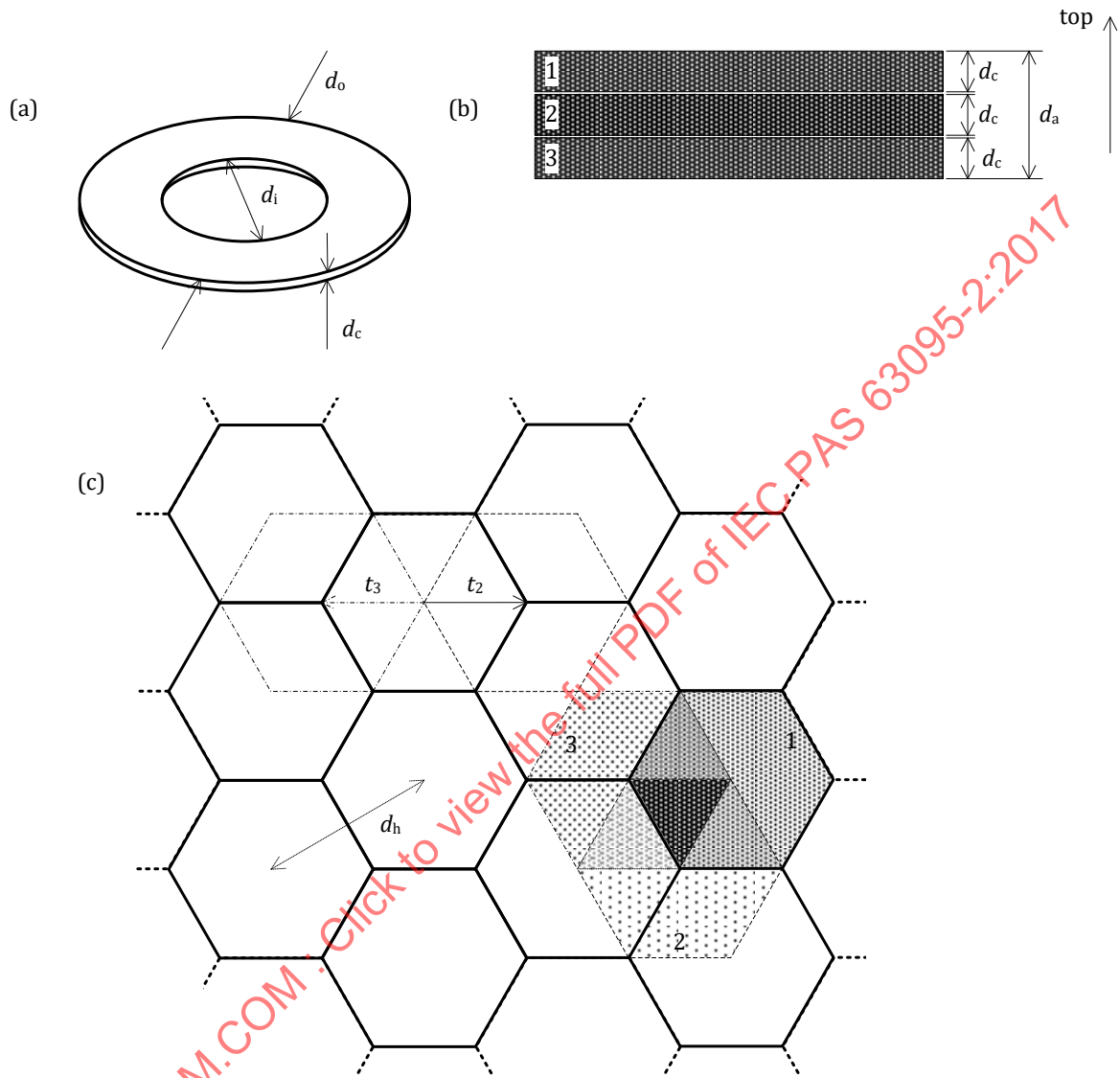
2.3.1.1 Mechanical details

Power Transmitter design B1 includes a Primary Coil array as defined in Section 2.3.1.1.1, Shielding as defined in Section 2.3.1.1.2, and an Interface Surface as defined in Section 2.3.1.1.3.

2.3.1.1.1 Primary Coil array

The Primary Coil array consists of 3 layers. Figure 141(a) shows a top view of a single Primary Coil, which is of the wire-wound type, and consists of litz wire having 24 strands of no. 40 AWG (0.08 mm diameter), or equivalent.

Figure 141. Primary Coil array of Power Transmitter design B1



As shown in Figure 141(a), the Primary Coil has a circular shape and consists of a single layer. Figure 141(b) shows a side view of the layer structure of the Primary Coil array. Figure 141(c) provides a top view of the Primary Coil array, showing that the individual Primary Coils are packed in a hexagonal grid. The solid hexagons show the closely packed structure of the grid of Primary Coils on layer 1 of the Primary Coil array. The dashed hexagon illustrates that the grid of Primary Coils on layer 2 is offset over a distance t_2 to the right, such that the centers of the Primary Coils in layer 2 coincide with the corners of Primary Coils in layer 1. Likewise, the dash-dotted hexagon illustrates that the grid of Primary Coils on layer 3 is offset over a distance t_3 to the left, such that the centers of the Primary Coils in layer 3 coincide with the corners of Primary Coils in layer 1. As a result, the centers, respectively corners, of the Primary Coils on layer 2 and the corners, respectively centers, of the Primary Coils on layer 3 coincide as well. All Primary Coils are stacked with the same polarity. See Section 2.3.1.2 for the meaning of the shaded hexagons.

Table 95 lists the relevant parameters of the Primary Coil array.

Table 95. Primary Coil array parameters of Power Transmitter design B1

Parameter	Symbol	Value
Outer diameter	d_o	$28.5_{-0.7}$ mm
Inner diameter	d_i	$10.5^{+0.3}$ mm
Layer thickness*	d_c	$0.6^{+0.05}_{-0.1}$ mm
Number of turns	N	16
Array thickness	d_a	$1.9^{+0.3}_{-0.2}$ mm
Center-to-center distance	d_h	28.6^{+1} mm
Offset 2 nd layer array	t_2	$16.5^{+0.6}$ mm
Offset 3 rd layer array	t_3	$16.5^{+0.6}$ mm

* Value includes thickness of connection wires.

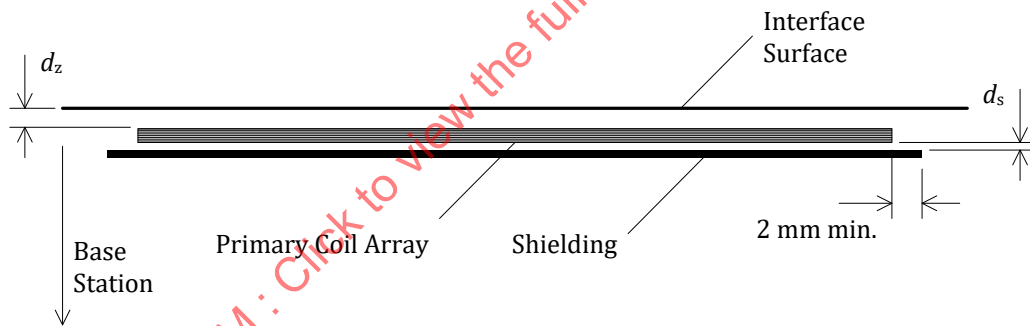
2.3.1.1.2 Shielding

As shown in Figure 142, Transmitter design B1 employs Shielding to protect the Base Station from the magnetic field that is generated in the Primary Coil array. The Shielding extends to at least 2 mm beyond the outer edges of the Primary Coil array, and is placed at a distance of at most $d_s = 0.5$ mm below the Primary Coil array.

The Shielding consists of soft magnetic material that has a thickness of at least 0.5 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 78 — Fair Rite Corporation.
- 3C94 — Ferroxcube.
- N87 — Epcos AG.
- PC44 — TDK Corp.
- FK2 — TDK Corp (at least 0.8 mm thickness).

Figure 142. Primary Coil array assembly of Power Transmitter design B1



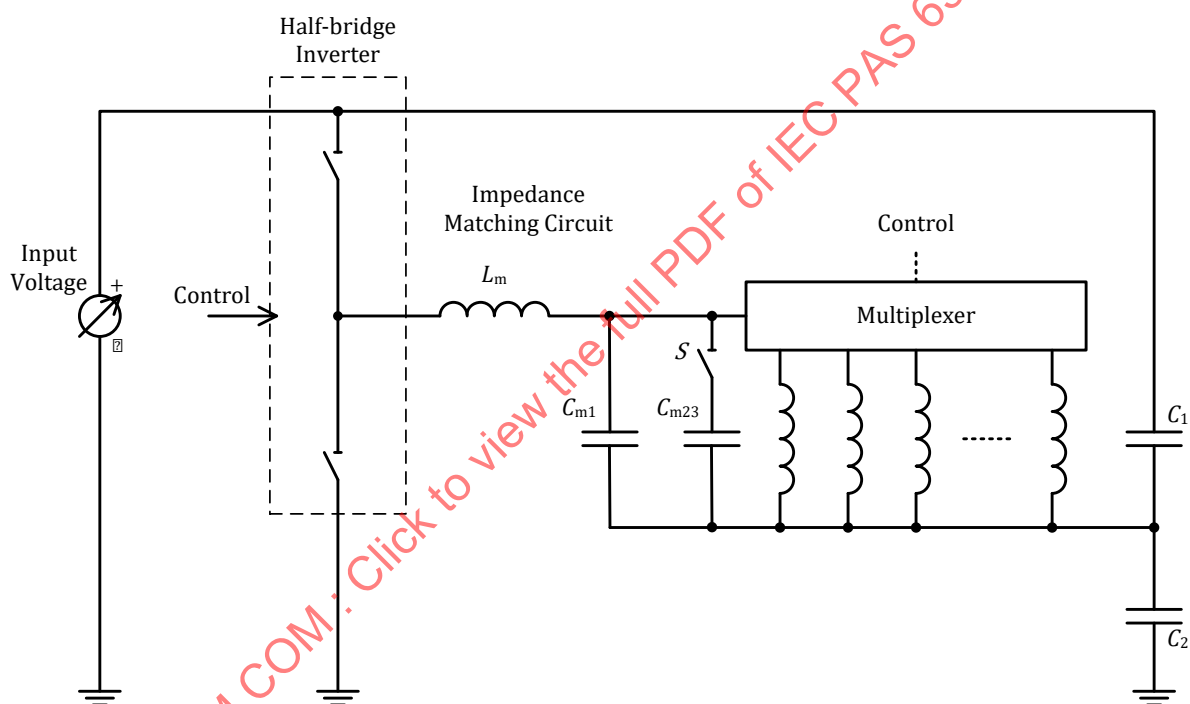
2.3.1.1.3 Interface Surface

As shown in Figure 142, the distance from the Primary Coil array to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.25}$ mm, across the top face of the Primary Coil array. In addition, the Interface Surface extends at least 5 mm beyond the outer edges of the Primary Coil array.

2.3.1.2 Electrical details

As shown in Figure 143, Power Transmitter design B1 uses a half-bridge inverter to drive the Primary Coil array. In addition, Power Transmitter design B1 uses a multiplexer to select the position of the Active Area. The multiplexer shall configure the Primary Coil array in such a way that one, two, or three Primary Coils are connected—in parallel—to the driving circuit. The connected Primary Coils together constitute a Primary Cell. As an additional constraint, the multiplexer shall select the Primary Coils such that each selected Primary Coil has an overlap with every other selected Primary Coil; see Figure 140(c) for an example.

Figure 143. Electrical diagram (outline) of Power Transmitter design B1



Within the Operating Frequency range $f_{op} = 105 \dots 113$ kHz, the assembly of Primary Coil array and Shielding has an inductance of $8.1^{\pm 1} \mu\text{H}$ for each individual Primary Coil in layer 1 (closest to the Interface Surface), $8.7^{\pm 1} \mu\text{H}$ for each individual Primary Coil in layer 2, and $9.6^{\pm 1} \mu\text{H}$ for each individual Primary Coil in layer 3. The capacitances and inductance in the impedance matching circuit are, respectively, $C_{m1} = 300^{\pm 5\%} \text{ nF}$, $C_{m23} = 200^{\pm 5\%} \text{ nF}$, and $L_m = 3.8^{\pm 5\%} \mu\text{H}$. The capacitances C_1 and C_2 in the half-bridge inverter both are $68 \mu\text{F}$. The switch S is open if the Primary Cell consists of a single Primary Coil; otherwise, the switch S is closed.

NOTE The voltage across the capacitance C_m can reach levels exceeding 36 V pk-pk.

Power Transmitter design B1 uses the input voltage to the half-bridge inverter to control the amount of power that is transferred. For this purpose, the input voltage range is 0...20 V, where a lower input voltage results in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type B1 Power Transmitter shall be able to control the input voltage with a resolution of 35 mV or better.

When a type B1 Power Transmitter first applies a Power Signal (see the *Digital Ping* section in *Parts 1 and 2: Interface Definitions*), it shall use an initial input voltage of 12 V.

Control of the power transfer shall proceed using the PID algorithm, which is defined in the *Power transfer control* section in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(c)}$ introduced in the definition of that algorithm represents the input voltage to the half-bridge inverter. In order to guarantee sufficiently accurate power control, a type B1 Transmitter shall determine the amplitude of the current into the Primary Cell with a resolution of 5 mA or better. In addition to the PID algorithm, a type B1 Power Transmitter shall limit the current into the Primary Cell to at most 4 A RMS in the case that the Primary Cell consists of two or three Primary Coils, or at most 2 A RMS in the case that the Primary Cell consists of one Primary Coil. For that purpose, the Power Transmitter may limit the input voltage to the half-bridge inverter to value that is lower than 20 V. Finally, Table 96 provides the values of several parameters, which are used in the PID algorithm.

