

TECHNICAL REPORT



**Power quality management –
Part 100: Impact of power quality issues on electric equipment and power
system**

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.020

ISBN 978-2-8322-7443-9

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POWER QUALITY MANAGEMENT –

**Part 100: Impact of power quality issues
on electrical equipment and power system**

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IEC TR 63222-100 has been prepared by IEC technical committee 8: System aspects of electrical energy supply. It is a Technical Report.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
8/1648/DTR	8/1660/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available

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A list of all parts in the IEC 63222 series, published under the general title *Power quality management*, can be found on the IEC website.

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INTRODUCTION

The impacts of power quality issues increasingly attract much attention with modern industrial development. The integration of nonlinear loads, such as power-electronic based equipment, electric arc furnace, electric locomotive, etc., and faults or other events such as short-circuit and lightning strikes directly or indirectly cause power quality issues.

If public supply system power quality is not within the reasonable range defined in IEC TS 62749, and/or the demand-side power quality is not appropriately managed (e.g. IEC TR 63191) and/or the equipment immunity does not accommodate the expected environment, the performance of equipment may be impacted, likely causing malfunction, maloperation, or damage, and likewise the power system itself.

On the other hand, the quality of power is not absolute. Regarding the levels of power quality, the situation differs. So called “poor” power quality level for one grid may be acceptable or good for another internal application depending on the system configuration, the transfer characteristics between the different voltage levels (attenuation or amplification), the immunity of the equipment /installations/appliances, the actual disturbance levels on the system, etc.

In terms of power quality, the situation in micro-grid on islanding mode, off grid, mini-grid or weak grid may differ from that in public supply system. The level of power quality may worsen even far outside the recommended values defined by IEC TS 62749. In those forementioned grids, appliances may need to be better designed for immunity to power quality issues.

This document, which is a Technical Report, collects relevant information on power quality impact from, e.g., CIGRE reports, case study, research findings, etc., in order to uncover the mechanism of how electrical equipment/installations are impacted under specific power quality condition, as well as to fully understand the reasons of power quality management.

This document focuses on the public supply system. Notionally, the mechanisms of how electrical equipment/installations/system are impacted by power quality disturbances are applicable for so-called weak grids.

The contents of this document can help network users and equipment suppliers make rational investments and actively cooperate with network operators to take specific measures to improve power quality.

The contents of this document can also support IEC TR 63222-101, namely, power quality management-power quality data applications.

POWER QUALITY MANAGEMENT –

Part 100: Impact of power quality issues on electrical equipment and power system

1 Scope

This part of IEC 63222, which is a Technical Report, collects relevant information on power quality impacts from, e.g., CIGRE reports, case studies, research findings, etc., in order to uncover the mechanisms of how electrical equipment/installations/system are impacted by power quality disturbances, as well as to fully understand the guidelines for power quality management.

The contents of this document aim to help network operators, network users and equipment suppliers make rational investments and actively cooperate to manage power quality and keep it consistent with relevant EMC standards.

NOTE 1 The boundaries between the various voltage levels may be different for different countries/regions. In the context of this document, the following terms for system voltage are used:

- low voltage (LV) refers to $U_N \leq 1 \text{ kV}$
- medium voltage (MV) refers to $1 \text{ kV} < U_N \leq 35 \text{ kV}$
- high voltage (HV) refers to $35 \text{ kV} < U_N \leq 230 \text{ kV}$

NOTE 2 Because of existing network structures, in some countries/regions, the boundary between medium and high voltage can be different.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

3.1

electricity

set of phenomena associated with electric charges and electric currents

Note 1 to entry: In the context of electric power systems, electricity is often described as a product with particular characteristics.

[SOURCE: IEC 60050-121:1998, 121-11-76]

3.2

flicker

impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time

[SOURCE: IEC 60050-161:1990, 161-08-13]

3.3

frequency deviation

difference between power supply frequency ($f_{h,1}$) and nominal frequency (f_n)

[SOURCE: IEC 60050-614:1990, 614-01-10, modified]

3.4

harmonic frequency

$f_{H,h}$ (abbreviation)

the frequency which is an integer multiple of the power supply (fundamental) frequency

[SOURCE: IEC 61000-4-7:2009, 3.2.1, modified (removal of formula and Note to entry)]

3.5

Harmonic order

h (abbreviation)

(Integer) the ratio of a harmonic frequency ($f_{H,h}$) to the power supply frequency ($f_{H,1}$)

[SOURCE: IEC 60050-161:1990, 161-02-19, modified]

3.6

System operator

network operator

the party responsible for safe and reliable operation of a part of the electric power system in a certain area and for connection to other parts of the electric power system

[SOURCE: IEC 60050-617:2009, 617-02-09]

3.7

nominal frequency

f_N (abbreviation)

value of frequency used to designate or identify a system

3.8

nominal voltage (of a system)

U_N (abbreviation)

value of voltage used to designate or identify a system

[SOURCE: IEC 60050-601:1985, 601-01-21, modified (addition of abbreviation, removal of "suitable approximate" from the beginning of definition)]

3.9

point of common coupling

PCC (abbreviation)

point in a public power supply network, electrically nearest to a particular load, at which other loads are or may be connected

Note 1 to entry: These loads can be either device, equipment or systems, or distinct network user's installations.

[SOURCE: IEC 60050-161:1990, 161-07-15, modified ("consumer's installation" replaced by "load")]

3.10**supply terminals****point of supply**

point in a distribution network designated as such and contractually fixed, at which electric energy is exchanged between contractual partners

Note 1 to entry: Supply terminals may be different from the boundary between the electricity supply system and the user's own installation or from the metering point.

[SOURCE: IEC 60050-617:2009, 617-04-02, modified Note 1 to entry]

3.11**(power) network user**

party supplying electric power and energy to, or being supplied with electric power and energy from, a transmission system or a distribution system

[SOURCE: IEC 60050-617:2009, 617-02-07]

3.12**power quality**

characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters

Note 1 to entry: These parameters might, in some cases, relate to the compatibility between electricity supplied on a network and the loads connected to that network.

Note 2 to entry: In the context of this Technical Specification, power quality refers to supply terminals and focuses on defining the characteristics of the voltage and frequency.

[SOURCE: IEC 60050-617:2009, 617-01-05, modified ("electric current, voltage and frequencies" replaced by "electricity" and Note 2 to entry added)]

3.13**rapid voltage change****RVC (abbreviation)**

quick transition (that may last more than several cycles) in RMS voltage between two steady-state conditions while the voltage stays in-between the thresholds defined for voltage swells and dips (otherwise, it would be considered as a swell or a dip)

Note 1 to entry: For more information, see IEC 61000-4-30.

3.14**transient over-voltage****voltage surge**

transient voltage wave propagating along a line or a circuit and characterized by a rapid increase followed by a slighter decrease of the voltage

[SOURCE: IEC 60050-161:1990, 161-08-11]

3.15**voltage deviation**

difference between supply voltage (U) and nominal voltage (U_N), often expressed by relative value

Note 1 to entry: In some circumstance, U_N may be replaced by U_C by contract or agreement.

3.16**voltage dip**

sudden reduction of the voltage at a point in an electrical system followed by voltage recovery after a short period of time, usually from a few cycles to a few seconds

Note 1 to entry: The starting threshold of voltage dip generally is 90 % of the reference voltage.

[SOURCE: IEC 60050-161:1990, 161-08-10, modified (addition of Note 1 to entry)]

3.17

voltage fluctuation

series of voltage changes or a cyclic variation of the supply voltage envelope

Note 1 to entry: For the purpose of this document, the reference voltage is the nominal or declared voltage of the supply system.

[SOURCE: IEC 60050-161:1990, 161-08-05, modified (addition of "supply voltage" and Note 1 to entry)]

3.18

voltage swell

sudden increase of the voltage at a point in an electrical system followed by voltage recovery after a short period of time, usually from a few cycles to a few seconds

Note 1 to entry: The starting threshold of voltage swell generally is 110 % of reference voltage.

3.19

voltage unbalance

in a poly-phase system, a condition in which the magnitudes of the phase voltages or the phase angles between consecutive phases are not all equal (fundamental component)

[SOURCE: IEC 60050-161:1990, 161-08-09, modified ("RMS values" replaced by "magnitudes")]

3.20

voltage unbalance factor

in a three-phase system, the degree of unbalance is expressed by the ratio (in per cent) between the RMS values of the negative sequence (or, rarely, of the zero-sequence) component and the positive sequence component of voltage

[SOURCE: IEC 60050-604:1987, 604-01-30, modified (addition of "voltage" to term)]

4 General impacts of power quality issues

4.1 General

Generally, for electrical equipment exposing under continuous power quality phenomenon disturbances, the impacts of long-time accumulated effects may be the key aspect, while immediate impact may arise in case of events of discontinuous power quality phenomenon, e.g., voltage dip/swell/short time interruption.

IEC TS 62749:2020, Annex C describes the general impacts of power quality issues. This clause refers to IEC TS 62749:2020, Annex C.

4.2 Harmonic distortion

Generally, harmonic impacts due to long-time accumulated effects are often of concern, but harmonic resonance will lead to harmonic over-voltage which will lead to harmonic over-voltage which produces dielectric stress of electrical equipment, and even causes dielectric breakdown.

- Capacitors for power factor correction often act as sinks for a particular order of harmonic currents. In this case, it can lead to capacitor over current if no forethought is given at the designing stage.
- Non-sinusoidal power supplies result in the reduction of torque of induction motors.

- Harmonics will increase interference with telephone, communicating and analogue circuits.
- Excessive levels of harmonics can cause errors in the reading of induction type energy meters which are calibrated for pure sinusoidal AC power.
- High-order harmonics cause voltage stresses.
- Harmonic currents flowing through power system networks can cause additional losses.

It is reported that the level of inter-harmonics in power supply systems is increasing due to the development of frequency converters and similar electronically controlled equipment. Harmonic voltages and inter-harmonic voltages, if not controlled, might lead (among other effects) to overloading or disturbance of equipment on the supply networks and in electricity users' installations.

In some cases, inter-harmonic voltages, even at low levels, can give rise to flicker or cause interference in ripple control systems.

4.3 Voltage unbalance

Voltage unbalance is always a concern as it affects the transformers, electrical motors, electrical generators, transmission losses and relay protection.

- Voltage unbalance degrades the performance and shortens the life of a three-phase motor.
- Current unbalance caused by voltage unbalance essentially creates counter-torque (resisting torque). That is, it tries to make the motor turn in the opposite direction. This may create heating.
- Voltage unbalance may also reduce the capacity of equipment such as motors or generators if not properly taken into consideration at the design stage (equipment is normally designed and rated to account for some degree of voltage unbalance normally present in any power system).
- Voltage unbalance causes distance protection and negative-sequence protection to malfunction, which may result in abnormal starting or even tripping of relay protection.
- Current unbalance caused by voltage unbalance may cause additional losses of distribution lines and cable lines. It may also lead to the shift of neutral point of high voltage side of the transformer.
- Voltage unbalance may increase non-characteristics harmonics produced by converters.
- Voltage unbalance may transfer triple harmonic currents in the transmission system, normally blocked by delta-connected transformer windings.