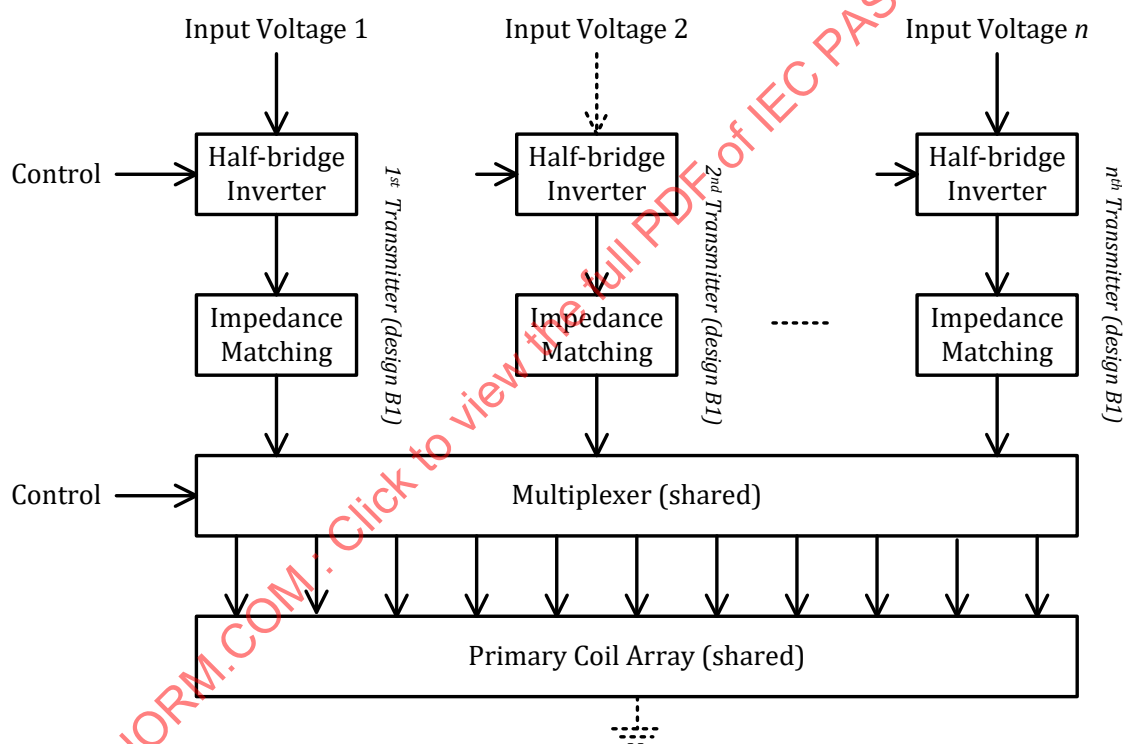
Table 96. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	N.A.	N.A.
PID output limit	M_{PID}	2,000	N.A.
Scaling factor	S_v	-1	mV

2.3.1.3 Scalability

Sections 2.3.1.1 and 2.3.1.2 define the mechanical and electrical details of Power Transmitter design B1. As defined in Section 2.1, a type B1 Power Transmitter serves a single Power Receiver only. In order to serve multiple Power Receivers simultaneously, a Base Station may contain multiple type B1 Power Transmitters. As shown in Figure 144, these Power Transmitters may share the Primary Coil array and multiplexer. However, each individual Power Transmitter shall have a separately controllable inverter, impedance matching circuit, and means to determine the Primary Cell current, as defined in Section 2.3.1.2. In addition, the multiplexer shall ensure that it does not connect multiple inverters to any individual Primary Coil.

Figure 144. Multiple type B1 Power Transmitters sharing a multiplexer and Primary Coil array



2.3.2 Power Transmitter design B2

Power Transmitter design B2 enables Free Positioning. The main difference between Power Transmitter design B2 and Power Transmitter design B1 is the Primary Coil array. Power Transmitter design B2 is based on a Printed Circuit Board (PCB) type Primary Coil array. The functional block diagram of a type B2 Power Transmitter is identical to the functional block diagram of a type B1 Power Transmitter; see Figure 140 and the descriptive text in Section 2.3.1.

2.3.2.1 Mechanical details

Power Transmitter design B2 includes a Primary Coil array as defined in Section 2.3.2.1.1, Shielding as defined in Section 2.3.2.1.2, and an Interface Surface as defined in Section 2.3.2.1.3.

2.3.2.1.1 Primary Coil array

The Primary Coil array consists of an 8 layer PCB. The inner six layers of the PCB each contain a grid of Primary Coils, and the bottom layer contains the leads to each of the individual Primary Coils. The top layer can be used for any purpose, but shall not influence the inductance values of the Primary Coils. Figure 145(a) shows a top view of a single Primary Coil, which consists of a trace that runs through 18 hexagonal turns. As shown in the top inset of Figure 145(a), the corners of this hexagonal shape are rounded. The bottom inset of Figure 145(a) shows the width of the trace as well as the distance between two adjacent turns. Figure 145(b) shows a side view of the layer structure of the PCB. Copper layers 2, 3, 4, 5, 6, and 7 each contain a grid of Primary Coils. Copper layer 8 contains the leads to each of the Primary Coils. Figure 145(c) provides a top view of the Primary Coil array, showing that the individual Primary Coils are packed in a hexagonal grid. The solid hexagons show the closely packed structure of the grids of Primary Coils on layer 2 and layer 7 of the Primary Coil array. Each solid hexagon represents a set of two identical Primary Coils—in this case one Primary Coil on layer 2 and one Primary Coil on layer 7, respectively—which are connected in parallel. The dashed hexagon illustrates that the grids of Primary Coils on layer 3 and layer 6 are offset over a distance t_2 to the right, such that the centers of the Primary Coils in layer 3 and layer 6 coincide with the corners of Primary Coils in layer 2 and layer 7. Likewise, the dash-dotted hexagon illustrates that the grids of Primary Coils on layer 4 and layer 5 are offset over a distance t_3 to the left, such that the centers of the Primary Coils in layer 4 and layer 5 coincide with the corners of Primary Coils in layer 2 and layer 7. As a result, the centers, respectively corners, of the Primary Coils on layer 3 and layer 6 and the corners, respectively centers, of the Primary Coils on layer 4 and layer 5 coincide as well. See Section 2.3.2.2 for the meaning of the shaded hexagons.

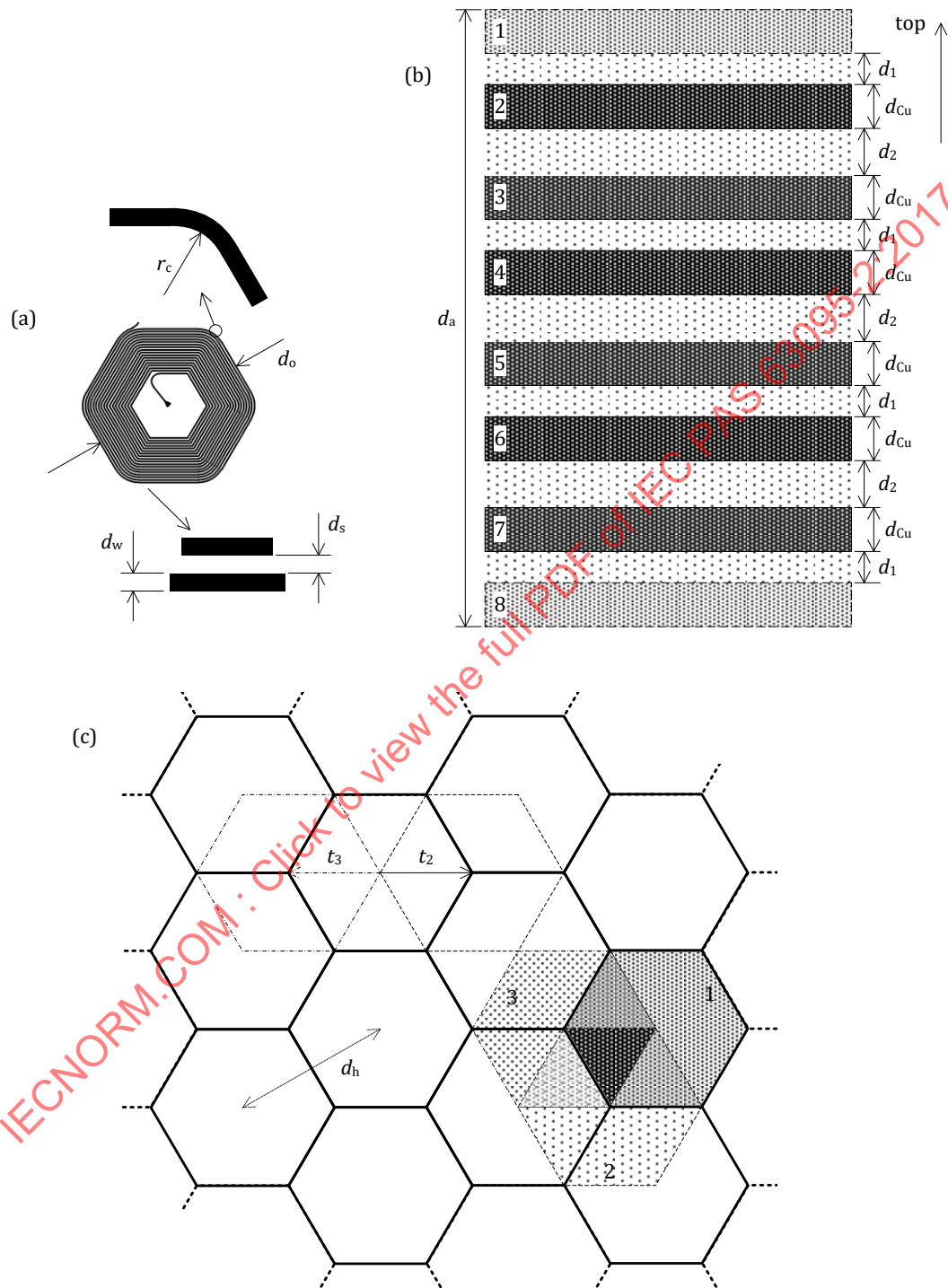
Table 97. Primary Coil array parameters of Power Transmitter design B2

Parameter	Symbol	Value
Outer diameter	d_o	$31^{\pm 0.4}$ mm
Track width	d_w	$0.42^{\pm 0.03}$ mm
Track width plus spacing	$d_w + d_s$	$0.6^{\pm 0.03}$ mm
Corner rounding*	r_c	$5^{\pm 3}$ mm
Number of turns	N	18
Track thickness	d_{Cu}	$0.07^{\pm 0.014}$ mm
Dielectric thickness 1	d_{d1}	$0.089^{+0.15}_{-0}$ mm
Dielectric thickness 2	d_{d2}	$0.1^{\pm 0.013}$ mm
Array thickness	d_a	$1.14^{\pm 0.05}$ mm
Center-to-center distance	d_h	$31.855^{\pm 0.2}$ mm
Offset 2 nd layer array	t_2	$18.4^{\pm 0.1}$ mm
Offset 3 rd layer array	t_3	$18.4^{\pm 0.1}$ mm

* Value applies to the outermost winding.

Table 97 lists the relevant parameters of the Primary Coil array. The finished PCB thickness is $1.3^{\pm 10\%}$ mm.

Figure 145. Primary Coil array of Power Transmitter design B2



2.3.2.1.2 Shielding

Power Transmitter design B2 employs Shielding that is identical to the Shielding of Power Transmitter design B1. See Section 2.3.1.1.2.

2.3.2.1.3 Interface Surface

The distance from the Primary Coil array to the Interface Surface of the Base Station is $d_z = 2^{+0.1}_{-0.5}$ mm, across the top face of the Primary Coil array. See also Figure 142 in Section 2.3.1.1.3. In addition, the Interface Surface extends at least 5 mm beyond the outer edges of the Primary Coil array.

2.3.2.2 Electrical details

The outline of the electrical diagram of Power Transmitter design B2 follows the outline of the electrical diagram of Power Transmitter design B1. See also Figure 143 in Section 2.3.1.2.

Power Transmitter design B2 uses a half-bridge inverter to drive the Primary Coil array. In addition, Power Transmitter design B2 uses a multiplexer to select the position of the Active Area. The multiplexer shall configure the Primary Coil array in such a way that one, two, or three sets of two Primary Coils are connected—in parallel—to the driving circuit. The connected Primary Coils together constitute a Primary Cell. As an additional constraint, the multiplexer shall select the Primary Coils such that each selected Primary Coil has an overlap with every other selected Primary Coil; see Figure 145(c) for an example.

Within the Operating Frequency range $f_{op} = 105 \dots 113$ kHz, the assembly of Primary Coil array and Shielding has an inductance of $11.7^{\pm 1}$ μ H for each set of Primary Coils in layer 2 and layer 7 (connected in parallel), $11.8^{\pm 1}$ μ H for each set of Primary Coils in layer 3 and layer 6 (connected in parallel), and $12.3^{\pm 1}$ μ H for each set of Primary Coils in layer 4 and 5 (connected in parallel). The capacitance and inductance in the impedance matching circuit (Figure 143) are, respectively, $C_{m1} = 256^{\pm 5\%}$ nF, $C_{m23} = 147^{\pm 5\%}$ nF and $L_m = 3.8^{\pm 5\%}$ μ H. The capacitances C_1 and C_2 in the half-bridge inverter both are 68 μ F. The switch S is open if the Primary Cell consists of a single Primary Coil; otherwise, the switch S is closed.

NOTE The voltage across the capacitance C_m can reach levels exceeding 36 V pk-pk.

Power Transmitter design B2 uses the input voltage to the half-bridge inverter to control the amount of power that is transferred. For this purpose, the input voltage range is 0...20 V, where a lower input voltage results in the transfer of a lower amount of power. In order to achieve a sufficiently accurate adjustment of the power that is transferred, a type B2 Power Transmitter shall be able to control the input voltage with a resolution of 35 mV or better.

When a type B2 Power Transmitter first applies a Power Signal (see the *Digital Ping* section in *Parts 1 and 2: Interface Definitions*), it shall use an initial input voltage of 12 V.

Control of the power transfer shall proceed using the PID algorithm, which is defined in the *Power transfer control* section in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the input voltage to the half-bridge inverter. In order to guarantee sufficiently accurate power control, a type B2 Transmitter shall determine the amplitude of the current into the Primary Cell (i.e. the sum of the currents through each of its three constituent Primary Coils) with a resolution of 5 mA or better. In addition to the PID algorithm, a type B2 Power Transmitter shall limit the current into the Primary Cell to at most 3.5 A RMS in the case that the Primary Cell consists of two or three Primary Coils, or at most 1.75 A RMS in the case that the Primary Cell consists of one Primary Coil. For that purpose, the Power Transmitter may limit the input voltage to the half-bridge inverter to value that is lower than 20 V. Finally, Table 96 in Section 2.3.1.2 provides the values of several parameters, which are used in the PID algorithm.

2.3.2.3 Scalability

Power Transmitter Design B2 offers the same scalability options as Power Transmitter design B1. See Section 2.3.1.3.

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2.3.3 Power Transmitter design B3

Power Transmitter design B3 enables Free Positioning, and has a design similar to Power Transmitter design B1. See Section 2.3.1 for an overview.

2.3.3.1 Mechanical details

Power Transmitter design B3 includes a Primary Coil array as defined in Section 2.3.3.1.1, Shielding as defined in Section 2.3.3.1.2, and an Interface Surface as defined in Section 2.3.3.1.3.

2.3.3.1.1 Primary Coil array

The Primary Coil array consists of a hybrid PCB/wire wound coil structure. As shown Figure 146(a), the central part of this structure is a 4-layer PCB. The inner two layers of this PCB each contain an identical grid of coils, where corresponding coils are connected in parallel to form a single two-layer Primary Coil. The outer two layers of the PCB serve as a mounting area for the wire wound Primary Coils (layers (a) and (b)). In addition, layer 4 of the PCB contains the leads to both the internal and the wire wound Primary Coils; and layer 1 can be used for any purpose, but shall not influence the inductance values of the Primary Coils.

The wire-wound Primary Coils consist of litz wire having 24 strands of no. 40 AWG (0.08 mm diameter), or equivalent. Each wire wound Primary Coil has a circular shape as shown in Figure 146(b).

Each Primary Coil inside the PCB consists of a trace that runs through 18 hexagonal turns as shown in Figure 146(c), and are identical to the Primary Coils of Power Transmitter design B2 defined in Section 2.3.2.1.1.

Figure 146(d) provides a top view of the Primary Coil array, showing that the individual Primary Coils are packed in a hexagonal grid. The solid hexagons show the closely packed structure of the grid of Primary Coils on layer (a) of the Primary Coil array. The dashed hexagon illustrates that the identical grids of Primary Coils on layers (2) and (3) are offset over a distance t_2 to the right, such that the centers of the Primary Coils in layers (2) and (3) coincide with the corners of Primary Coils in layer (a). Likewise, the dash-dotted hexagon illustrates that the grid of Primary Coils on layer (b) is offset over a distance t_3 to the left, such that the centers of the Primary Coils in layer (b) coincide with the corners of Primary Coils in layer (a). As a result, the centers, respectively corners, of the Primary Coils on layer (2) and (3), and the corners, respectively centers, of the Primary Coils on layer (b) coincide as well. All Primary Coils are stacked with the same polarity. See Section 2.3.3.2 for the meaning of the shaded hexagons.

Table 98 lists the relevant parameters of the Primary Coil array.

Figure 146. Primary Coil array of Power Transmitter design B3

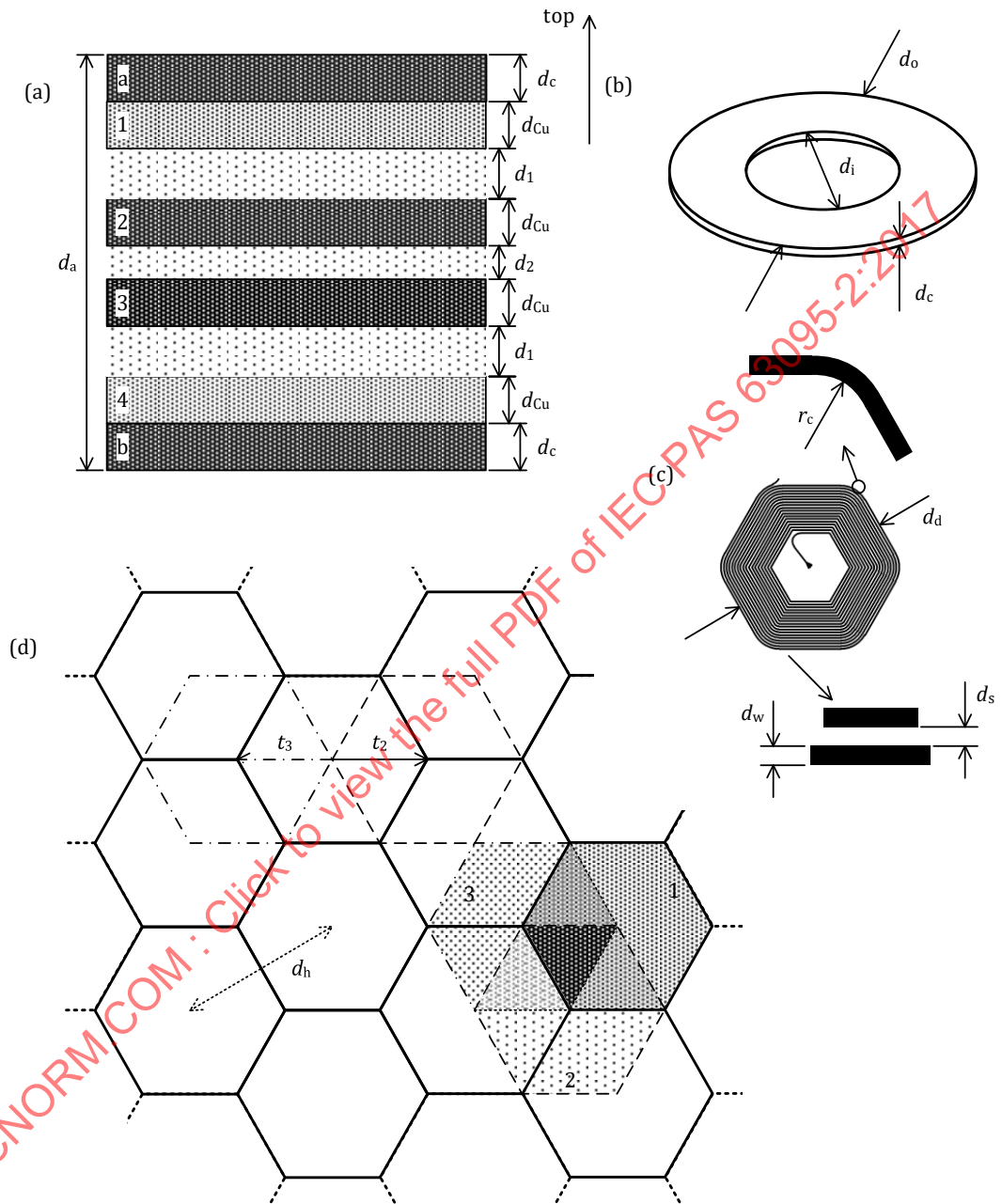


Table 98. Primary Coil array parameters of Power Transmitter design B3

Parameter	Symbol	Value
Outer diameter	d_o	$31.1^{\pm 0.5}$ mm
Inner diameter	d_i	$10.6^{\pm 0.3}$ mm
Layer thickness	d_c	$0.4^{\pm 0.05}$ mm
Number of turns	N	18
Outer diameter	d_d	$31^{\pm 0.4}$ mm
Track width	d_w	$0.42^{\pm 0.03}$ mm
Track width plus spacing	$d_w + d_s$	$0.6^{\pm 0.03}$ mm
Corner rounding*	r_c	$5^{\pm 3}$ mm
Number of turns	N	18
Track thickness	d_{Cu}	$0.07^{\pm 0.015}$ mm
Dielectric thickness 1	d_{d1}	$0.088^{+0.1}_{-0}$ mm
Dielectric thickness 2	d_{d2}	$0.145^{\pm 0.02}$ mm
PCB thickness		$0.6^{\pm 0.1}$ mm
Array thickness	d_a	$1.5^{\pm 0.2}$ mm
Center-to-center distance	d_h	$31.855^{\pm 0.2}$ mm
Offset 2 nd layer array	t_2	$18.4^{\pm 0.1}$ mm
Offset 3 rd layer array	t_3	$18.4^{\pm 0.1}$ mm

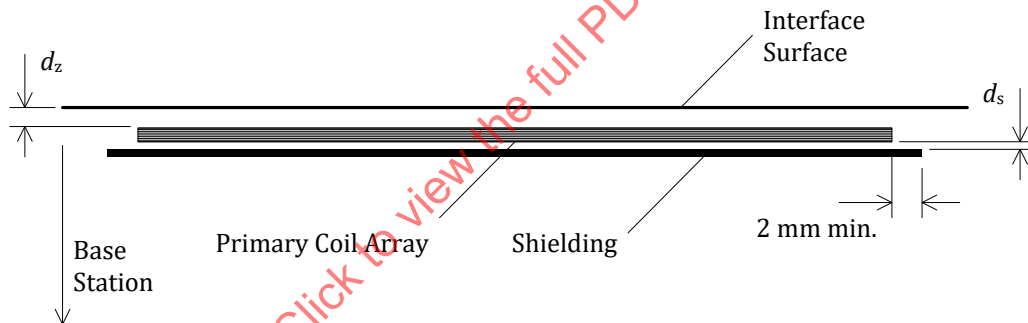
2.3.3.1.2 Shielding

As shown in Figure 147, Transmitter design B3 employs Shielding to protect the Base Station from the magnetic field that is generated in the Primary Coil array. The Shielding extends to at least 2 mm beyond the outer edges of the Primary Coil array, and is placed at a distance of at most $d_s = 0.5$ mm below the Primary Coil array.

The Shielding consists of soft magnetic material that has a thickness of at least 0.5 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 78 — Fair Rite Corporation.
- 3C94 — Ferroxcube.
- N87 — Epcos AG.
- PC44 — TDK Corp.

Figure 147. Primary Coil array assembly of Power Transmitter design B3



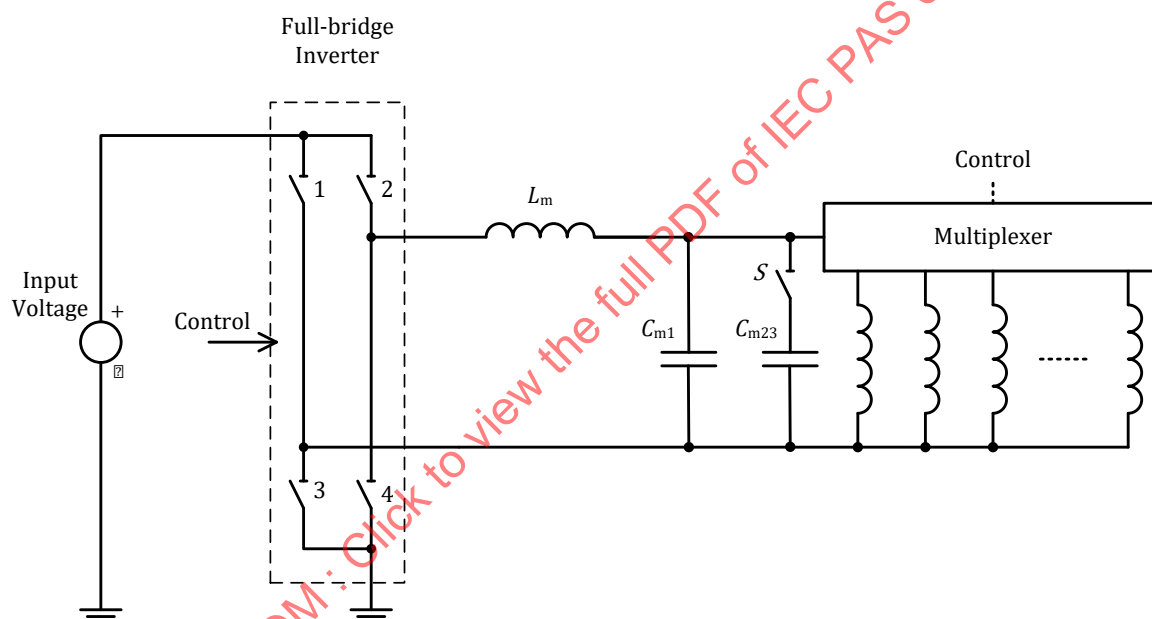
2.3.3.1.3 Interface Surface

As shown in Figure 147, the distance from the Primary Coil array to the Interface Surface of the Base Station is $d_z = 2^{+0.1}_{-0.5}$ mm, across the top face of the Primary Coil array. In addition, the Interface Surface extends at least 5 mm beyond the outer edges of the Primary Coil array.