4.4 Voltage deviation

Large voltage deviations from the nominal values may shorten the life of electrical equipment, lower the stable limit of the power system, increase the cost of network operation and reduce the output of reactive power compensation. Electrical equipment operating under this condition may malfunction, break down or be damaged.

4.5 Frequency deviation

Frequency deviation will endanger the reliability and stability of power system operation and production efficiency of end-users. The rapid change of frequency will bring great harm to the normal operation of the equipment of units, such as induction motor or feed water pump. The accuracy of the energy meter may be impacted by the frequency deviation. Frequency disturbances in the main network causing local electrical resonance may lead to a large-scale off-grid accident of renewable energy, e.g. sub-synchronous resonance.

If frequency deviation exceeds the limit, motors are usually protected by means of stopping their operation. Sustained operation will alter the speed of motors and potentially create unsafe conditions for the processes in which they function.

Where frequency deviations occur frequently, such as islanded power systems, users may notice time drift with their analogue clocks.

4.6 Flicker and rapid voltage change

Flicker is considered to be an annoying problem for network users. Most of the time, it does not have a high financial impact. However, at high levels it can cause inconvenience and adverse health effects to people when frequent flickering of lights (different technology of lamps may have different sensitivity to voltage fluctuation) occurs at their work-places or homes.

Flicker can cause photosensitive epileptic seizures, asthenopia (i.e. eyestrain) and stroboscopic effects (noting that stroboscopic effects pose a danger in industrial settings due to the possibility that rotating machinery can appear stationary).

Voltage fluctuations and rapid voltage change can cause a number of harmful technical effects such as data errors, memory loss, equipment shutdown, flicker, motors stalling and reduced motor life, resulting in disruption to production processes and substantial costs. In addition, large voltage fluctuations damage electrical equipment such as LED lamps.

4.7 Voltage dip

Motor drives, including variable speed drives, are particularly susceptible because the load still requires energy that is no longer available except the inertia of the drive. In processes where several drives are involved, individual motor control units may sense the loss of voltage and shut down the drive at a different voltage level from its peers and at a different rate of deceleration, resulting in a complete loss of process control. Data processing and control equipment is also very sensitive to voltage dips and can suffer from data loss and extended downtime.

4.8 Transient over-voltages

Transient over-voltage can cause large dV/dt values that can damage or reduce the lifetime of variable speed drives, motors, transformers, and cables. It also causes the abnormal operation of wind farms, HVDC systems and energy systems along with flash-over and partial discharge phenomena and damage their key equipment after events.

4.9 Voltage swell

Voltage swell can affect the operation of wind turbines and may lead it off the grid. When the grid voltage is disturbed by a temporary rise, the stator flux will generate positive (forced) component, negative (asymmetric temporary rise) component and DC (free) component, which will generate over-voltage at wind turbine.

Besides, the surge arresters can be exposed to swells during their lifetime. If the voltage is high enough, a swell is likely to damage or destroy the surge arrester. There are indications that swells can damage surge arresters more often than surges.

5 Continuous power quality disturbances impact

5.1 The impact of voltage deviation

5.1.1 General

Voltage deviations from nominal levels will affect electrical equipment for power suppliers and end-users. The performance of the equipment under different voltage deviation levels is identified using the equations and flowchart in the references in Table 1.

Table 1 – reference information of voltage deviation impacts

Equipment		Impact description	Reference
Electrical equipment	DC and AC Electric Motor	• An increase in power loss. • A reduction in load-carrying capacity. • An incremental change in winding temperature. • Under deviation results in reduced starting torque and increased full load temperature rise. • Over deviation results in increased torque, increased starting current, and decreased power factor. • Increase of even and triple harmonics (case saturation).	Ref.[1] P82,83 Ref. [2] P1095Ref. [10] P3
	Illumination Equipment	• The light output of Illumination equipment. • The lifetime of Illumination equipment. • Perform below the minimum acceptable illumination level.	Ref. [1] P84 Ref. [4] P53
	Household Appliances	• Perform less efficiently. • Higher losses and reduced lifetime. • Malfunction of the equipment. • Damage of the appliances	Ref. [1] P85 Ref. [3] P1064
	Transformer	• High voltage will increase the magnetizing current of a transformer. • Over deviation will accelerate insulation aging • Under deviation will increase winding loss. • More inrush current if high power supply voltage.	Ref. [4] P53 Ref. [5] P55
	Industrial Equipment	• Increase power loss. • The quality of the product is declining. • The output is reduced. • Equipment damage. • Reduced Lifetime.	Ref. [5] P55
	Power electronic Converter	• The current-carrying ability. • The firing order on the thyristor could be inefficient. • Damage of the component.	Ref. [1] P86
Power system	Reactive power compensation	• The reactive power output of capacitors varies with the square of the impressed voltage. • Under deviation reduces the output reactive power. • Over deviation reduces insulation life. • Increase temperature/cost of supply.	Ref. [5] P55,56
	Stability	• A large number of users may have power outages. • Power system instability. • System collapse. • Damage to appliances/equipment in line.	Ref. [1] P86 Ref. [5] P56
	Transmission losses	• Increasing the line loss rate. • Increasing the cost of power supply.	Ref. [5] P56
Numbers in square brackets refer to the Bibliography.			

5.1.2 Impact on equipment

5.1.2.1 DC and AC electric motor

Motor voltages less than the nameplate rating result in decreased starting torque and an increased temperature at full load. Increased torque, increased starting current, and a decreased power factor occur when motor voltages exceed the nameplate rating. Increased starting torque results in increased accelerating forces applied to couplings and driven equipment. Increased starting current results in a larger voltage drop in the supply circuit, which caused the voltage dips.

In general, voltage above the nameplate rating has a less detrimental effect on motor performance than voltage below the nameplate rating.

Synchronous motors behave similarly to induction motors, except that the speed remains constant (unless the frequency changes) and the maximum or pull-out torque varies directly with the voltage if the field voltage remains constant. If the field voltage varies in proportion to the line voltage, as in the case of a static rectifier source, the maximum or pull-out torque varies proportionally to the voltage squared, almost the same consequences as that of LED because the electronic part is similar.

5.1.2.2 Illumination equipment

Incandescent lamps: The voltage deviation has an effect on the light output and life of these kinds of lamps. A few percent increases in the voltage reduces the expected life of an incandescent lamp. While lower-than-nominal voltages extend the lifetime, but it cannot compensate for the decrease in lifetime caused by higher-than-nominal voltages. A large deviation in voltage results in a shorter lifetime when compared to a constant voltage.

LED equipment: Lower-than-nominal voltages affect the brightness of LED lamps, and LED equipment may not work normally. Higher-than-nominal voltages reduce the service life of LED equipment and even damage LED equipment.

Compact Fluorescent lamps (CFL): The voltage deviation affects the brightness and life of CFL.

Fluorescent lamps: The light output varies proportionally to the voltage. Voltage deviation has a smaller effect on the lifetime of fluorescent lamps than that of incandescent lamps.

5.1.2.3 Household appliances

Due to under-deviation, household appliances perform less efficiently. Under-deviation makes appliances more sensitive to voltage dips. An over-deviation makes the equipment more sensitive to transient over-voltages. Because the internal voltage control keeps the voltage of household appliances constant, an under-deviation in terminal voltage causes an increase in current, which results in higher losses and a shorter lifetime.

5.1.2.4 Transformer

A higher-than-nominal voltage between the transformer terminals increases the magnetizing current of a transformer. Because the magnetizing current is distorted, an increase in voltage magnitude amplifies the waveform distortion. The increase in electric field strength on the surface of transformer oil and winding accelerates the aging of these components. Serious voltage deviation damages the insulation.

Voltage deviation increases winding current under the same power transmission conditions, and winding loss is proportional to the square of the current. Since winding loss is proportional to the square of the current, voltage deviation increases winding loss.

5.1.2.5 Industrial equipment

Voltage deviation affects industrial equipment in different ways like power loss, product quality, equipment output, and equipment being damaged or forced to shut down. For instance, the output of thermal energy from electric heating equipment such as a resistance furnace is proportional to the square of the voltage. When the voltage is reduced, the melting and heating times become longer, resulting in a significant reduction in production efficiency. In addition, the electrolytic equipment supplies current through the rectifier device, and the reduction of voltage increases its electrical loss.

5.1.3 Impact on power system

5.1.3.1 Reactive power compensation

For the simple transmission system, the relationship between reactive power and voltage is as follows:

$$Q = \frac{U(E \cos \delta - U)}{X_{\Sigma}} \quad (1)$$

Where Q is the three-phase reactive power; U is the system line voltage; E is the electromotive force of the generator; δ is the phase angle between E and U ; X_{Σ} is the total line impedance (between E and U).

As shown in Formula (1), when $E \cos \delta > U$, the generator delivers reactive power to the power system. The greater the difference between E and U , the greater is the reactive power output. When $E \cos \delta < U$, the generator absorbs the reactive power from the system. From the perspective of the system's reactive power and voltage requirements, it is necessary for the generator to output or absorb reactive power in order to maintain the system's reactive power and voltage balances. At the peak of electricity consumption, the power system is carrying a heavy load and requires additional reactive power to maintain system line voltage U constant. To generate reactive power, the generator's electromotive force E must be increased. In terms of power grid economy, the transfer reactive power from the generator to the power system for the long-distance transmission lines could be avoided.

5.1.3.2 Stability

The transmission line's static stable power limit is proportional to the generator back-EMF and system voltage and inversely proportional to the reactance. The lower the system voltage, the lower the stable power limit, and the smaller the difference between the power limit and the transmission power, the more prone the system is to instability and serious system collapse. When the power grid is deficient in reactive power and its operating voltage is low, the system may collapse due to voltage instability, or a large number of users may experience power outages. For example, when the voltage is low, the reactive power emitted by the system is less than the reactive power absorbed by the load, resulting in an increase in current and a fall in voltage. The voltage reduction further aggravates the reactive power shortage. This vicious circle results in voltage collapse.

5.1.3.3 Transmission losses

If the transmission line's delivered power is constant, its voltage and current are inversely proportional. When the line voltage is increased, the current and network loss decrease proportionately. The decrease of line voltage leads to the current and network loss increase proportionately.

The transmission loss is determined by the relationship between active power, reactive power, and voltage deviation:

$$R_{\text{loss}} = \frac{Q^2 + P^2}{U^2} R_L = \frac{Q^2 + P^2}{U_N^2 (1 + \beta)^2} R_L \quad (2)$$

Where β is the voltage deviation; U is the system line voltage; R_L is the equivalent resistance of the transmission line; P is the active power and Q is the reactive power delivered. U_N is the rated voltage; P_{loss} is the line loss.

Therefore, the transmission loss caused by voltage deviation is obtained as follows:

$$\Delta P_{\text{loss}} = - \frac{(2\beta + \beta^2)(Q^2 + P^2)}{U_N^2 (1 + \beta)^2} R_L \quad (3)$$

Suppose the line impedance is 10 ohm and the transmission power is 100 MVA, the influence of under-voltage deviation on transmission loss is shown in Figure 1.