2.3.3.2 Electrical details

As shown in Figure 148, Power Transmitter design B3 uses a full-bridge inverter to drive the Primary Coil array. In addition, Power Transmitter design B3 uses a multiplexer to select the position of the Active Area. The multiplexer shall configure the Primary Coil array in such a way that one, two, or three Primary Coils are connected—in parallel—to the driving circuit. The connected Primary Coils together constitute a Primary Cell. As an additional constraint, the multiplexer shall select the Primary Coils such that each selected Primary Coil has an overlap with every other selected Primary Coil; see Figure 146(d) for an example.

Figure 148. Electrical diagram (outline) of Power Transmitter design B3

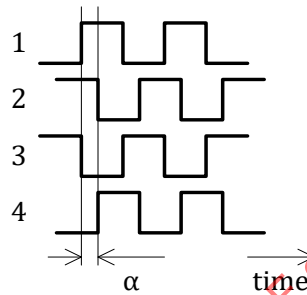


Within the Operating Frequency range $f_{op} = 105 \dots 113$ kHz, the assembly of Primary Coil array and Shielding has an inductance of $11.6^{\pm 1} \mu\text{H}$ for each individual Primary Coil in layer (a) (closest to the Interface Surface), $12.4^{\pm 1} \mu\text{H}$ for each individual Primary Coil in PCB layers 2 and 3, and $13.5^{\pm 1.5} \mu\text{H}$ for each individual Primary Coil in layer (b). The capacitances and inductance in the impedance matching circuit are, respectively, $C_{m1} = 222^{\pm 5\%} \text{ nF}$, $C_{m23} = 133^{\pm 5\%} \text{ nF}$, and $L_m = 3.8^{\pm 5\%} \mu\text{H}$. The switch S is open if the Primary Cell consists of a single Primary Coil; otherwise, the switch S is closed. The input voltage to the full-bridge inverter is $12^{\pm 5\%} \text{ V}$.

NOTE The voltage across the capacitance C_m can reach levels exceeding 36 V pk-pk.

Power Transmitter design B3 uses the phase difference between the control signals to two halves of the full-bridge inverter to control the amount of power that is transferred, see Figure 149. For this purpose, the range of the phase difference α is $0\ldots 180^\circ$ —with a larger phase difference resulting in a lower power transfer. In order to achieve a sufficient accurate adjustment of the power that is transferred, a type B3 Power transmitter shall be able to control the phase difference with a resolution of 0.42° or better. When a type B3 Power Transmitter first applies a Power Signal (see the *Digital Ping* section in *Parts 1 and 2: Interface Definitions*), it shall use an initial phase difference of 120° .

Figure 149. Control signals to the inverter



Control of the power transfer shall proceed using the PID algorithm, which is defined in the *Power transfer control* section in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the phase difference between the two halves of the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type B3 Transmitter shall determine the amplitude of the current into the Primary Cell with a resolution of 5 mA or better. In addition to the PID algorithm, a type B3 Power Transmitter shall limit the current into the Primary Cell to at most 4 A RMS in the case that the Primary Cell consists of two or three Primary Coils, or at most 2 A RMS in the case that the Primary Cell consists of one Primary Coil. Finally, Table 99 provides the values of several parameters that are used in the PID algorithm.

Table 99. PID parameters for voltage control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	2,000	N.A.
Scaling factor	S_v	0.01	$^\circ$

2.3.3.3 Scalability

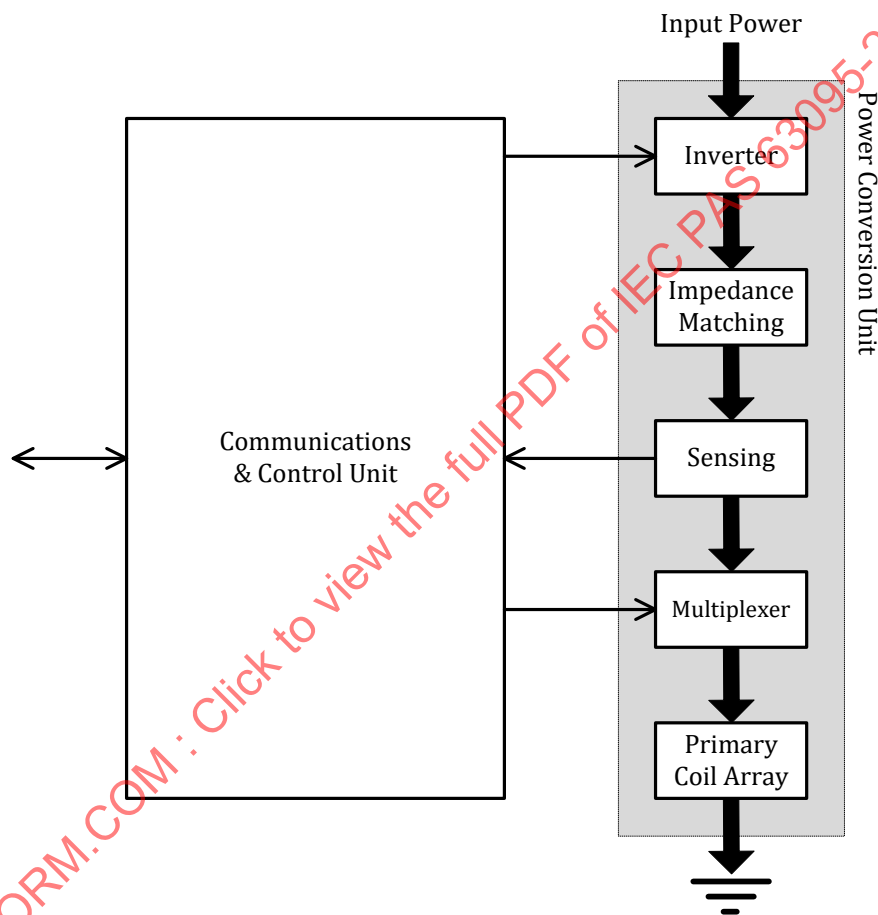
Power Transmitter Design B3 offers the same scalability options as Power Transmitter design B1. See Section 2.3.1.3.

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2.3.4 Power Transmitter design B4

Power Transmitter design B4 enables Free Positioning. Figure 150 illustrates the functional block diagram of this design, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 150. Functional block diagram of Power Transmitter design B4



The Power Conversion Unit on the right-hand side of Figure 150 comprises the analog parts of the design. The design uses an array of partly overlapping Primary Coils to provide for Free Positioning. Depending on the position of the Power Receiver, the multiplexer connects and/or disconnects the appropriate Primary Coils. The impedance matching network forms a resonant circuit with the parts of the Primary Coil array that are connected. The sensing circuits monitor (amongst others) the Primary Cell current and voltage, and the inverter converts the DC input to an AC waveform that drives the Primary Coil array.

The Communications and Control Unit on the left-hand side of Figure 150 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the multiplexer to connect the appropriate parts of the Primary Coil array, executes the relevant power control algorithms and protocols, and drives the inverter to control the amount of power provided to the Power Receiver. The Communications and Control Unit also interfaces with the other subsystems of the Base Station, e.g. for user interface purposes.

2.3.4.1 Mechanical details

Power Transmitter design B4 includes a Primary Coil array as defined in Section 2.3.4.1.1, Shielding as defined in Section 2.3.4.1.2, and an Interface Surface as defined in Section 2.3.4.1.3.

2.3.4.1.1 Primary Coil array

The Primary Coil array consists of partly overlapping square shaped planar coils. Figure 151(a) shows a top view of a single Primary Coil, which consists of a bifilar trace that runs through 11 square shaped turns in a single layer of a PCB. Another realization of a single Primary Coil is to construct it from litz wire having 24 strands of no. 40 AWG (0.08 mm diameter), or equivalent. Figure 151(b) shows a top view of such wire-wound Primary Coil. Table 100 lists the relevant parameters of the coils shown in Figure 151.

Figure 151. Top view of PCB and wire-wound Primary Coil of Power Transmitter design B4

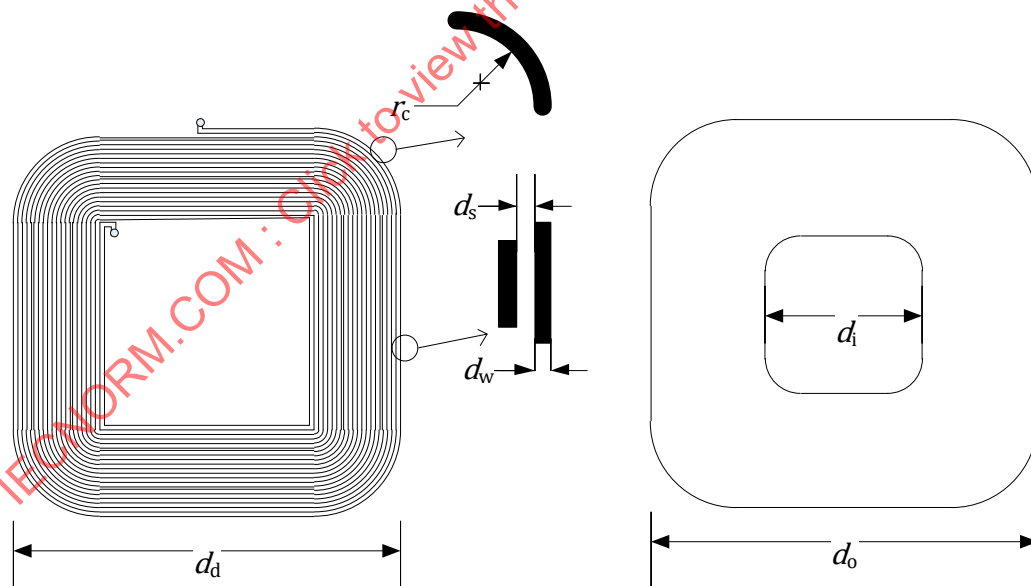


Table 100. Primary Coil parameters of Power Transmitter design B4

Parameter	Symbol	Value
<i>Litz wire based Primary Coil</i>		
Outer diameter	d_o	$45.0^{+0.5}_{-1.0}$ mm
Inner diameter	d_i	$18.6^{+0.3}$ mm
Number of turns	N	11
<i>PCB based Primary Coil</i>		
Outer diameter	d_d	$45^{+0.4}$ mm
Track width	d_w	$0.42^{+0.03}$ mm
Track width plus spacing	$d_w + d_s$	$0.6^{+0.03}$ mm
Corner rounding*	r_c	9^{+1} mm
Number of turns	N	11

* Value applies to the outermost winding.

The Primary Coil array may be constructed from PCB-coils, wire-wound coils or any combination thereof (hybrid). Power Transmitter design B4 enables one-dimensional freedom of positioning. For that purpose the Primary Coils are placed in a row, such that there is an overlap of approximately two-thirds of the area. Each Primary Coil (except for the Primary Coils at both ends of the Primary Coil array) overlaps with two Primary Coils in different layers. Figure 152 shows the layout of the Primary Coil array. Figure 153 shows the layered structure of the Primary Coil array in the case of a PCB only implementation, a litz wire only implementation and a hybrid PCB-litz wire implementation. Table 101 lists the relevant parameters of the Primary Coil array. Any layer of the PCB—if present—may contain functionality other than, or in addition to, the Primary Coils. If such other functionality is present, that functionality shall not affect the inductance values of the Primary Coils.

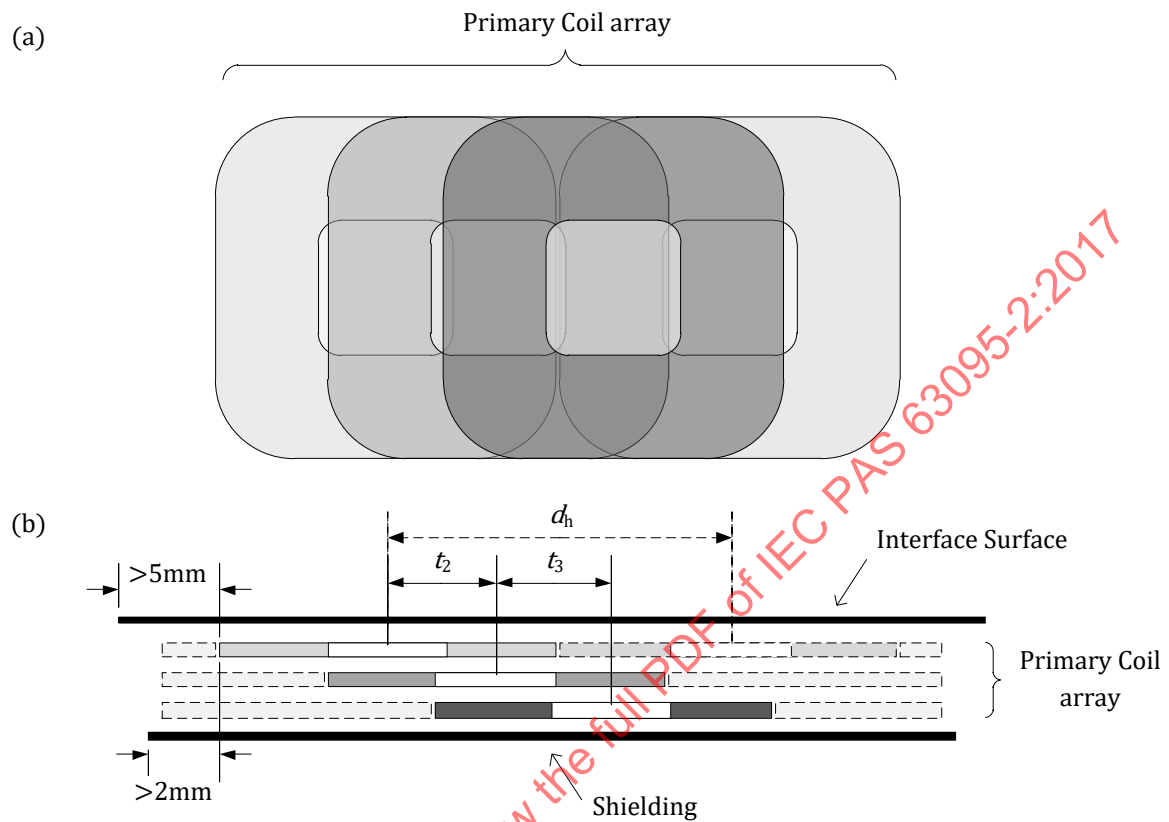
Figure 152. Top view (a) and cross section (b) of the Primary Coil array of Power Transmitter design B4.