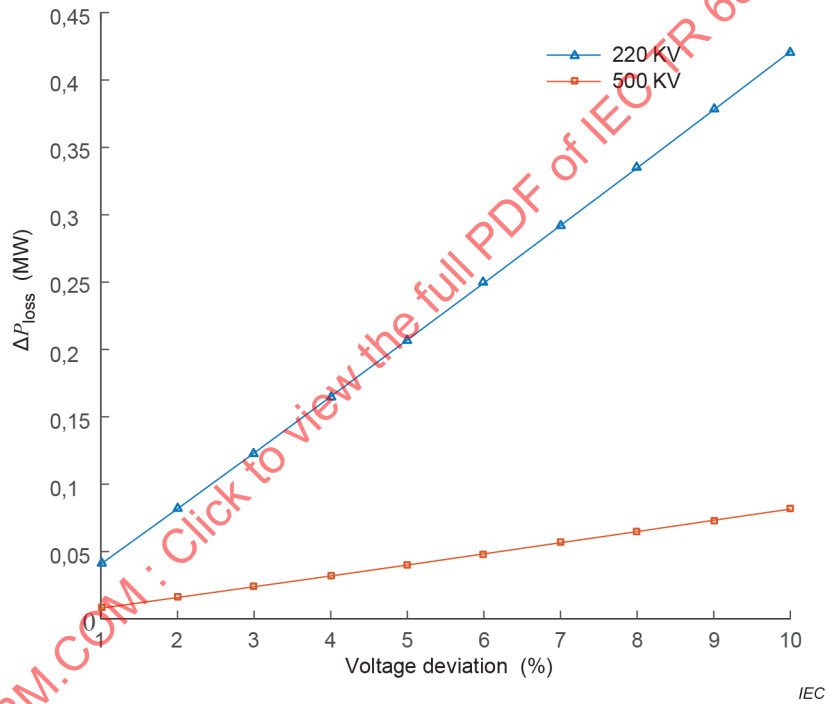


Figure 1 –The influence of under-voltage deviation on transmission loss

5.2 The impact of frequency deviation

5.2.1 General

The reference documents on impact of frequency deviation are listed in Table 2.

Table 2 – reference documents on impact of frequency deviation

Equipment	Impact description	Reference
Data processing equipment	• Cause abnormal function • Calculation error • Measurement error • Cause damages to power unit, supply cable	Ref. [6] P15 Ref. [7] P10
Electric feed pump	• Increase torque and reduce output • Increases power consumption • Decrease the efficiency and operational economic effectiveness • Mechanical vibration	Ref. [8] P2-3
Induction motor	• Temperature rise • Cause additional iron and mechanical loss • Impact output torque and speed • Mechanical vibration	Ref. [9] P2-3
Thyristor-based AC/DC converter	• Firing (commutation) error of thyristors • Thyristor damage if in generation mode of ASD • Important fluctuation of DC voltage • Stop of process	
Numbers in square brackets refer to the Bibliography.		

5.2.2 Impact on electrical equipment

5.2.2.1 Data processing equipment

Many new scientific equipment and precision instruments have stricter frequency requirements for data processing units. IEEE 446-1995 states that the maximum range of frequency deviation for many devices is 0,5 Hz; IEEE 1159-2019 further proposes the impact of frequency deviation on data processing equipment.

A ferromagnetic AC / DC power supply that works on the principle of a tuning circuit can only allow a 1 % frequency deviation in 50 Hz or 60 Hz system. Australian standard AS1284.5 points out that, for general electronic energy meters, the allowable frequency deviation tolerance of the level 1 meter is 0,3 % of the reference frequency, and the allowable frequency deviation tolerance of the level 2 meter is 0,5 % of the reference frequency. When the frequency deviation is up to 5 % of the reference frequency, the error of these electronic devices can reach 0,8 % to 1,5 %. When the frequency is changed by 1 %, the measurement error of the inductive energy meter increases by about 0,1 %. As the frequency increases, the inductive energy meter may not count electricity.

5.2.2.2 Electric feed pump

The steam turbine and blades of a thermal power plant are designed according to the rated speed and the guaranteed maximum shaft power. Lowering the rotation frequency will cause the loss of steam impacting the blade and increase the torque.

The change of frequency will bring great harm to the normal operation of the equipment of units, such as feed-water pump, circulating water pump, etc.

The relationship between the pump output and angular frequency can be expressed as

$$Q = \sqrt{(k_1 \omega^2 - H_{st}) / \Sigma R} \quad (4)$$

where ω represents the angular frequency; H_{st} is the static head to be overcome; k_1 is the coefficient determined by the structure and size of the unit. Q is the pump output. With the static pressure head, the pump can stop the water supply at a certain frequency before the frequency reaches zero. The critical frequency can be written as:

$$\omega_{cr} = \sqrt{H_{st}/k_1} \quad (5)$$

When the power supply frequency exceeds the rated value, the pressure head sent by the feed pump exceeds the required pressure head, which increases the power consumption of the entire plant.

In addition to water pumps, thermal power plants also have a large amount of ventilation torque machinery, such as primary blowers, secondary blowers and induced draft fans. In the absence of a static pressure head, the output of these machines is proportional to the first power of the frequency. The test proves that, as the frequency decreases, the output of the blower and induced draft fan decreases much faster than the frequency. When the frequency is increased, the pressure head generated by the blower and induced draft fan increases. The economy of the boiler is closely related to the content of carbon monoxide and carbon dioxide in the exhaust gas, and the excess amount of air in the combustion chamber. As the frequency of the power system decreases, chemical incomplete combustion increases. When the frequency is increased, the output of the blower is increased. The lowest loss in a boiler typically occurs at determined excess carbon dioxide content.

5.2.2.3 Induction motor

When the system frequency changes, the speed and loss of the induction motor will change differently, the temperature rise will change, and the efficiency may be affected.

1) Torque and speed

The relationship between the speed and frequency of the motor is:

$$n = \frac{60f}{p} \quad (6)$$

where n is speed; f is frequency; p is the number of pole-pairs.

The relationship between the torque and frequency of the motor is:

$$M = \frac{m_1 p U_1^2 \frac{r_2'}{s}}{2\pi f \left\{ \left(r_1 + C \frac{r_2'}{s} \right)^2 + \left(X_1 + C X_2' \right)^2 \right\}} \quad (7)$$

where U_1 is the stator terminal voltage; r_1 , X_1 is the stator resistance and reactance; r_2' , X_2' is the rotor resistance and reactance converted to the stator; m_1 is the content depending on structure; p is the number of pole pairs; s is the slip rate. When the motor running s is very small, the relationship can be simplified to:

$$M \approx \frac{m_1 p U_1^2}{2\pi f} \cdot \frac{s r_2'}{C r_2'^2} \propto \frac{U_1^2}{f} \quad (8)$$

When the motor is running normally, if the terminal voltage remains unchanged, the torque and frequency are close to being inversely proportional. For example, when a motor with a

nominal frequency of 60Hz is used for a power source with a nominal frequency of 50 Hz, the torque of the motor will increase to 1,25 times the original torque.

The maximum torque $M_{\max}$ is:

$$M_{\max} \approx \frac{m_1 p U_1^2}{4\pi C_1} \cdot \frac{1}{f(X_1 + CX_2')} \propto \frac{U_1^2}{f^2} \quad (9)$$

The absolute value of the maximum torque is inversely proportional to the square of frequency and close to the square of voltage.

2) Loss

The losses of induction motors include iron loss (hysteresis loss and eddy current loss), copper loss, mechanical loss (friction loss and wind loss), and stray loss. Mainly affected by frequency are iron loss and mechanical loss.

i) Iron loss

Iron loss contains hysteresis loss and eddy current loss. For iron loss, it refers to Formula (10). The iron consumption per 1 kg of steel sheet can be expressed by the following formula:

$$w_f = B^2 \left[\sigma_h \frac{f}{100} + \sigma_e d^2 \left(\frac{f}{100} \right)^2 \right] (W/kg) \quad (10)$$

where: w_f is the iron loss, B is the magnetic flux density, d is the thickness of the steel sheet, σ_h is the hysteresis loss coefficient, σ_e is the eddy current loss coefficient. It can be seen that the higher the frequency, the greater the iron loss.

ii) Mechanical loss

The mechanical loss comprises of the friction loss and wind loss of the bearing. General mechanical loss W_m can be approximated by Formula (11):

$$W_m = \frac{W_m\%}{100} \times (KVA)(KW) \quad (11)$$

where: $w_m\% = 0.0312(KVA)^{1/6} (rpm)^{1/3}$ if wind consumption is negligible; the mechanical loss is proportional to frequency.

5.2.2.4 Thyristor-based AC/DC converter

Thyristor-based AC/DC converter (rectifier and inverter) is also very sensitive to grid frequency. The deviation will cause an event of commutation error of thyristors and even damage thyristors if the converter operating in generation mode. Moreover, the fluctuation of DC voltage happens and may force converter to shut down.

5.3 The impact of voltage unbalance

5.3.1 General

Voltage unbalance can affect the operation performance of for example: the generator, electric motor, transformer, wind farm, reactive compensation equipment, Induction motor, and adjustable speed drive. As for the power system, this may result in abnormal relay movement, worsening transmission losses, and voltage deviation.

The Reference documents on impact of voltage unbalance are listed in Table 3.

Table 3 – reference documents on the impact of voltage unbalance

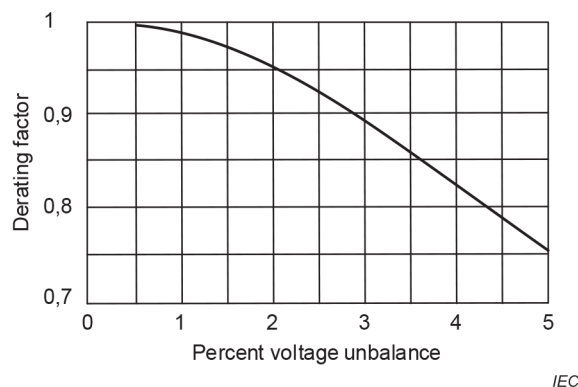
Equipment		Impact description	Reference
Electrical equipment	Generator and electric motor	• Cause additional negative-sequence currents • Temperature rise • Losses increase • Shorten winding life • Mechanical Vibration	Ref. [11] P89-90 Ref. [12] P12 Ref. [13] P905
	Transformer	• Hot-spot temperature rise • Losses increase • Shorten insulation life	Ref. [14] P503 Ref. [15] P2-3 Ref. [16] P324-325
	Wind farm	• Cause damage to equipment • Unbalance heat on wind turbines • Mechanical vibration of generator shafting	Ref. [17] P1074-1075 Ref. [18] P667
	Reactive compensation equipment	• The output instantaneous power appears the power fluctuation of twice frequency • Negative sequence and third harmonic currents appear in the inverter • Power Losses	Ref. [19] P239-241 Ref. [20] P3900-3901
	Induction motor	• Decrease in torque • Excessive heating due to more losses • Mechanical Vibration	Ref. [21] P263 Ref. [22] P3
	Adjustable speed drive (ASD)	• High input-current harmonic distortion • Overstressed DC-bus capacitors	Ref. [23] P733 Ref. [24] P4068
Power system	Relay protection	• Malfunction in distance protection and negative-sequence protection • Cause abnormal starts or even tripping of protection devices	Ref. [25] P689
	Transmission losses	• Cause additional losses of distribution lines and cable lines	Ref. [15] P2-3 Ref. [26] P365
	Voltage deviation	• The shift of neutral point of high voltage side of transformer • One phase voltage amplitude decreases and the other two phases voltage amplitudes increase • Damage to loads on line and increase in cost of power	Ref. [27] P4947-4948
Numbers in square brackets refer to the bibliography.			