Figure 153. Layered structure of the Primary Coil array

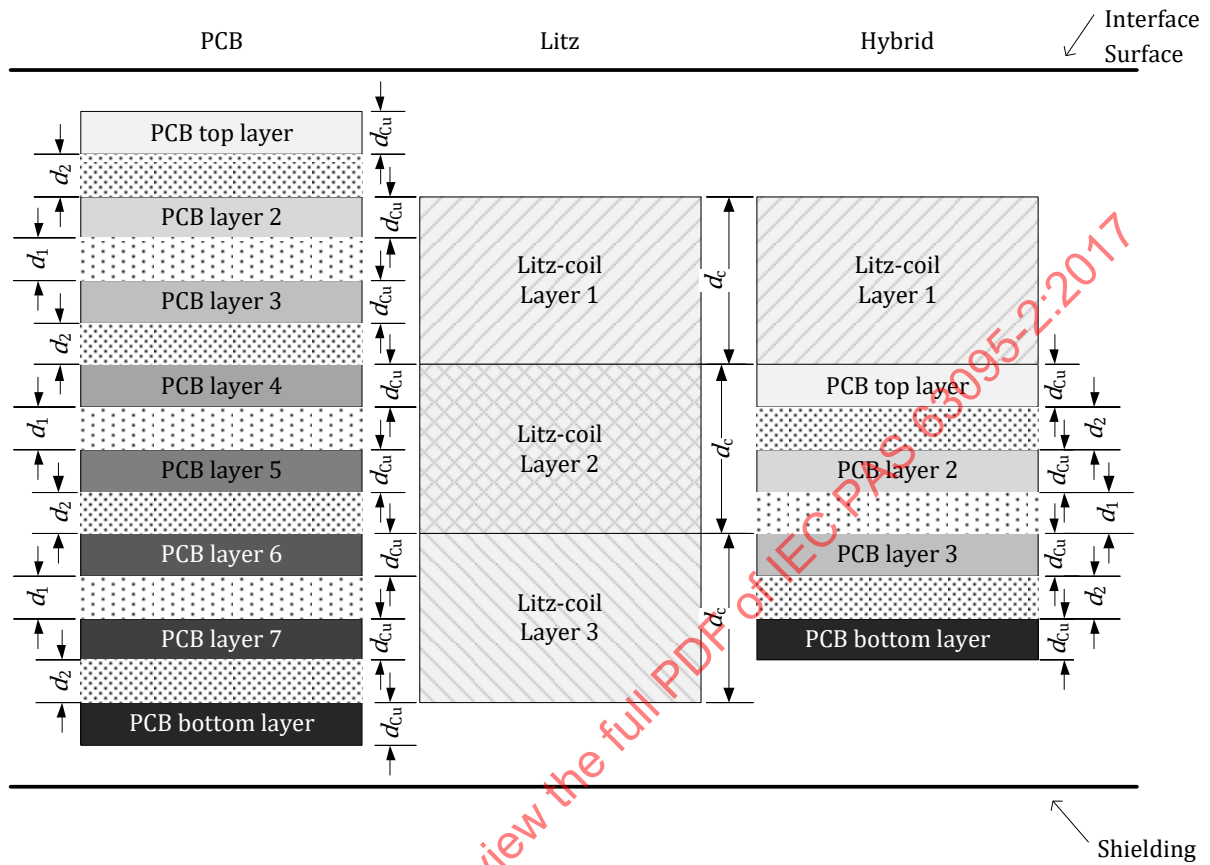


Table 101. Primary Coil array parameters of Power Transmitter design B4

Parameter	Symbol	Value
Center-to-center distance	d_h	$46.5^{+0.2}_{-0.2}$ mm
Offset 2 nd layer array	t_2	$15.5^{+0.1}_{-0.1}$ mm
Offset 3 rd layer array	t_3	$15.5^{+0.1}_{-0.1}$ mm
Litz-layer thickness	d_c	$0.4^{+0.1}_{-0.05}$ mm
PCB-copper thickness	d_{Cu}	$0.07^{+0.015}_{-0.015}$ mm
Dielectric thickness 1	d_{d1}	$0.088^{+0.15}_{-0}$ mm
Dielectric thickness 2	d_{d2}	$0.126^{+0.039}_{-0.039}$ mm

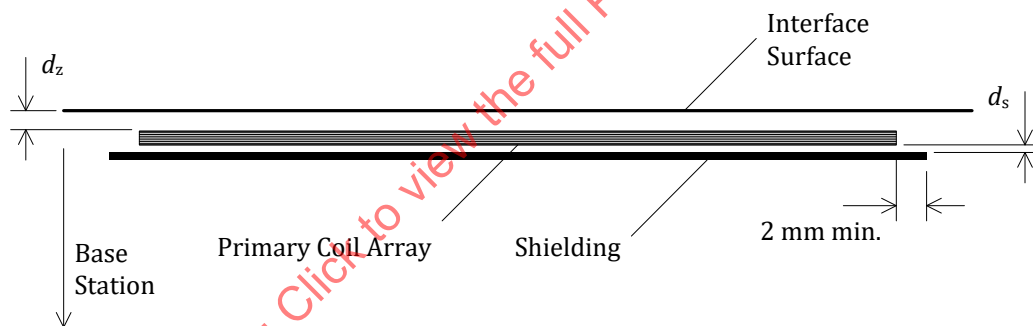
2.3.4.1.2 Shielding

As shown in Figure 153, Transmitter design B4 employs Shielding to protect the Base Station from the magnetic field that is generated in the Primary Coil array. The Shielding extends to at least 2 mm beyond the outer edges of the Primary Coil array, and is placed at a distance of at most $d_s = 0.5$ mm below the Primary Coil array.

The Shielding consists of soft magnetic material that has a thickness of at least 0.5 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 78 — Fair Rite Corporation.
- 3C94 — Ferroxcube.
- N87 — Epcos AG.
- PC44 — TDK Corp.
- FK2 — TDK Corp (at least 0.8 mm thickness).

Figure 154. Primary Coil array assembly of Power Transmitter design B4



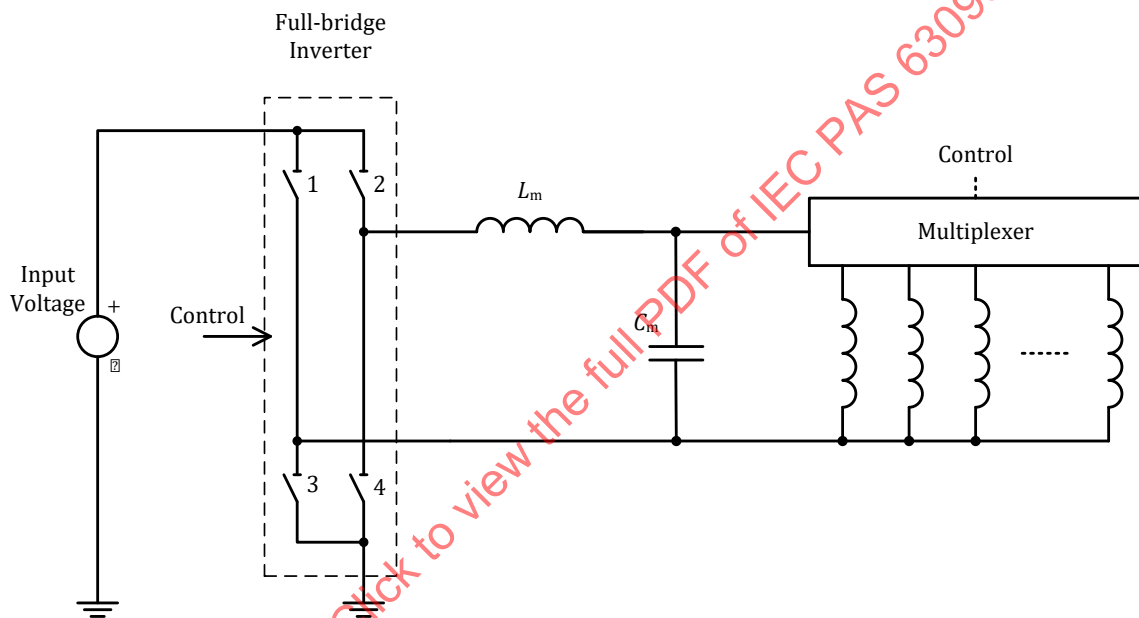
2.3.4.1.3 Interface Surface

As shown in Figure 154, the distance from the Primary Coil array to the Interface Surface of the Base Station is $d_z = 2^{\pm 0.5}$ mm, across the top face of the Primary Coil array. In addition, the Interface Surface extends at least 5 mm beyond the outer edges of the Primary Coil array.

2.3.4.2 Electrical details

As shown in Figure 155, Power Transmitter design B4 uses a full-bridge inverter to drive the Primary Coil array. In addition, Power Transmitter design B4 uses a multiplexer to select the position of the Active Area. The multiplexer shall configure the Primary Coil array in such a way that one, or two Primary Coils are connected—in parallel—to the driving circuit. The connected Primary Coils together constitute a Primary Cell. In the case that two Primary Coils are selected, these two Primary Coils shall have an overlap of two-thirds of the area of a single Primary Coil.

Figure 155. Electrical diagram (outline) of Power Transmitter design B4



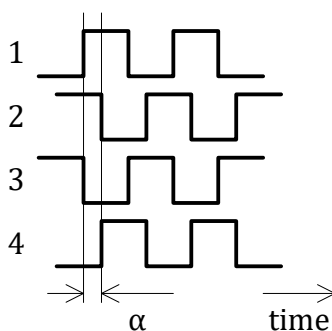
Within the Operating Frequency range $f_{op} = 105 \dots 113$ kHz, the assembly of Primary Coil array and Shielding has an inductance of $8.8^{\pm 1} \mu\text{H}$ for each individual Primary Coil in layer (a) (closest to the Interface Surface), $9.1^{\pm 1} \mu\text{H}$ for each individual Primary Coil in layer (b), and $9.5^{\pm 1} \mu\text{H}$ for each individual Primary Coil in layer (c) (closest to the Shielding). The capacitances and inductance in the impedance matching circuit are, respectively, $C_m = 300^{\pm 5\%} \text{ nF}$, and $L_m = 3.8^{\pm 5\%} \mu\text{H}$. The input voltage to the full-bridge inverter is $12^{\pm 5\%} \text{ V}$.

NOTE The voltage across the capacitance C_m can reach levels exceeding 36 V pk-pk.

Power Transmitter design B4 uses the phase difference between the control signals to two halves of the full-bridge inverter to control the amount of power that is transferred, see Figure 156. For this purpose, the range of the phase difference α is $0 \dots 180^\circ$ —with a larger phase difference resulting in a lower power transfer. In order to achieve a sufficient accurate adjustment of the power that is transferred, a type B4 Power Transmitter shall be able to control the phase difference with a resolution of 0.42° or better. When

a type B4 Power Transmitter first applies a Power Signal (see the *Digital Ping* section in *Parts 1 and 2: Interface Definitions*), it shall use an initial phase difference of 120° .

Figure 156. Control signals to the inverter



Control of the power transfer shall proceed using the PID algorithm, which is defined in the *Power transfer control* section in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the phase difference between the two halves of the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type B4 Transmitter shall determine the amplitude of the current into the Primary Cell with a resolution of 5 mA or better. In addition to the PID algorithm, a type B4 Power Transmitter shall limit the current into the Primary Cell to at most 4 A RMS in the case that the Primary Cell consists of two Primary Coils, or at most 2 A RMS in the case that the Primary Cell consists of one Primary Coil. Finally, Table 102 provides the values of several parameters, which are used in the PID algorithm.

Table 102. Control parameters for power control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	N.A.	N.A.
PID output limit	M_{PID}	2,000	N.A.
Scaling factor	S_v	0.01	$^\circ$

2.3.4.3 Scalability

Power Transmitter Design B4 offers the same scalability options as Power Transmitter design B1. See Section 2.3.1.3.

2.3.5 Power Transmitter design B5

Figure 157 illustrates the functional block diagram of Power Transmitter design B5, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

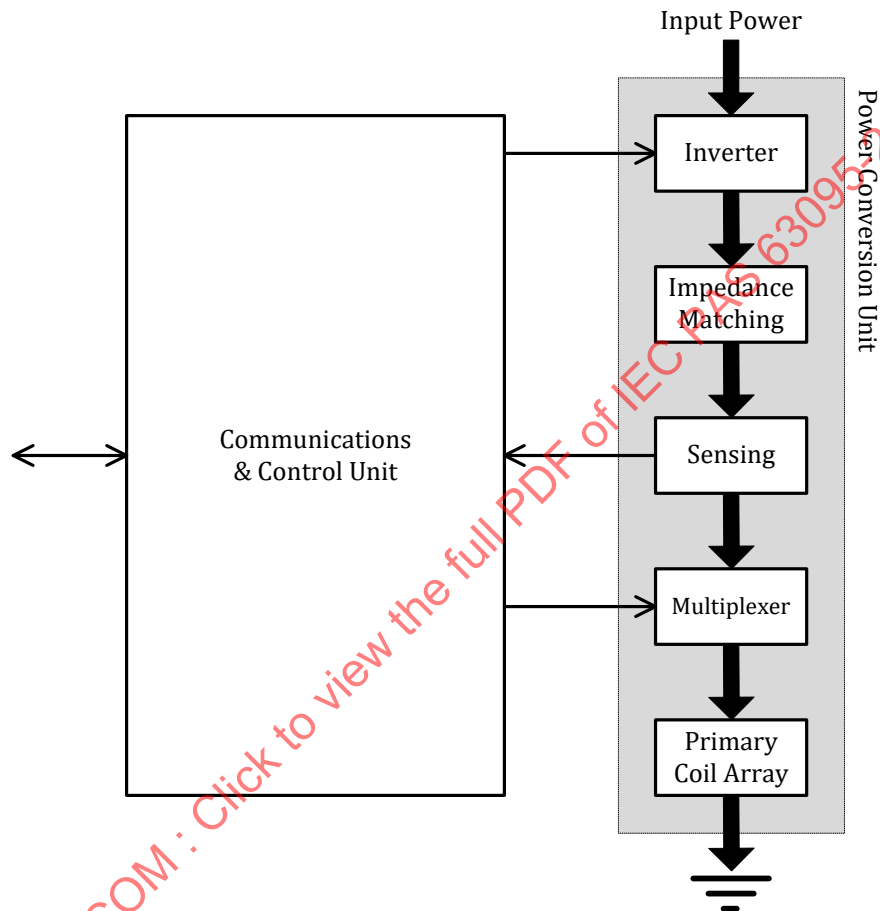


Figure 157. Functional block diagram of Power Transmitter design B5

The Power Conversion Unit on the right-hand side of Figure 157 comprises the analog parts of the design. The design uses an array of partly overlapping Primary Coils to provide for Free Positioning. Depending on the position of the Power Receiver, the multiplexer connects and/or disconnects the appropriate Primary Coils. The impedance matching network forms a resonant circuit with the parts of the Primary Coil array that are connected. The sensing circuits monitor (amongst others) the Primary Cell current and voltage, and the inverter converts the DC input to an AC waveform that drives the Primary Coil array.

The Communications and Control Unit on the left-hand side of Figure 157 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the multiplexer to connect the appropriate parts of the Primary Coil array, executes the relevant power control algorithms and protocols, and drives the inverter to control the amount of power provided to the Power Receiver. The Communications and Control Unit also interfaces with the other subsystems of the Base Station, e.g. for user interface purposes.

2.3.5.1 Mechanical details

Power Transmitter design B5 includes a Primary Coil array as defined in Section 2.3.5.1.1, Shielding as defined in Section 2.3.5.1.2, and an Interface Surface as defined in Section 2.3.5.1.3.

2.3.5.1.1 Primary Coil array

The Primary Coil array consists of partly overlapping square shaped planar coils. Figure 158(a) shows a top view of a single Primary Coil, which consists of a bifilar trace that runs through 11 square shaped turns in a single layer of a PCB. Another realization of a single Primary Coil is to construct it from litz wire having 24 strands of no. 40 AWG (0.08 mm diameter), or equivalent. Figure 158(b) shows a top view of such wire-wound Primary Coil. Table 103 lists the relevant parameters of the coils shown in Figure 158.

Figure 158. Top view of PCB and wire-wound Primary Coil of Power Transmitter design B5

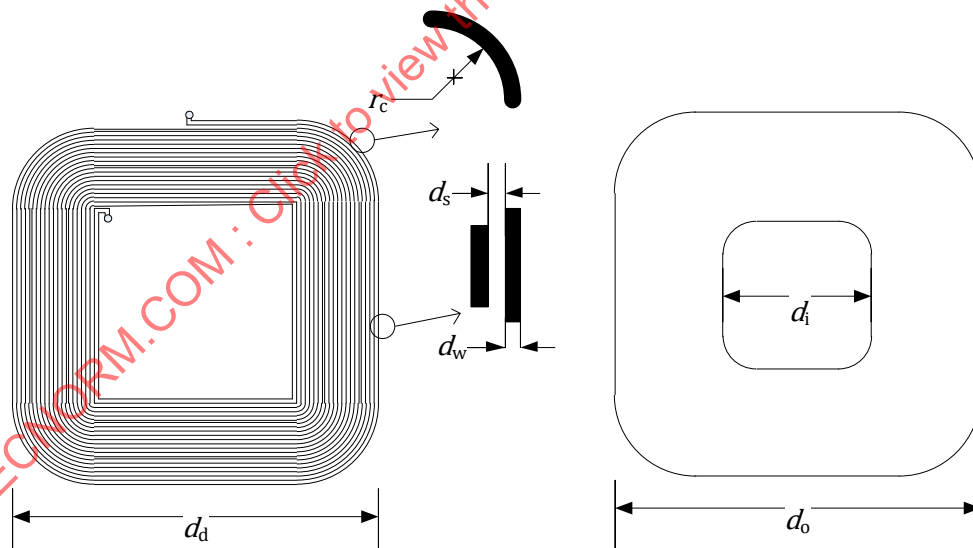


Table 103. Primary Coil parameters of Power Transmitter design B5

Parameter	Symbol	Value
<i>Litz wire based Primary Coil</i>		
Outer diameter	d_o	$45.0^{+0.5}_{-1.0}$ mm
Inner diameter	d_i	$18.6^{±0.3}$ mm
Number of turns	N	11
<i>PCB based Primary Coil</i>		
Outer diameter	d_d	$45^{±0.4}$ mm
Track width	d_w	$0.42^{±0.03}$ mm
Track width plus spacing	$d_w + d_s$	$0.6^{±0.03}$ mm
Corner rounding*	r_c	$9^{±1}$ mm
Number of turns	N	11

* Value applies to the outermost winding.

The Primary Coil array may be constructed from PCB-coils, wire-wound coils or any combination thereof (hybrid). Power Transmitter design B5 enables one-dimensional freedom of positioning. For that purpose the Primary Coils are placed in a row, such that there is an overlap of approximately two-thirds of the area. Each Primary Coil (except for the Primary Coils at both ends of the Primary Coil array) overlaps with two Primary Coils in different layers. Figure 159 shows the layout of the Primary Coil array. Figure 160 shows the layered structure of the Primary Coil array in the case of a PCB only implementation, a litz wire only implementation and a hybrid PCB-litz wire implementation. Table 104 lists the relevant parameters of the Primary Coil array. Any layer of the PCB—if present—may contain functionality other than, or in addition to, the Primary Coils. If such other functionality is present, that functionality shall not affect the inductance values of the Primary Coils.

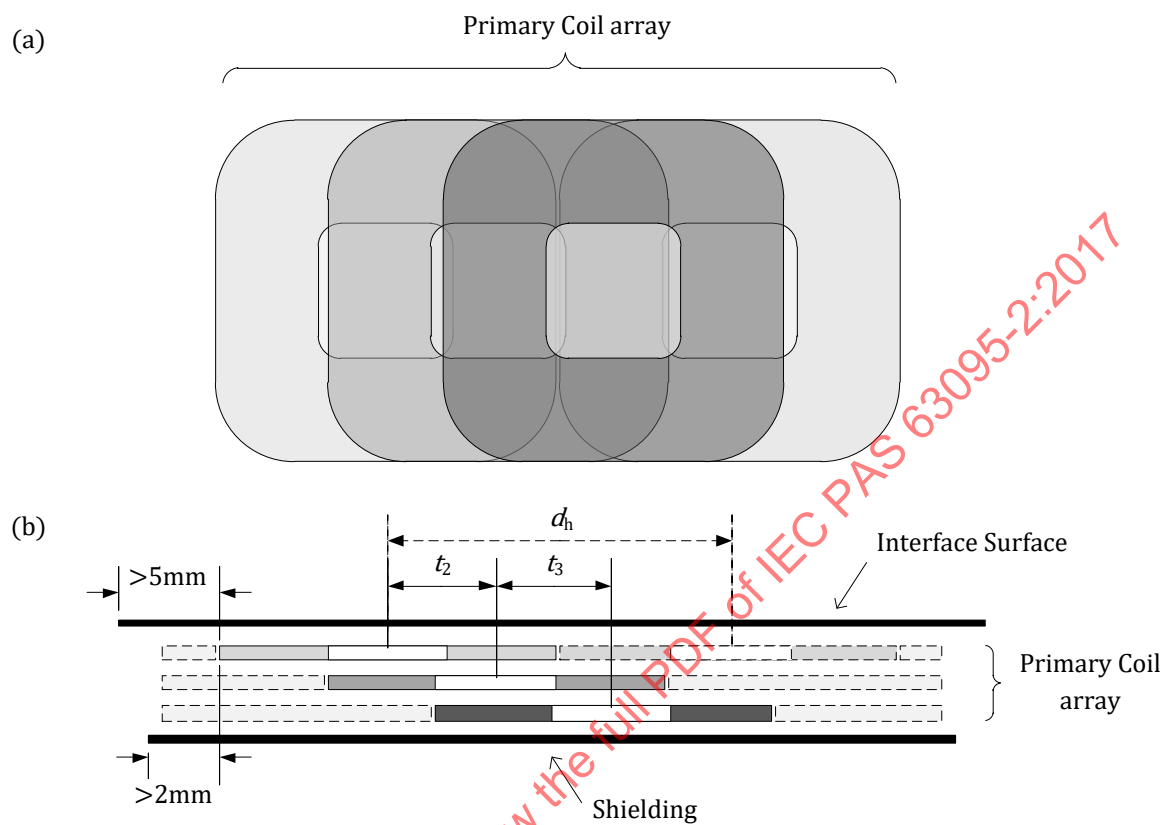
Figure 159. Top view (a) and cross section (b) of the Primary Coil array of Power Transmitter design B5.

Figure 160. Layered structure of the Primary Coil array

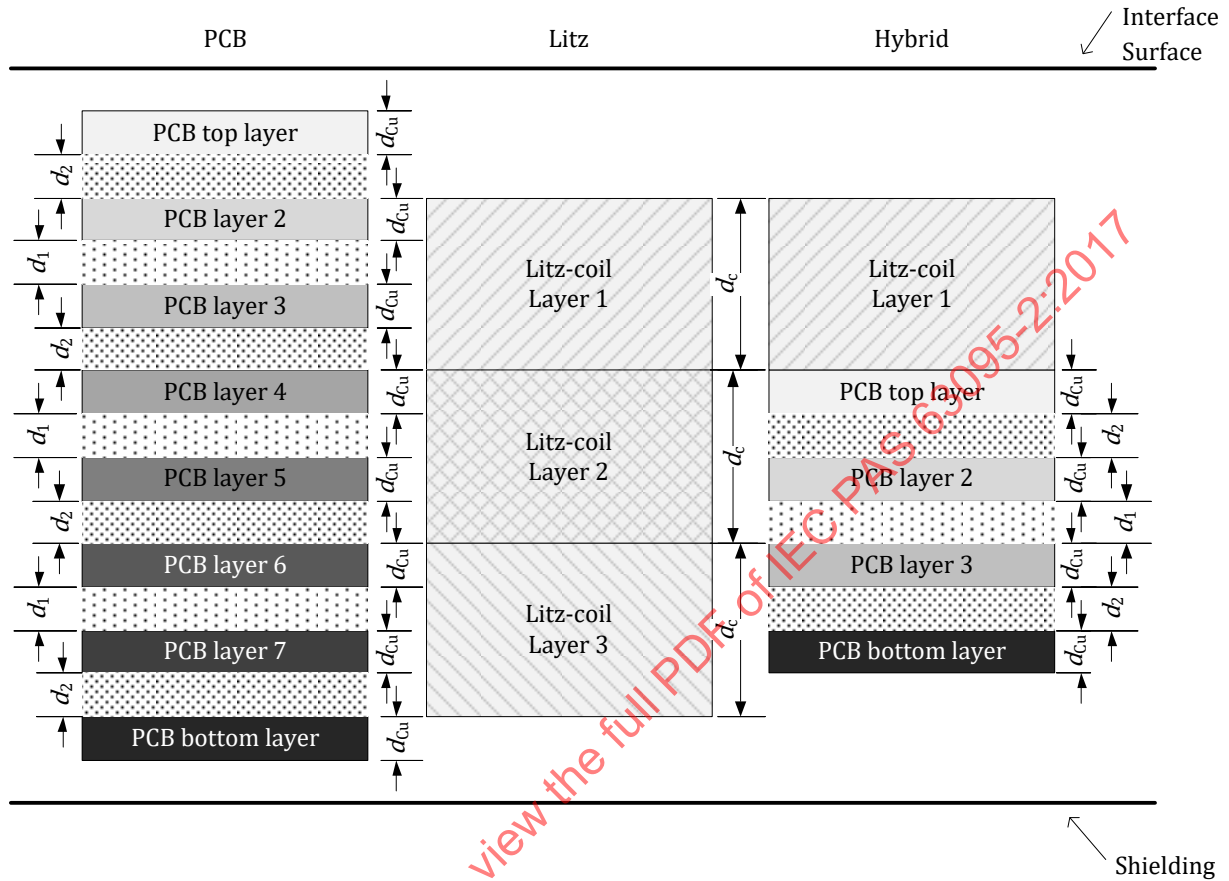


Table 104. Primary Coil array parameters of Power Transmitter design B5

Parameter	Symbol	Value
Center-to-center distance	d_h	$46.5^{+0.2}_{-0.1}$ mm
Offset 2 nd layer array	t_2	$15.5^{+0.1}_{-0.1}$ mm
Offset 3 rd layer array	t_3	$15.5^{+0.1}_{-0.1}$ mm
Litz-layer thickness	d_c	$0.4^{+0.1}_{-0.05}$ mm
PCB-copper thickness	d_{Cu}	$0.07^{+0.015}_{-0.015}$ mm
Dielectric thickness 1	d_{d1}	$0.088^{+0.15}_{-0}$ mm
Dielectric thickness 2	d_{d2}	$0.126^{+0.039}_{-0.039}$ mm