5.3.2 Impact on electrical equipment

5.3.2.1 Generator and electric motor

1) Motor loss and temperature rise

When unbalanced phase voltages are applied to three-phase motors, this creates additional negative-sequence currents, increasing the heat losses primarily in the rotor. When single-phase power is used, the most severe condition occurs. Figure 2 illustrates the recommended derating for motors as a function of percent phase-voltage unbalance.



IEC

Figure 2 – Derating factor for motors operating with phase voltage unbalance

Quantitatively, negative sequence considerations result in the following:

Positive sequence impedance is predominately the effective rotor resistance R_r/S . With S normally 2 to 5 percent, this becomes 20 to 50 times R_r . Negative sequence slip because of the reversed rotation of the resulting flux is: $S_- = -2 + S_+ \doteq -2$. Because of this negative slip, the resulting high rotor frequencies of 115 to 120 Hz leads to skin effects that increase rotor resistance to these frequencies by up to five times its low-frequency value. The same phenomenon may also reduce rotor high-frequency inductance to 1/2. Thus the effective rotor resistance $R_r/(-2)$ is only 1/8 to 1/20 the effective full load (positive sequence) value. This leads to a motor negative sequence impedance of about 80 percent of its locked rotor impedance, and a small negative torque of 1/2 to 5 percent of the positive value.

Rotor losses increase more than stator losses. They may be approximately five times greater for a given negative sequence current than positive because of the higher negative sequence resistance.

The positive and negative sequence effects can be treated separately and then added together to obtain the motor's total response to a given set of input conditions. This independence is a result of the motor network's linear nature. It is slightly influenced by conductor saturation and changing resistance as a result of temperature rises. Thus, a 10 % negative sequence current would result in an increase of stator losses of $(0,10)^2$, or 1 %. However, if this current is in phase with the positive sequence current in a single-phase winding, the loss in this winding becomes $(1 + 0,10)^2 = 1,21$, or a 21 % increase.

Under unbalanced conditions, the temperature profile will differ significantly between stator and rotor, rotor parts, and stator phases than under balanced conditions causing the same total motor loss.

Table 4 summarizes a number of these effects for small unbalances. The data is a magnified version of the NEMA (National Electrical Manufacturers Association) illustration. As a composite of numerous motors, such a table cannot be precise. It is based on the following assumptions: motor starting inrush is five times the full load, negative sequence impedance is 80 % of locked rotor impedance, and negative sequence rotor resistance is five times the DC value. The losses in the maximum stator phase are determined by the fact that the negative sequence current is in phase with the positive sequence current during that phase.

Table 4 – Effect of voltage Unbalance on motors at full load

Voltage unbalance (percent)	0	2.0	3.5	5.0
Current, negative sequence (percent)	0	15	27	38
Current, stator (rms percent)	100	101	104	107.5
Increase in losses (percent)				
Stator average	0	2	8	15
Stator maximum	0	33	63	93
Rotor	0	12	39	76
Total motor	0	8	25	50
Temperature rise (°C)				
Class A	60	65	75	90
Class B	80	86	100	120

2) Winding life

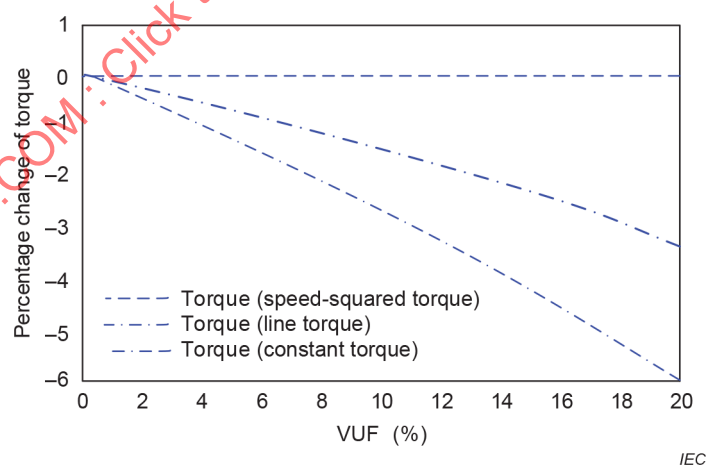
One potential issue that may arise from unbalanced voltage operation is higher temperatures, which dramatically stress the insulation system and shorten winding lives. A popular "rule of thumb" is that for every 10 degrees Celsius warmer a motor runs, its life is shortened by 50%. The life time is determined by Formula (12).

$$\text{Hours of Life} = A \times 0,5^{(T_m - T_{ref})/10} \quad (12)$$

3) Torque

For induction motors, the quality of supply voltages can significantly affect the overall performance of the motor. Undesired unbalanced voltages have negative effects on induction motors. The unbalanced voltage supplied to the induction motor may cause problems such as excessive heating due to more losses, over-voltages, mechanical oscillations, acoustic noise, decreased torque, and shortened induction motor life.

Figure 3 shows the percentage changes in torques of induction motor.

**Figure 3 – Percentage changes in torques of induction motor**

5.3.2.2 Transformer

1) Hot-spot temperature rise

According to the statement in Table E.1 of IEC 60076-7:2018 and the research in [10]¹, the hot-spot to top-oil (in tank) gradient for distribution transformers can be approximated by 23 °C, and $T_{\text{hot-spot}} = T_{\text{top-oil}} + T_{\text{rise hot-spot}}$. For distribution transformers, the top-oil temperature rise can be taken as uniform within the tank. According to IEC 60076-7:2018, Equation 5 and Table E.1, temperature rise can be approximated by:

$$T_{\text{rise hot-spot}} = 55 \left(\frac{1 + 5K^2}{1 + 5} \right)^{0.8} \quad (13)$$

Where $T_{\text{rise hot-spot}}$ represents the temperature rise of hot-spot temperature; K is the load factor for each phase (RMS phase current as a fraction of nominal current). If three phases are unbalanced, additional transformer losses occur especially when calculation is based on one-phase maximum current. This phenomenon exerts errors in calculating hot-spot temperature. The load factor K in (13) replaces $\sqrt{1 + \frac{\gamma_a^2 + \gamma_b^2 + \gamma_c^2}{3}} K_{\text{av}}$. Then, the $T_{\text{rise hot-spot}}$ under three-phase unbalanced meets:

$$T_{\text{rise hot-spot}} = 55 \left[\frac{1}{6} + \frac{5}{6} \left(1 + \frac{\gamma_a^2 + \gamma_b^2 + \gamma_c^2}{3} \right) K_{\text{av}}^2 \right]^{0.8} \quad (14)$$

where $K_{\text{av}} = I_{\text{av}} / I_R$; $\gamma_a, \gamma_b, \gamma_c$ are the phase current unbalance of phase a , b , and c .

According to Formulae (12), (13) and (14), it is clear that the transformer temperature is increased due to voltage unbalance, thus reducing the transformer's insulation life.

2) Insulation life

Transformer hot-spot temperature is the key to determining its life and load capacity. When three phases are unbalanced, the overload phase generates heat and the transformer's internal temperature is uneven during operation, causing insulation ages to decrease. Overall, the insulation aging is severely reduced at the hot-spot temperature location, which causes the transformer lifespan to decrease.

When $T_{\text{rise hot-spot}}$ increases due to the voltage unbalance, $T_{\text{hot-spot}}$ will also increase. The accelerated aging factor denotes a ratio between hot-spot temperature and base-spot temperature. The accelerating aging factor FAA can be obtained through:

$$F_{\text{AA}} = 2^{\frac{T_{\text{hot-spot}} - 98}{6}} \quad (15)$$

where F_{AA} represents the accelerated aging factor to calculate the transformer lifespan reduction; $T_{\text{hot-spot}}$ is the hot-spot temperature of the oil-immersed transformer.

5.3.2.3 Wind farm

In general, unbalanced grid voltage will cause unbalanced winding heating of the wind turbine. Wind turbine's electromagnetic torque also produces a frequency multiplier, causing mechanical vibration of generator shaft. In severe cases, grid voltage unbalance may cause wind turbine to shut down and cause damage to electrical equipment.

5.3.2.4 Reactive compensation equipment

The power network voltage imbalance will affect the output characteristics of the reactive power compensation device, and when the long-term over-voltage resulting from the voltage

¹ Numbers in square brackets refer to the Bibliography.

imbalance reaches 110 % of its rated voltage, the equipment may be out of operation. In the case of asymmetric power supply voltage, the intersection of positive and negative sequence components of current and voltage causes fluctuation with second harmonic in the instantaneous active power and instantaneous reactive power of STATCOM output, and an instantaneous active power fluctuation with second harmonic will also cause capacitor voltage fluctuation with the same frequency. Protection relay settings will also affect reactive compensation equipment performance. The smaller the set-value, the more sensitive the protection is. However, the likelihood of misoperation is higher. Thus, when designing the unbalance protection setting value, it is necessary to ensure sensitivity and protection will not be misoperating under these inherent unbalance conditions.

Simultaneously, the STATCOM inverter voltage output contains not only the positive sequence component, but also the fundamental wave negative sequence and the third harmonic component. Therefore, when the voltage is asymmetric due to the negative sequence component, the DC capacitance at both ends of the double-FM wave voltage is mapped to the inverter output via the switching function. The output voltage contains the fundamental frequency's 3-fold negative sequence and harmonic component, where the output current also contains the fundamental wave's negative sequence and third harmonic current. Moreover, due to the over-current of the third harmonic current, a large number of negative fundamental wave sequences can easily cause STATCOM device to quit operation.

5.3.2.5 Adjustable speed drive

Input-voltage unbalance can have serious effects on adjustable speed drives (ASDs), including abnormally low input line power factor, high input-current harmonic distortion, over-stressed DC-bus capacitors, high pulsating torque, and motor heating. Resulting in reduced power capabilities of the adjustable speed drive (ASD).

Most of the three-phase ASD systems are equipped with a three-phase diode rectifier as a front-end AC-DC conversion stage. During voltage unbalance events, three-phase diode rectifiers may enter single-phase operating mode (depending on the load level and unbalance level) which can generate low-order harmonic components in the DC-link voltage (second harmonic, fourth harmonic and fundamental). These low-order harmonics result in an undesirable impact on electrothermal stresses and thus the reliability of DC-link capacitors. Figure 4 shows the standard drive with DC-link LC filter under 5 % grid voltage amplitude unbalanced condition.

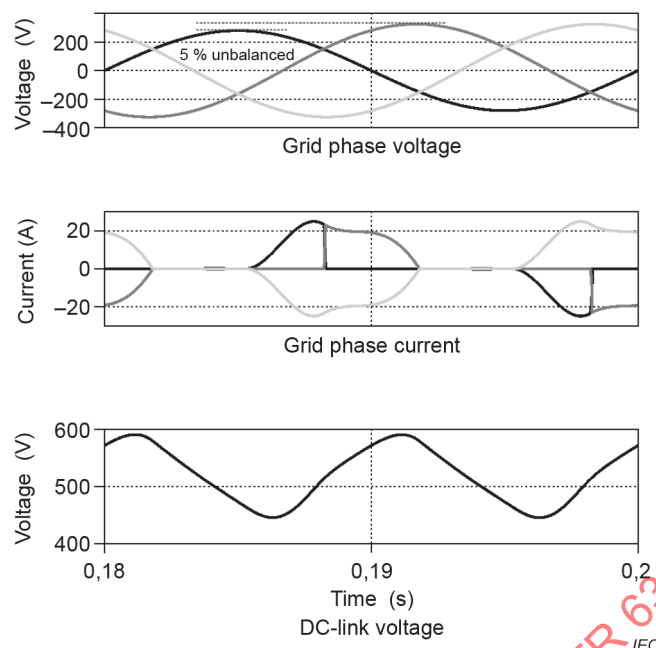


Figure 4 – Standard drive with DC-link LC filter under 5 % grid voltage amplitude unbalanced condition

5.3.3 Impact on power system

5.3.3.1 Relay protection

Power line distance protection or negative-sequence protection equipment often starts due to power unbalance characteristics. The operators choose to block the delay protection when the protection impedance element does not need to operate. During this period, if a fault occurs in the corresponding protection area, the protection device may refuse to operate, causing an override trip event and expanding the outage area. On the other hand, since the negative-sequence protection equipment starts, this event can cause the entire set of protective devices to malfunction, especially when system oscillation or other occasional factors, e.g. voltage collapse, occur.

In addition, the unbalance voltage may also cause devices of transformer negative over-current protection, generators negative over-current protection, bus-differential protection, high-frequency phase differential protection, and distance protection, abnormal starts or even tripping. It might be noted that the negative sequence protection of generators or other electrical equipment could not be considered a malfunction under the influence of harmonics and negative-sequence.

5.3.3.2 Transmission losses

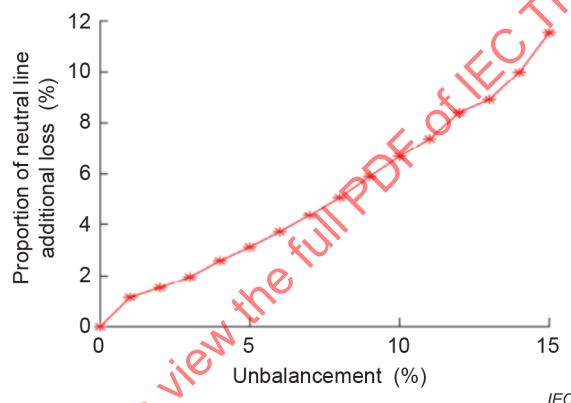
In the neutral point voltage imbalance, the neutral current through the neutral wire loop will result in additional losses due to the three-phase four-wire system.

The line loss will increase with the three-phase current unbalance. When the current three-phase unbalance reaches 15 %, the line loss increases by 4,8 %. Table 5 shows laboratory measurement results:

Table 5 – Line loss and additional loss increase under three-phase current unbalance

Unbalance / %	Line loss / W	Additional loss increment / %	Unbalance / %	Line loss / W	Additional loss increment / %
0	4 416	0	8	4 517	2,29
1	4 427	0,25	9	4 535	2,69
2	4 441	0,57	10	4 545	2,92
3	4 458	0,94	11	4 563	3,33
4	4 470	1,22	12	4 576	3,62
5	4 482	1,50	13	4 591	3,96
6	4 496	1,81	14	4 609	4,37
7	4 508	2,08	15	4 628	4,80

The proportion of additional neutral line loss is positively correlated with three-phase unbalance. When the unbalance increases to 15 %, the proportion of additional neutral loss reaches 11,54 %. Figure 5 shows a lab's measurement results curve:

**Figure 5 – Proportion of neutral line additional loss (%)**

5.3.3.3 Voltage deviation

The voltage unbalance may cause voltage deviation in a low-voltage supply network where transformer type Yyn0 is often introduced. When the three-phase load is balanced, the impedance of the whole system at each phase is balanced if the neutral point of the high voltage side is neither grounded nor connected to upstream power transformer neutral. The neutral point of the high voltage side of the Yyn0-type transformer locates at the central position N of vector triangle of phase voltage shown in Figure 6. When voltage unbalance occurs, the system's phase-impedance is unbalanced, leading to a neutral point shift. In particular, the position N1 denotes the unbalance degree of the three-phase load. This shift rises from the blocking of zero-sequence component and hence causes the cross-linked zero-sequence flux. Due to the magnetic circuit wye structure, this flux brings a neutral point shift. Neutral's shift direction indicates peak phase load, i.e. the smallest phase-impedance. This phase's voltage amplitude decreases, and the other two phases increase, see Annex B for demonstration by simulation. This phenomenon causes voltage deviation in the rural supply network. The Dyn11 type transformer can be applied to handle neutral point shift issues.

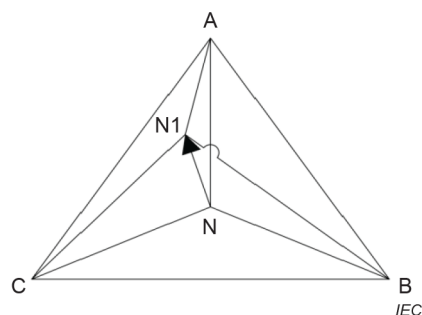


Figure 6 – Neutral shift vector diagram

5.3.3.4 Impact of flicker and rapid voltage change (RVC)

Voltage fluctuations and rapid voltage change cause impacts on numerous electrical equipment such as illumination equipment, precision processing equipment, induction motor, capacitor, and adjustable speed driver. Some system aspects also need attention.

The reference documents on impact of flicker and RVC are listed in Table 6.

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Table 6 – Reference documents on the impact of flicker and RVC

Equipment		Impact description	Reference
Electrical equipment	Illumination equipment (traditional florescent, energy saved light, LED)	- Flux fluctuation - Light flicker - Affect human vision (e.g. asthenopia) and cause health impacts such as photosensitive epileptic seizures. - Stroboscopic effects can introduce workplace risks particularly where rotating machines operate.	Ref. [28]P12
	Precision processing equipment (Numerical control machine)	- High vibration and noise of motor - Data loss caused by CNC crash - Malfunction of relay protection - Out of control of the numerical control system	Ref. [29]P25
	Induction motor	- Losses increase - Temperature rise - Energy efficiency decrease - Shorten insulation life	Ref. [30]P3 Ref. [31]P36
	Capacitor	- Ripple current dramatically increase - Temperature rise - Lifetime reduced	Ref. [32]P3-4
	Adjustable speed driver	- Rectifier capacitor RMS and peak currents increase - Trip due to the operation of the thermal protection	Ref. [33]P257
Power system	Transmission and distribution losses	Losses increase due to equipment exit	Ref. [34]P1-2 P1-2
	Reactive power compensation equipment	- Cause the fluctuation of DC-link voltage and depress the performance of equipment - Cause the exit of equipment	Ref. [35]P1744-1745 Ref. [36]P992 P992
Numbers in square brackets refer to the Bibliography.			

5.3.4 Impact on electrical equipment

5.3.4.1 Illumination equipment

When the supply voltage of lighting equipment fluctuates with time, the most direct effect is the obvious light flux fluctuation, which results in the light flicker. Then human vision is affected, leading to a sense of visual discomfort and asthenopia (i.e. eyestrain). Flickering lights can also cause photosensitive epileptic seizures in susceptible persons and stroboscopic effects (noting that stroboscopic effects pose a danger in industrial settings due to the possibility that rotating machinery can appear stationary).

The ballasts of fluorescent lamps are sensitive to the supply voltage. They provide the starting voltage and operating voltage for fluorescent lamps. In addition, they can also play a role in limiting the working currents of fluorescent lamps. If the supply voltage fluctuates rapidly, the ballasts will be damaged, and thus the life of fluorescent lamps will be shortened.

Generally, the power supply part of CFL and LED is sensitive to supply voltage quality. Fast voltage fluctuation and harmonics stress DC capacitor and reduce its lifespan.

5.3.4.2 Precision processing equipment (numerical control machine)

Some precision machinery and test instruments have strict power voltage requirements. Excessive voltage variation will damage equipment, affect accuracy, and cause errors, leading to severe accidents. On CNC machine tools, voltage fluctuation has the following effects:

- Unsteady operation of the motor and violently shaking.
- Crash and reset, resulting in data loss.
- Cause relay and contactor jitter or malfunction.
- Servo drive DC bus voltage instability, resulting in large motor noise.
- Control system reports over-voltage/over-current and even out of control.

5.3.4.3 Induction motor

Rapid voltage changes generate harmonics and inter-harmonics, increase motor loss, and cause motor heating, reducing the motor's energy efficiency and service life.

The energy efficiency of motors is inversely proportional to the frequency of voltage fluctuation, inversely proportional to the square of the voltage fluctuation amplitude, and inversely proportional to the product of the voltage fluctuation frequency and amplitude.

The decrease of induction motor life caused by voltage fluctuation is related to voltage change, modulation frequency and load level. The hot spot temperature indicates the insulation condition and predicts the motor's aging.

5.3.4.4 Capacitor

Operating temperature is the main factor causing the capacitor parameters to degrade, especially the equivalent series resistance (ESR). The ripple current and ambient temperature contribute to the temperature rise of the capacitor. Significant heating-accelerated degradation mechanisms are chemical changes in the oxide layer and electrolyte vapor leakage through the capacitor and seal. Both factors increase ESR over the operating life of a capacitor.

The supply voltage fluctuations lead to a dramatic increase in the electrolyte capacitor peak recharging current at a particular cycle and also cause the cyclic recharging-current RMS value to rise dramatically, so temperature also increase.

Figure 7 shows the relationship between the capacitor peak value and RMS current under different voltage fluctuations.