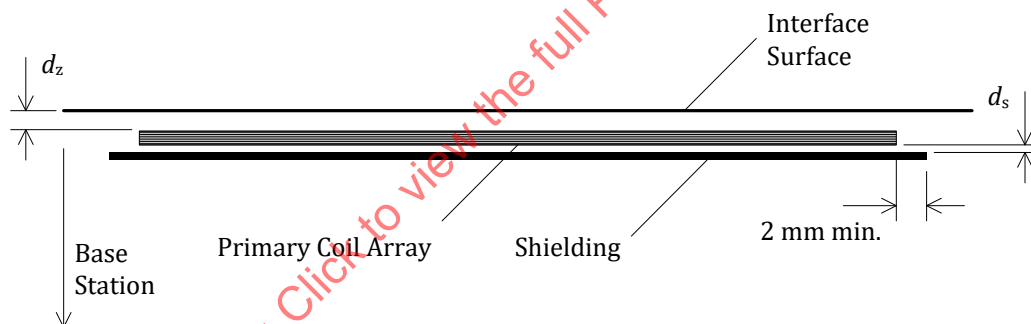
2.3.5.1.2 Shielding

As shown in Figure 159, Transmitter design B5 employs Shielding to protect the Base Station from the magnetic field that is generated in the Primary Coil array. The Shielding extends to at least 2 mm beyond the outer edges of the Primary Coil array, and is placed at a distance of at most $d_s = 0.5$ mm below the Primary Coil array.

The Shielding consists of soft magnetic material that has a thickness of at least 0.5 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- Material 78 — Fair Rite Corporation.
- 3C94 — Ferroxcube.
- N87 — Epcos AG.
- PC44 — TDK Corp.
- FK2 — TDK Corp (at least 0.8 mm thickness).

Figure 161. Primary Coil array assembly of Power Transmitter design B5



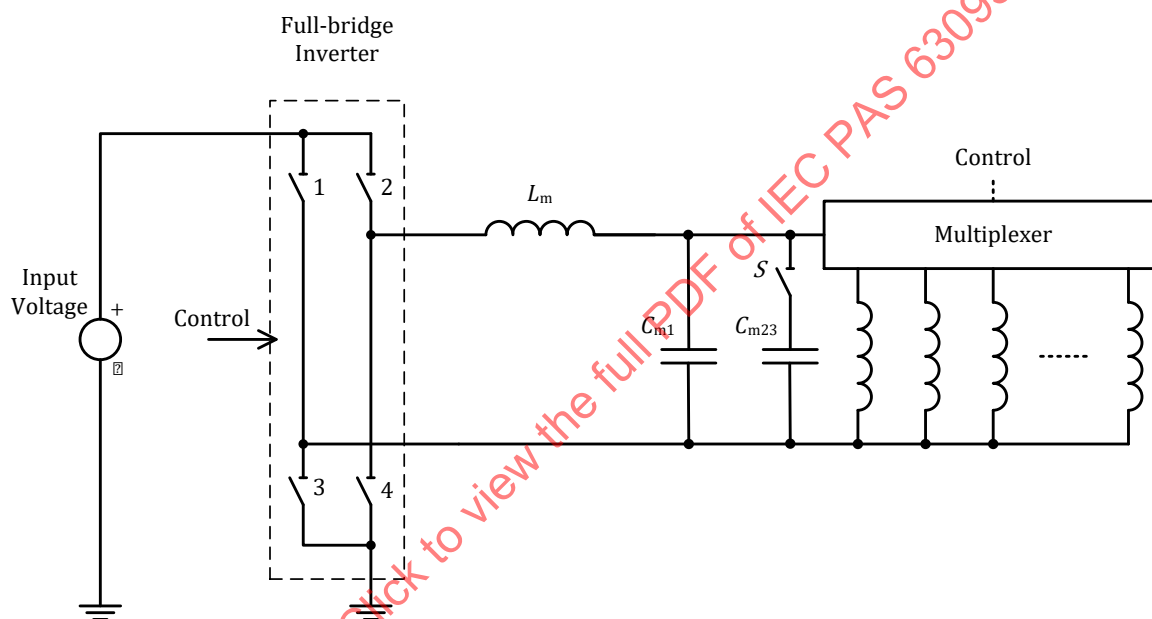
2.3.5.1.3 Interface Surface

As shown in Figure 161, the distance from the Primary Coil array to the Interface Surface of the Base Station is $d_z = 2^{+0.5}_{-0.25}$ mm, across the top face of the Primary Coil array. In addition, the Interface Surface extends at least 5 mm beyond the outer edges of the Primary Coil array.

2.3.5.2 Electrical details

As shown in Figure 162, Power Transmitter design B5 uses a full-bridge inverter to drive the Primary Coil array. In addition, Power Transmitter design B5 uses a multiplexer to select the position of the Active Area. The multiplexer shall configure the Primary Coil array in such a way that one, or two Primary Coils are connected—in parallel—to the driving circuit. The connected Primary Coils together constitute a Primary Cell. In the case that two Primary Coils are selected, these two Primary Coils shall have an overlap of two-thirds of the area of a single Primary Coil.

Figure 162. Electrical diagram (outline) of Power Transmitter design B5

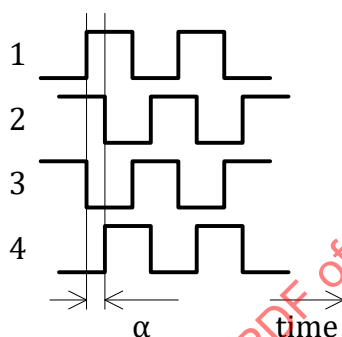


Within the Operating Frequency range $f_{op} = 96 \pm 2$ kHz, the assembly of Primary Coil array and Shielding has an inductance of 8.8^{+1}_{-1} μ H for each individual Primary Coil in layer (a) (closest to the Interface Surface), 9.1^{+1}_{-1} μ H for each individual Primary Coil in layer (b), and 9.5^{+1}_{-1} μ H for each individual Primary Coil in layer (c) (closest to the Shielding). The capacitances and inductance in the impedance matching circuit are, respectively, $C_{m1} = 356^{+5\%}_{-5\%}$ nF, $C_{m23} = 82^{+5\%}_{-5\%}$ nF, and $L_m = 3.8^{+5\%}_{-5\%}$ μ H. The switch S is open if the Primary Cell consists of a single Primary Coil; otherwise, the switch S is closed. The input voltage to the full-bridge inverter is $12^{+5\%}_{-5\%}$ V.

NOTE The voltage across the capacitance C_m can reach levels exceeding 36 V pk-pk.

Power Transmitter design B5 uses the phase difference between the control signals to two halves of the full-bridge inverter to control the amount of power that is transferred, see Figure 163. For this purpose, the range of the phase difference α is $0\ldots 180^\circ$ —with a larger phase difference resulting in a lower power transfer. In order to achieve a sufficient accurate adjustment of the power that is transferred, a type B5 Power Transmitter shall be able to control the phase difference with a resolution of 0.42° or better. When a type B5 Power Transmitter first applies a Power Signal (see the *Digital Ping* section in *Parts 1 and 2: Interface Definitions*), it shall use an initial phase difference of 120° .

Figure 163. Control signals to the inverter



Control of the power transfer shall proceed using the PID algorithm, which is defined in the *Power transfer control* section in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the phase difference between the two halves of the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type B5 Transmitter shall determine the amplitude of the current into the Primary Cell with a resolution of 5 mA or better. In addition to the PID algorithm, a type B5 Power Transmitter shall limit the current into the Primary Cell to at most 4 A RMS in the case that the Primary Cell consists of two Primary Coils, or at most 2 A RMS in the case that the Primary Cell consists of one Primary Coil. Finally, Table 105 provides the values of several parameters, which are used in the PID algorithm.

Table 105. Control parameters for power control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_I	N.A.	N.A.
PID output limit	M_{PID}	2,000	N.A.
Scaling factor	S_v	0.01	$^\circ$

2.3.5.3 Scalability

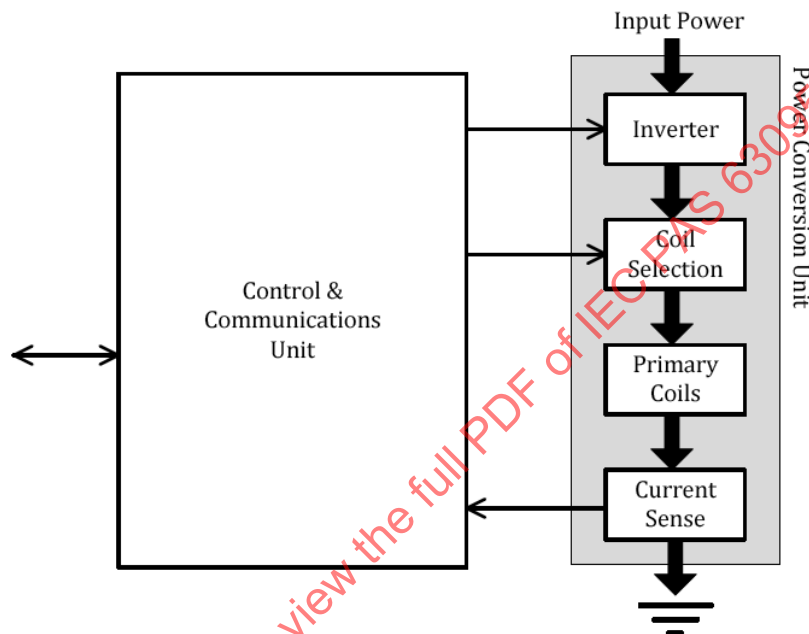
Power Transmitter Design B5 offers the same scalability options as Power Transmitter design B1. See Section 2.3.1.3.

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2.3.6 Power Transmitter design B6

Figure 164 illustrates the functional block diagram of Power Transmitter design B6, which consists of two major functional units, namely a Power Conversion Unit and a Communications and Control Unit.

Figure 164. Functional block diagram of Power Transmitter design B6



The Power Conversion Unit on the right-hand side of Figure 164 comprises the analog parts of the design. The design uses an array of partly overlapping Primary Coils to provide for Free Positioning. Depending on the position of the Power Receiver, the multiplexer connects and/or disconnects the appropriate Primary Coil(s). The resonance capacitor forms a resonant circuit with the parts of the Primary Coil array that are connected. The sensing circuits monitor (amongst others) the Primary Cell current and voltage, and the inverter converts the DC input to an AC waveform that drives the Primary Coil array.

The Communications and Control Unit on the left-hand side of Figure 164 comprises the digital logic part of the design. This unit receives and decodes messages from the Power Receiver, configures the multiplexer to connect the appropriate parts of the Primary Coil array, executes the relevant power control algorithms and protocols, and drives the inverter to control the amount of power provided to the Power Receiver. The Communications and Control Unit also interfaces with the other subsystems of the Base Station, e.g. for user interface purposes.

2.3.6.1 Mechanical details

Power Transmitter design B6 includes a Primary Coil array as defined in Section 2.3.6.1.1, Shielding as defined in Section 2.3.6.1.2, and an Interface Surface as defined in Section 2.3.6.1.3.

2.3.6.1.1 Primary Coil array

Each Primary Coil within the Primary Coil array is of the wire-wound type, and consists of 2 bifilar windings of each 11 turns of litz wire having 24 strands of no. 40 AWG (0.08 mm diameter), or equivalent¹. As shown in Figure 165, the Primary Coil has an oval shape and consists of a single layer. Table 106 lists the dimensions of the Primary Coil.