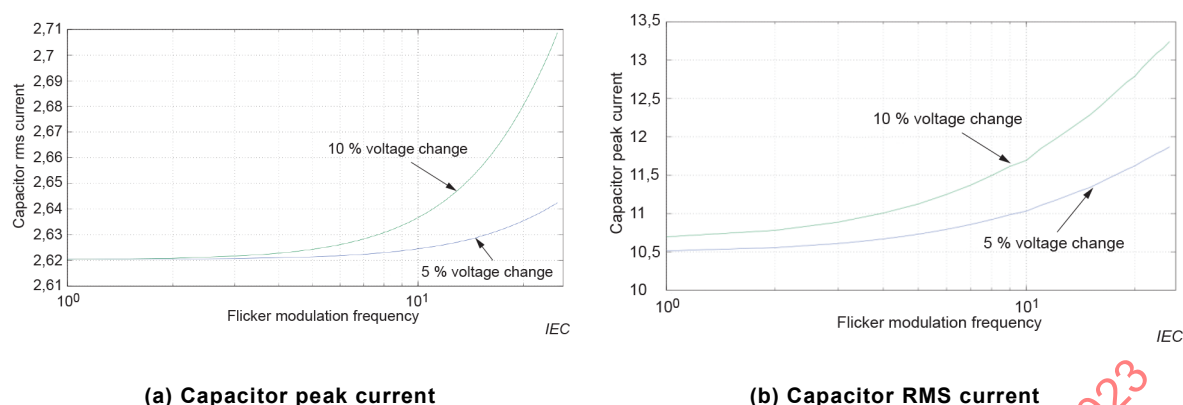


Figure 7 – Capacitor current value under different voltage fluctuations condition

5.3.4.5 Adjustable speed driver

For the ASD open-loop operating mode, a fluctuating supply voltage will increase the RMS and peak currents of the rectifier capacitor. The capacitor RMS and peak currents continues to rise as voltage changes and modulation frequency increases.

The AC supply side fluctuations pass through the rectifier and inverter unit for the combination of ASD and induction motor, resulting in fluctuation in the induction motor stator current, and further increasing the stator current RMS value under full and light load conditions.

Moreover, a large enough variation in voltage amplitude will cause the ASD to trip due to thermal protection action, and the required voltage variation level will decrease with the increase of modulation frequency.

For the ASD in close-loop operating mode (majority case in actual applications), in addition to the impacts mentioned above for open-loop ASD, grid voltage variation may result in over current (case heavy voltage drop and constant power regulation mode).

5.3.5 Impact on power system

5.3.5.1 Transmission and distribution losses

When the network voltage fluctuates leading to system voltage above the rated value, the no-load losses of motors and transformers will be increased, thus leading to the increase of the overall network loss. When the network voltage fluctuates leading to system voltage below the rated value, the currents on transmission and distribution lines with constant power loads will be increased, thus increasing the transmission and distribution losses. Furthermore, the rapid voltage change (RVC) will make the reactive power compensation device unable to work normally, and the reactive power compensation effect will be greatly reduced and the transmission and distribution losses will increase.

5.3.5.2 Reactive power compensation equipment

The voltage fluctuation affects the reactive compensation equipment in the power grid. For shunt active power filters (SAPF), the supply-voltage fluctuation affects the DC-link voltage of the shunt active power filter, which causes the fluctuation of DC-link voltage and reduces equipment performance. However, the strong voltage fluctuation will easily lead to the voltage beyond the safe operating range of the equipment, preventing the equipment from working normally and stopping operation.

5.3.5.3 Impact of harmonics, inter-harmonics and high frequency components

The reference documents on impact of harmonic and inter-harmonic are listed in Table 7.

Table 7 – Reference documents on impact of harmonic and inter-harmonic

Equipment		Impact description	Reference
Electrical equipment	Synchronous generator	• Bring a lot of heat and reduce the efficiency • Distort the armature reaction • Output voltage distortion • Cause severe mechanical vibration • Shorten the life	Ref. [37] P1-4
	Transformer	• Cause additional losses • Shorten insulation life • Cause mechanical vibration noise	Ref. [38] P1-4
	Illumination Equipment	• Cause the flicker of the light • Reduce the service life • Interfere with the normal operation	Ref. [39] P6-7 Ref. [40] P17-20
	DC/AC Electric Motor	• Cause additional losses • Overheating • Destroy the insulation • Decrease the efficiency • Humming noise	Ref. [41] P1-3
	Household appliances (TV/ Refrigerator/PC, etc)	• Change the size and brightness of the TV image • Reduce the service life of the refrigerator • Cause memory loss, program corruption, etc in PC	Ref. [42] P1-4 Ref. [43] P1-6
	Precision processing equipment (Numerical control machine)	• Cause additional losses and result in heating • Produce pulsating torques • Bring electromagnetic interference to control circuit • Causes measurement errors	Ref. [44] P85-86
	Power electronic Converter	• Displace the triggering angular • Thyristor failure • Cause operating errors • Temperature rise	Ref. [45] P1-5
	Switchgear equipment	• Damage the insulation • Generate heat • Malfunction	Ref. [46] P1475-1483
	Reactive power compensation equipment	• Affect compensation efficiency • Shorten the life • Malfunction of the protection device	Ref. [47] P82-84
	Passive filters	• Risk of harmonic resonance if existing excessively even and inter-harmonics	Ref. [49] P241
	Power Cable	• Increase power loss • Produce additional heat • Decrease the expected useful life	Ref. [48] P3-

	Ripple control and Main Communicating Systems	- Affect transmission signal quality and communication clarity - Threaten equipment and personal safety	Ref. [49] P137-138
Power system	Relay protection	- Malfunction - Operation rejection	Ref. [49] P139-140 Ref. [50] P1-6
	Power transmission losses	- Increase transmission losses - Produce harmonic voltage drop	Ref. [51] P19-23
	Harmonic resonance	- Impact the power grid - Damage the electrical equipment	Ref. [52] P875-861 Ref. [53] P31-36
	Sub-synchronous oscillation	- Produce severe torsional vibration of shafting - Reduce the service life of shafting	Ref. [54] P33-34 Ref. [55] P24-30
	Power measurement	- Generate additional torque in the electric energy meter - Cause measurement error	Ref. [56] P944-946 Ref. [57] P1-3
	Insulation aging	Shorten the insulation life of electrical equipment and transmission power cables	Ref. [37] P1-4 Ref. [38] P1-4 Ref. [47] P82-84 Ref. [48] P3-6
Numbers in square brackets refer to the Bibliography.			

5.3.6 Impact on electrical equipment

5.3.6.1 Synchronous generator

When a synchronous generator supplies power to the nonlinear load, harmonic current flows through its armature and this part of the current distorts the armature reaction. The output voltage will also be distorted by the armature impedance.

Harmonic will cause the following consequences on synchronous generators:

- Lead to heavy mechanical vibration along with the electromagnetic torque pulsation of the synchronous generator.
- Reduce the life of the generator.
- Increase the losses and temperature that may even burn the generator and reduce efficiency.

5.3.6.2 Transformer

Figure 8 shows one example about harmonic loss effects on power transformer. A 200 kVA industrial ASD is connected to LV side of 1 MVA MV/LV transformer. Total harmonic distortion of input of the ASD is about 44 %. Under this distortion, the transformer will be derated due to harmonic losses. It is possible to assess actual supply capacity of the transformer either by derating factor = 0,875 (=1/Factor K in reference [38]). That means the transformer can only work at maximum 87,5 % of its rated capacity.

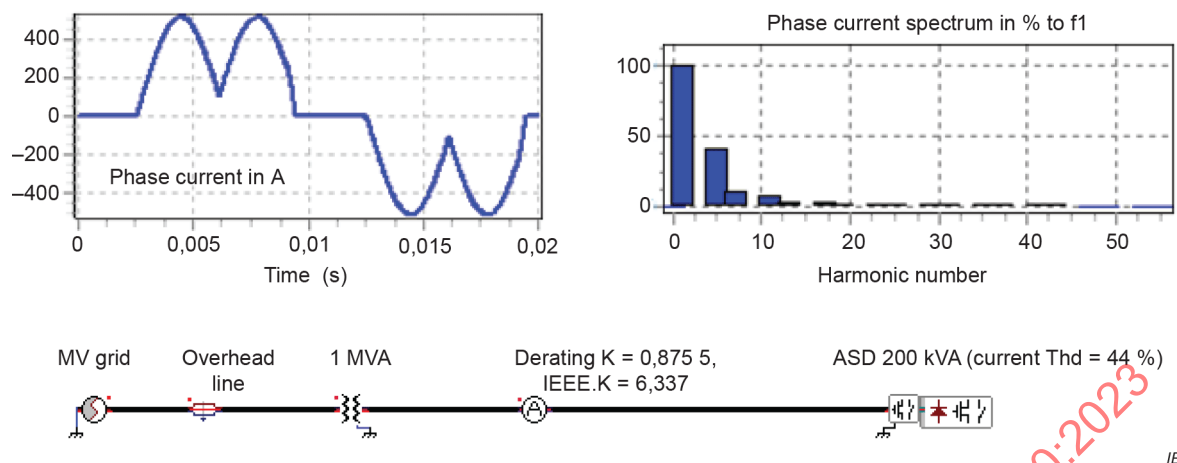


Figure 8 – Current waveform and spectrum, transformer derating due to current harmonic losses up to 2 kHz

5.3.6.3 Illumination equipment

Some illumination devices are very sensitive to fluctuations in peak voltage, such as fluorescent lamps. The harmonic current does not affect the brightness of the fluorescent lamp itself, but causes the flicker of light caused by the inter-harmonic. If the voltage level is increased due to harmonics, the service life of the illumination equipment will be reduced.

The high frequency components interfere with illumination equipment. There are cases in Austria, Germany, the Netherlands and other countries where dimming lamps are turned on and off randomly due to super-harmonic interference. The amplitude of the power line communication signal rises rapidly at the beginning and drops rapidly at the end, making the dimming lamp turn on and off due to the influence of the high frequency components.

5.3.6.4 DC/AC electric motor

The increasing of the harmonics produces an increase of the total copper losses which gives higher winding losses, and the most pronounced effects of harmonic voltage and current on the AC electric motor are the overheating due to the additional losses. Under non-sinusoidal voltage, higher frequency voltage components generate additional losses in the core of the induction motor, which in turn increases core operating temperature and surrounding windings.

Furthermore, note that harmonics increase the machine's current flow and thus increase conductor heating and may destroy cable insulation, leading to other catastrophic faults. In large machines, and due to skin effect, winding resistance is also subject to further increase.

The higher the frequency, the higher the resistance, so when harmonic current flows, the resistance associated with a given harmonic will get increased, amplifying the copper losses and increasing the heating of the machine. In addition to the stator losses, the increasing of harmonics also increases the rotor losses and rises the temperature of the rotor.

According to the impact on the increased heating of the motor, it is clear that the presence of a high level of harmonics increases the additional losses in the stator windings, the motor's steel lamination and the rotor, which in return raises the machine's temperature and decreases the machine's efficiency.

5.3.6.5 Household appliances (TV / refrigerator / PC etc.)

Household appliances are not only small or micro harmonic sources, but also affected by harmonics. When the harmonic voltage affects the peak voltage, the size and brightness of the TV image will be changed. High-frequency electromagnetic interference from communications

equipment can cause flickering light bands in TV images, especially when the TV's own viewing signal is weak. TV sets are sensitive to AM wave voltage. Harmonic voltage or inter-harmonic voltage of 0,5 % can cause the TV image to roll over. When the 5th to 13th harmonic voltage in the power supply voltage of some TV satellite transmitting stations is large, it can affect the signal transmission and cause the abnormal color band on the TV screen. In addition, the high frequency components voltage leads to deviations in the modulation depth and the average light intensity of LED TV.