Figure 165. Primary coil of Power Transmitter design B6

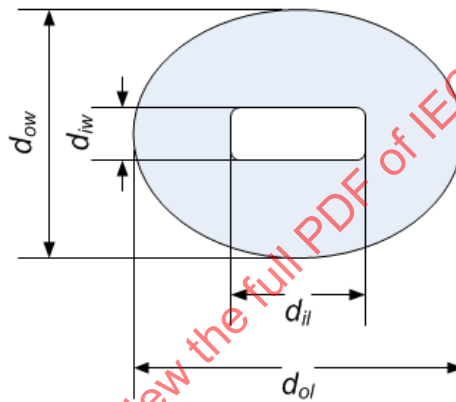


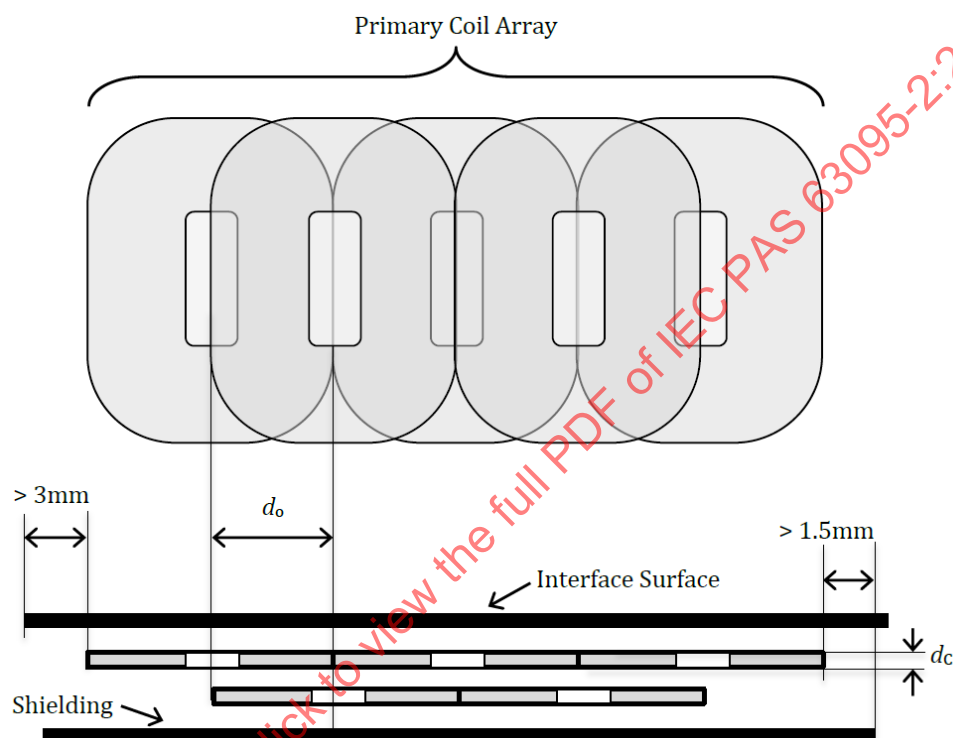
Table 106. Design parameters for Primary Coil array of Power Transmitter B6

Parameter	Symbol	Value
Outer length	d_{ol}	$45.0^{+0.5}$ mm
Inner length	d_{il}	$18.4^{+0.5}$ mm
Outer width	d_{ow}	$34.0^{+0.0}_{-1.0}$ mm
Inner width	d_{iw}	$7.2^{+0.5}$ mm
Litz layer thickness	dC	$0.65^{+0.3}$ mm
Number of turns per layer	N	11 turns
Number of layers	-	1

¹ One equivalent example is a single winding of 11 turns of Litz wire having 96 strands of no. 40 AWG (0.08mm diameter)

Power Transmitter design B6 contains at least two Primary Coils and allows for 1-dimensional freedom of positioning. All adjacent Primary Coils are placed with their long sides alongside each other with a displacement of $d_o = 17.0^{+2.0}_{-0.0}$ mm between their centers, such that there is an overlap of about 50% of the area. Figure 166 shows the functional arrangement of coils in the Primary Coil array. See also Table 106 for details of the parameters.

Figure 166. Arrangement of coils in the Primary Coil array of Power Transmitter B6



The Communications & Control Unit of a single Power Transmitter selects 1 or 2 coils from the array to form a Primary Cell for power transfer when a Power Receiver is positioned on the Active Area. In the case where 2 coils are selected, these 2 coils shall have an overlap.

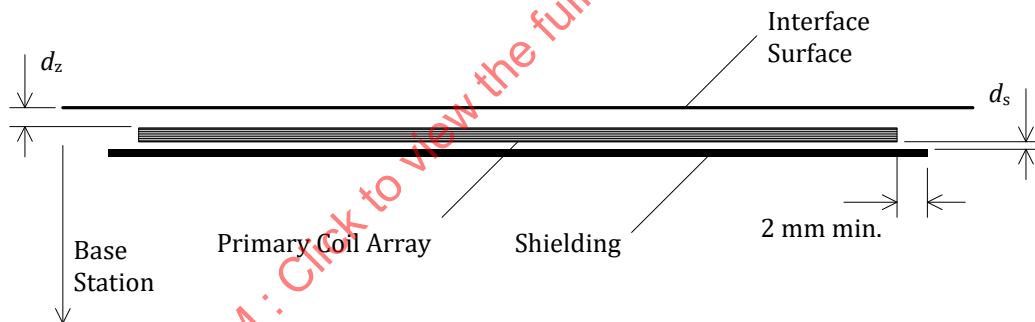
2.3.6.1.2 Shielding

As shown in Figure 166, Transmitter design B6 employs Shielding to protect the Base Station from the magnetic field that is generated in the Primary Coil array. The Shielding extends to at least 1.5 mm beyond the outer edges of the Primary Coil array, and is placed at a distance of at most $d_s = 0.5$ mm below the Primary Coil array.

The Shielding consists of soft magnetic material that has a thickness of at least 0.5 mm. This version of *Part 4: Reference Designs* limits the composition of the Shielding to a choice from the following list of materials:

- FK2 — TDK Corp.
- PC44 — TDK Corp.
- RM33 — EMICore.
- KNZWZKKC506 — Panasonic.
- Material 78 — Fair Rite Corp.

Figure 167. Primary Coil array assembly of Power Transmitter design B6



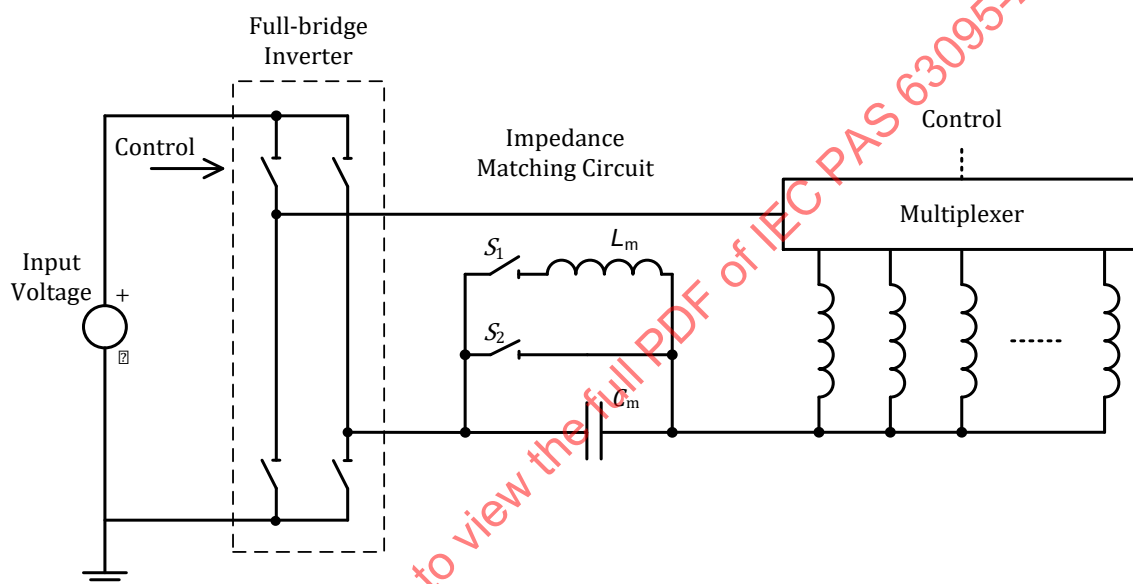
2.3.6.1.3 Interface Surface

As shown in Figure 167, the distance from the Primary Coil array to the Interface Surface of the Base Station is $d_z = 2^{+0.25}_{-0.5}$ mm, across the top face of the Primary Coil array. In addition, the Interface Surface extends at least 3 mm beyond the outer edges of the Primary Coil array.

2.3.6.2 Electrical details

As shown in Figure 168, Power Transmitter design B6 uses a full-bridge inverter to drive the Primary Coil array. In addition, Power Transmitter design B6 uses a multiplexer to select the position of the Active Area. The multiplexer shall configure the Primary Coil array in such a way that one or two (overlapping; see Section 2.3.6.1.1) Primary Coils are connected—in parallel—to the driving circuit. The connected Primary Coil(s) together constitute a Primary Cell.

Figure 168. Electrical diagram (outline) of Power Transmitter design B6



Within the Operating Frequency range $f_{op} = 125 \dots 135$ kHz, the assembly of Primary Coil array and Shielding has an inductance of $5.8^{\pm 0.5} \mu\text{H}$ for each individual Primary Coil in layer (a) (closest to the Interface Surface), and $6.2^{\pm 0.5} \mu\text{H}$ for each individual Primary Coil in layer (b) (closest to the Shielding). The capacitance in the impedance matching circuit is $C_m = 1000^{\pm 5\%} \text{ nF}$. The inductance in the impedance matching circuit is $L_m = 1 \mu\text{H}$. The input voltage to the full-bridge inverter is $5^{\pm 5\%} \text{ V}$.

NOTE The voltage across the capacitance C_m can reach levels exceeding 25V pk-pk.

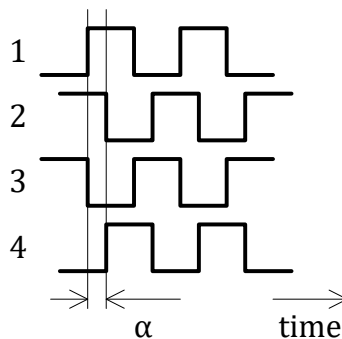
Switches S_1 and S_2 may be used to change the impedance the inverter sees when driving the Primary Cell, allowing the inverter to drive the Primary Cell at Operating Points that are more efficient (i.e. requiring less current). During normal operation both switches should be open. However, during a Digital Ping switch S_1 should be closed and switch S_2 should be open. Basically there are three combinations of switch positions as indicated in the Table 107 below. The initial Operating Point of the Power Transmitter occurs during a Digital Ping. In this situation a low amount of power is transferred to allow any Power Receiver to initialize and respond. Switch S_2 may be used to provide a smooth transition from the damped inductive state to the resonant state (both switches open) and ensures that there is no magnetizing current flowing through L_m when switch S_1 is turned off.

Table 107. Power Transmitter design B6 switch configurations

S_1	S_2	Inverter state	Comment
Closed	Open	Damped inductive	Digital Ping—low power
Any	Closed	Normal inductive	Transition—medium power
Open	Open	Resonant	Power Transfer—high power

Power Transmitter design B6 uses the phase difference between the control signals to two halves of the full-bridge inverter to control the amount of power that is transferred, see Figure 169. For this purpose, the range of the phase difference α is $0...180^\circ$ —with a larger phase difference resulting in a higher power transfer. In order to achieve a sufficient accurate adjustment of the power that is transferred, a type B6 Power Transmitter shall be able to control the phase difference with a resolution of 0.42° or better. When a type B6 Power Transmitter first applies a Power Signal (see the *Digital Ping* section in *Parts 1 and 2: Interface Definitions*), it shall use an initial phase difference of 180° and switch S_1 closed and switch S_2 open.

Figure 169. Control signals to the inverter



Control of the power transfer shall proceed using the PID algorithm, which is defined in the *Power transfer control* section in *Parts 1 and 2: Interface Definitions*. The controlled variable $v^{(i)}$ introduced in the definition of that algorithm represents the phase difference between the two halves of the full-bridge inverter. In order to guarantee sufficiently accurate power control, a type B6 Transmitter shall determine the amplitude of the current into the Primary Cell with a resolution of 5 mA or better. In addition to the PID algorithm, a type B6 Power Transmitter shall limit the current into the Primary Cell to at most 5 A RMS in the case that the Primary Cell consists of two Primary Coils, or at most 3 A RMS in the case that the Primary Cell consists of one Primary Coil. Finally, Table 108 provides the values of several parameters, which are used in the PID algorithm.

Table 108. Control parameters for power control

Parameter	Symbol	Value	Unit
Proportional gain	K_p	1	mA^{-1}
Integral gain	K_i	0	$\text{mA}^{-1}\text{ms}^{-1}$
Derivative gain	K_d	0	mA^{-1}ms
Integral term limit	M_i	N.A.	N.A.
PID output limit	M_{PID}	2,000	N.A.
Scaling factor	S_v	0.01	°

2.3.6.3 Scalability

Sections 2.3.6.1 and 2.3.6.2 define the mechanical and electrical details of Power Transmitter design B6. As defined in Section 2.1, a type B6 Power Transmitter serves a single Power Receiver only. In order to serve multiple Power Receivers simultaneously, a Base Station may contain multiple type B6 Power Transmitters. As shown in Figure 170, these Power Transmitters may share the Primary Coil array and multiplexer. However, each individual Power Transmitter shall have a separately controllable inverter, resonance circuit, and means to determine the Primary Cell current, as defined in Section 2.3.6.2. In addition, the multiplexer shall ensure that it does not connect multiple inverters to any individual Primary Coil.