Household refrigerators are equipped with shunt capacitors to improve the power factor. When the harmonic content of the power supply voltage is high, a large harmonic current will appear, causing overheating and reducing the service life of the refrigerator. When there are many capacitors, there may be resonance risk caused by matching capacitor reactance and power inductance.

Serious harmonic issues affect computer function, including data distortion, memory loss, a program corruption, and UPS failure. Computers are sensitive to voltage spikes when supplied directly from a general source and thus cause damage. The data transmission line is very sensitive to transient process electromagnetic induction, including pulse type, oscillation type and ringing type, which can produce high-frequency induction.

5.3.6.6 Precision processing equipment (numerical control machine)

Harmonics affect the normal operation of precision processing equipment and reduce its reliability. Taking numerical control machine as an example, the harmonic in the power grid is mainly coupled to the numerical control machine through the air switch, and the inverter and servo driver in the numerical control machine's main circuit contains rectifier circuit and inverter circuit, which will generate harmonics in normal operation.

The effects on the work of numerical control machine about harmonic are as follows:

- Increase the copper, iron and dielectric losses of equipment, resulting in overheating.
- Produce pulsating torques due to the interaction of the harmonics-generated magnetic fields and the fundamental.
- High-frequency harmonics bring electromagnetic interference to the internal control circuit.

The voltage distortion with 8 kHz frequency and 5 V amplitude caused by the inverter of numerical control machine is a kind of high frequency component, which can cause periodic fault of numerical control machine.

5.3.6.7 Power electronic converter

Power electronic converter devices switch circuits according to certain rules, which inject characteristic and non-characteristic harmonic current into the system. External distortion caused by harmonic input can also affect the converter's operation.

Harmonics will cause system error and displace the trigger angle. High di/dt and du/dt can cause thyristor failure, and thus affect the converter. The control logic of some controlled rectifiers often causes operating errors due to voltage distortion.

When the input harmonic frequency is higher, which is the high frequency components, the capacitance in the power electronic converter circuit will appear low impedance characteristics, producing high-frequency current, leading to temperature rise of the capacitor, affecting the converter's normal operation and life.

Power electronic converters such as those used in EV are also sensitive to even voltage harmonics.

5.3.6.8 Switchgear equipment

Due to the requirement for multiple switching cycles when there is harmonic current, the switchgear equipment produces a high current change rate at start-up, which increases the peak value of the transient recovery voltage and damages the switchgear equipment's insulation.

For some switchgear equipment, such as circuit breakers used for distribution networks, the existence of harmonic current will increase iron loss and generate heat, which will cause problems in the switchgear equipment, preventing it from connecting and breaking the circuit normally, resulting in malfunction.

5.3.6.9 Reactive power compensation equipment

Harmonics will also affect normal operation of reactive power compensation equipment, increasing the risk of harmonic resonance and even causing accidents and becoming fire and safety hazards.

The measured capacitance changes rates of 10 nodes after 1 year and 8 years of operation are given, as shown in Table 8. Long-term operation under large voltage distortion of harmonics will also accelerate capacitor aging and greatly shorten capacitor life. The protective device, such as electromagnetic relay, static relay and microprocessor-based relay, may not be able to protect the equipment, resulting in tripping or malfunction under serious harmonic conditions.

Table 8 – The actual measured capacitance value change rate

Node	1 year after	8 years after
1	0,09 %	-1,95 %
2	0,11 %	-0,89 %
3	0,11 %	-0,43 %
4	0,48 %	-1,42 %
5	0,24 %	-0,84 %
6	0,12 %	-2,38 %
7	0,08 %	-1,57 %
8	0,80 %	-2,01 %
9	0,06 %	-1,76 %
10	0,15 %	-7,86 %

5.3.6.10 Passive filters

Passive filters consist of inductance, capacitance and resistance components, and control harmonics through parameter tuning. Compared to other harmonic control methods, the passive filter has a simple working principle and structure that can compensate for both harmonics and reactive power. Therefore, it has been widely used to compensate for harmonics and reactive power in power systems. But when there are excessively inter-harmonics and the frequency of this inter-harmonic is lower than the frequency of the harmonic to be filtered by the passive filter, the passive filter branch impedance is capacitive, while the system impedance is inductive, may cause harmonic resonance and overloading of the passive filter.

5.3.6.11 Power cable

Overhead lines use bare conductors and are obviously less vulnerable to harmonics. However, their special construction makes underground cables more vulnerable to harmonics. With the increase of harmonic frequency, the skin effect of the cable conductor is evident, leading to increased conductor AC resistance and decreased allowable cable passing current. Loss and

heat will occur when power cable operates in a harmonic environment, affecting cable service life and power grid safety.

Power loss increases as the harmonics level increases. Thus, the heat produced in these cables also increases as harmonics level increases. This additional heat produced by harmonics increases the temperature. This ultimately results in accelerated thermal aging and decreases power cables expected useful life. Harmonics is one of the major causes of premature power cable failures in real-life situations.

Figure 9, Figure 10 and Figure 11 show the effect of harmonics on per unit power loss in underground cables, the temperature rise in underground cables and the expected useful life of underground cables, respectively. The power loss and temperature rise in power cables is seen to increase exponentially with increased harmonics, and the expected useful life of power cables decreases sharply with increased harmonics.

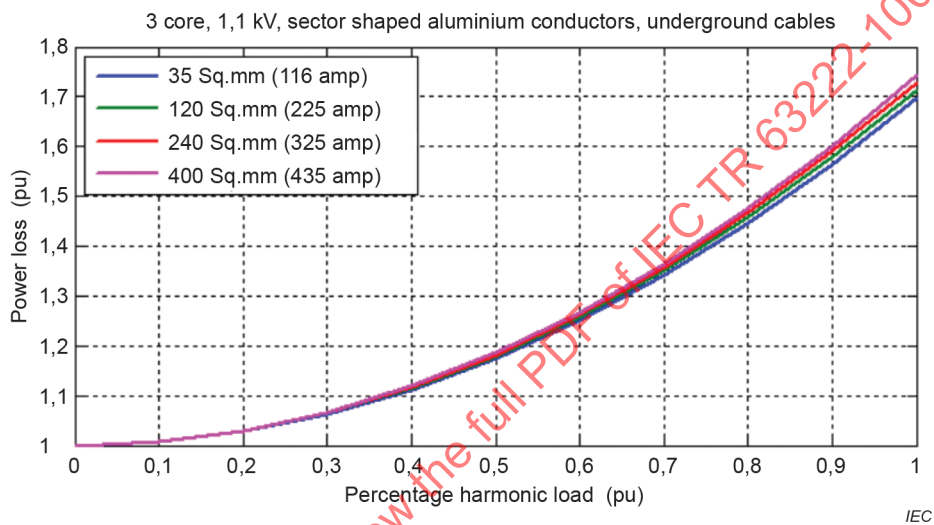


Figure 9 – Effect of harmonics on power loss

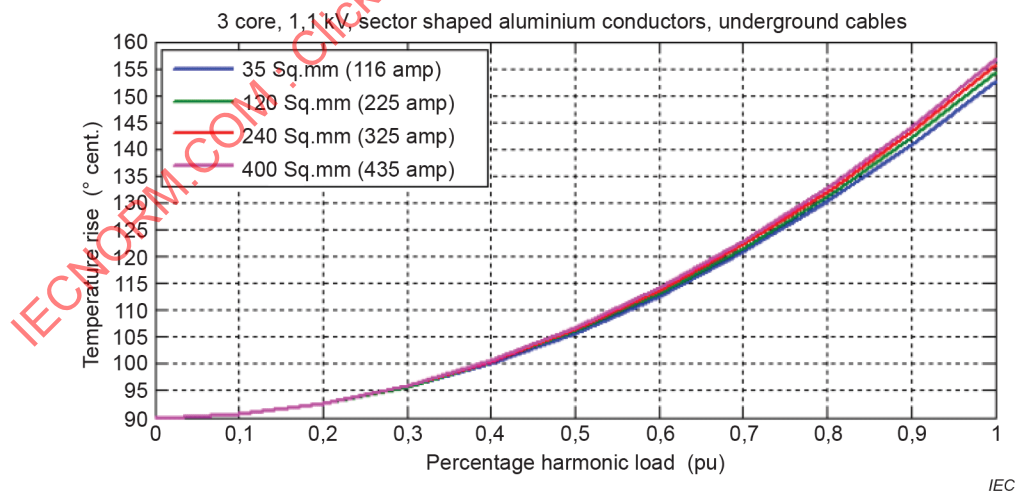


Figure 10 – Effect of harmonics on temperature rise

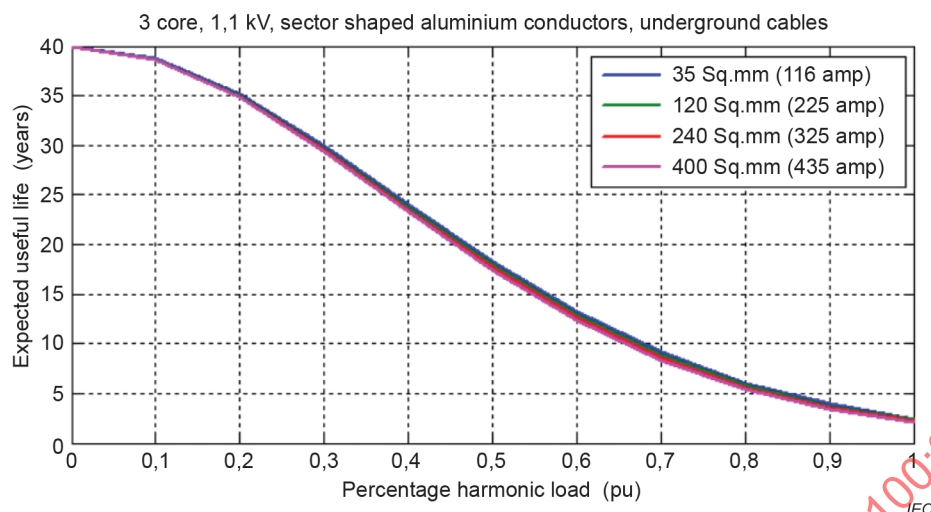


Figure 11 – Effect of harmonics on expected useful life

5.3.6.12 Ripple control and main communicating systems

Public networks may be used by the network operators or network users for the transmission of signals. Three types of systems are as following:

- ripple control systems that are used by electrical utilities in public supply networks, in the range of 100 Hz to 3 kHz, generally below 500 Hz, with signals up to 5 % of U_N under normal circumstances and up to 9 % of U_N in cases of resonance;
- power-line carrier systems used by electrical utilities in public supply networks, in the range 3 kHz to 95 kHz, with allowed signal levels up to 5 % of U_N . These signals are strongly attenuated in the network (> 40 dB);
- signalling systems for end-user premises (residential or industrial) in the range of 95 kHz to 148,5 kHz in Europe (ITU region 1), with allowed signal levels up to 0,6 % of U_N or 5 % of U_N , respectively. In some countries/regions the upper frequency is 500 kHz, with allowed signal levels between 2 to 0,6 mV.

For more information about the percentage values of mains communicating voltage, refer to IEC TS 62749.

The impact of high frequency components on communicating voltage systems is mainly reflected in their interference with communication lines, i.e. ripple control systems. This interference will not only affect the quality of transmission signal and the clarity of communication, but also, in serious cases, due to the combined effect of harmonic and fundamental waves, it will cause telephone ringing, and even threaten the safety of communication equipment and the person.

Usually, the working frequency range of the audio channel is less than 3 500 Hz, and many harmonics of the power supply system are in this frequency range. Harmonic will produce static and electromagnetic induction to the adjacent communication lines. Because the power levels of power lines and communication lines are very different, harmonics in power supply system will cause noticeable, sometimes even unacceptable, telephone noise.

Recent main communicating systems used in smart grids are often less than several hundred kHz (Power Line Carrier systems for grid control and electric meter reading), i.e. main communicating systems use the same frequency range of the high frequency components. Today, compatibility voltage levels less than 150 kHz have been well defined in IEC 61000-2-2; IEC TS 62749 also defines the relevant recommended values at power supply terminals, but the definition of relevant emission limits for equipment in this frequency range is ongoing work

within CISPR and IEC. In any case, excessive levels of on-site voltage the high frequency components may deteriorate the quality of MCS.

5.3.7 Impact on electrical equipment

5.3.7.1 Relay protection

Whether in the normal load state or in the transient process, the system harmonics affect the relay from various aspects, which may cause the relay to malfunction or refuse to operate. Harmonics have different effects on various types of relays and devices:

For the electromagnetic relay, the relay act relying on RMS values, therefore, it may malfunction under rich harmonics condition.

For induction relay, the harmonic current magnitude and phase angle will have the impact on its operation.

5.3.7.2 Power transmission losses

The impact of harmonic current on power transmission systems is to increase transmission losses and produce harmonic voltage in the power grid, thus reducing voltage waveform quality.

Indeed, when the harmonic current passes through the conductor due to the skin effect, the conductor's effective resistance will increase significantly with an increase in harmonic order and wire diameter, thus increasing the additional loss of harmonic. For example, the AC resistance of 11th, 13th, 23rd and 25th harmonics are 1,78, 1,91, 2,45 and 2,55 times of DC resistance respectively in LGJ-400 conductor.

5.3.7.3 Harmonic resonance

When shunt capacitor compensation equipment is used, in case of the harmonic inductance of the system is equal to the capacitive reactance of the capacitor at certain frequency, resonance will occur. The generation of resonance is unfavorable to the power system and the capacitor itself. Resonance may impact the power grid and damage the electrical equipment due to over-voltage and over-current, even lead transformer aging rapidly, electronic equipment intermittent fault, noise or power generation unit off the grid.

5.3.7.4 Sub-synchronous oscillation

Inter-harmonics are one of the causes of sub-synchronous oscillation of power systems. When the frequency of inter-harmonics matches the natural frequency of the turbine rotor shaft system and has a certain amplitude, it may trigger sub-synchronous oscillation, which will produce severe torsional vibration of the shaft system. If the amplitude of inter-harmonics is not large or the frequency of inter-harmonics is not strictly consistent with the natural frequency of shafting, another form of sub-synchronous oscillation will result in long-term cumulative shafting fatigue and shafting service life.

In sub-synchronous oscillation operation, the energy exchange between power system and turbine generator set is performed at one or more frequencies below the system's synchronous frequency, and a large torque is generated in the shaft, which can lead to cracks or even shaft fracture, or fatigue accumulation caused by the repeated bearing of large torque, which reduces the shaft's service life and further affects the power system's stable operation.

5.3.7.5 Power measurement

For an induction electric energy meter, when only the voltage or current in the grid is distorted, the harmonic cannot produce driving torque. However, harmonic voltage and harmonic current will affect power measurement in the following aspects:

- Under full load conditions, the current harmonic flux causes the current magnetic shunt to saturate prematurely, leading to an increase in current working flux and a positive watt-hour meter error.
- Harmonic voltage and current flux need to produce a self-made dynamic moment of additional torque, causing negative error in the electrical energy meter.
- If the voltage waveform is sinusoidal, and the current waveform is distorted. Due to the non-linearity of the magnetic circuit, components of the same order as the harmonic current flux in the voltage magnetic flux will generate additional driving torque.

When the voltage and current in the power grid are distorted, the total power of the circuit is generally composed of DC power, fundamental power and harmonic power. DC power cannot produce normal torque in an electric energy meter, and it will produce braking torque, which will cause measurement error. Harmonic power cannot be measured accurately, which also leads to the measurement error.

5.3.7.6 Insulation aging

The harmonic voltage in the power grid can sharpen the sine wave, increase the electrical stress of the insulation material, produces local overheating and increases noise, accelerating insulation aging. The power cable resistance will also increase with frequency increasing due to the skin effect and proximity effect caused by harmonics, resulting in overload and overheating of lines and damage conductor insulation.

6 Discontinuous power quality disturbances impact

6.1 The impact of voltage dip and short time interruptions

6.1.1 General

Voltage dip may cause numerous electrical equipment/installations/appliances like AC contactors, variable speed drives, logical signal system, power drives, IT equipment malfunction/maloperation.

The reference documents on impact of voltage dip and short time interruption are listed in Table 9.

Table 9 – Reference documents on impact of voltage dip and short time interruption

Equipment		Impact description	Reference
Power system equipment	Wind turbines	- Over-voltage or over-current in the DFIG rotor; - Destroy of rotor side converter.	Ref. [58] P4205
	Transformers	- Significant distortions in transformer waveforms; - Transformer winding conductors and insulation damage.	Ref. [59] P3
	Synchronous generators	- Affect excitation circuit; - Desynchronizing	Ref. [60] P17
End users' devices	Programmable logic controllers	The PS and DI/DO modules of the PLC send out incorrect control signals.	Ref. [61] P1
	AC contactors	- Traditional electromagnetic AC contactors (ACC) unpredictable trips. - Burnt control coil.	Ref. [62] P3910
	Adjustable speed drive	- The inverter trip; - Controller or protection trip; - Over current trip or fuse blowing during post dip; - Drop of speed or torque variations.	Ref. [63] P551 Ref. [64] P506
	IT and process control equipment	- Equipment failures; - Safety or other implications.	Ref. [60] P16
	Power drive systems	- The inverter trip; - Controller or protection trip; - Over current trip or fuse blowing during post dip; - Drop of speed or torque variations. - A reduction in the power that can be transferred to the motor and the driven equipment; - Loss of control. - Mechanical vibration.	Ref. [60] P17
	Lighting	- High-pressure discharge lamps are extinguished; - Require several minutes to restart. - Short life time and damage to lamp	Ref. [60] P18
Numbers in square brackets refer to the bibliography.			

6.1.2 Impact on power system equipment

6.1.2.1 Wind turbines

Compared with other renewable energy sources, wind power generation has higher energy efficiency and economic feasibility. With increasing wind power capacity, unexpected failures in wind turbines have a significant influence on the power system stability. Small capacity wind turbines are designed to stop working during specific system disturbances, because when the connection point voltage falls below a certain level, normal wind turbine operation is not guaranteed. However, disconnecting a turbine may cause overloading of other generators. This situation can lead to cascading generator failure, and instability of the whole system. The most common type of wind power generator is doubly-fed induction generators (DFIGs), which are sensitive to grid disturbances, particularly voltage dips. Sudden voltage dips at a wind turbine connected point can lead to over-voltage or over-current in the DFIG rotor, and the overload

may destroy the rotor side converter (RSC). Generally, the trip characteristics of wind turbines can be represented by the low voltage ride through curve.

6.1.2.2 Transformers

Voltage dip can cause significant distortions in transformer waveforms (flux, magnetizing current, output voltages and input/output currents). The peak phase current during voltage recovery stage becomes more severe with larger voltage dips. Such excessive peak currents may damage transformer winding conductors and insulation. The point-on-voltage waveform as determined by the starting dip angle introduces a DC component in the current and flux waveform, which influences the recovery behavior. The ending angle determines the initial offset of transformer phase fluxes and can cause severe core saturation, forcing undesired distortions in current waveform.

6.1.2.3 Synchronous generators

The operation of a synchronous motor is defined on the output side by torque and speed, and on the input side by voltage and active power. Flux, reactive power and internal rotor angle are variables that are linked to the voltage and torque. The voltage dip can be tolerated provided a new, stable operating conditions are established. This is generally the case for dips presenting a residual voltage of 75 % or 80 % (positive sequence). In addition, the excitation circuit may be affected, and could be considered. More severe conditions prevent new stable operating conditions from being established, and create a loss of synchronism by increasing the rotor angle up to the limit of stability. Whether this critical angle is reached depends on the duration of the voltage dip, the level to which the voltage is reduced and the mechanical time constant. The complete analysis is complex and must take into account the damping cage, which can develop an asynchronous torque.

6.1.3 Effects on end users' devices

6.1.3.1 Programmable logic controllers (PLC)

Programmable logic controllers (PLCs) are the automation backbone of industrial sectors. For example, a large automotive paint-drying process utilizes approximately 50 AC drives to control large fans working in pairs. Each pair of fans is controlled and interlocked with other pairs by a PLC. However, the working environment of PLCs is often adverse, particularly when the PLC is directly connected to the utility grid. Many disturbances can be coupled into the internal circuit through the power supply module and lead to an influence on the operation of the CPU. Tremendous economic losses to users can result from a PLC-based system suffering a sudden outage or outputting unscheduled instructions. When large motors start or short-circuit faults occur near the utility grid or internal faults on customer premises (internal faults on customer premises may also lead to voltage dips, swells and transients), the PS and DI/DO modules of the PLC may cause the normal process to be interrupted or may send out incorrect control signals due to voltage dips. In addition, the rated voltage, PLC power and DC bus capacitance will influence the sensitivity of the PLC to voltage dips.

The voltage dip impact evaluation method of the equipment can refer to the above evaluation process and the references in Table 9, and see the Annex for details.

6.1.3.2 AC contactors (ACC)

Compared with semiconductor devices, traditional electromagnetic AC contactors (ACC) are still widely used. Since they have low energy consumption, no conduction direction limitation and cheapness. However, their unpredictable trips under voltage dip result in the interruption of the production process, causing serious economic loss to users.

The voltage dip impact evaluation method for ACC can refer to the references in Table 9, and see the Annex for details.

6.1.3.3 IT and process control equipment

The principal functional units of IT and process control equipment require DC power supplies, and these are provided by means of power supply modules which convert the AC supply from the public power supply system. It is the minimum voltage reached during a voltage dip that is significant for the power supply modules. Figure 12 shows the well-known information technology industry council (ITIC) curve for minimum immunity objectives concerning dips (It also includes voltages above the normal range.). The user of the equipment must consider whether the consequences of dips that are more severe than shown by the curve are such that additional measures are necessary in order to maintain satisfactory performance. Depending on the application of the equipment, failures can have safety or other implications. Traffic signaling failure is one of many possible examples.

To evaluate the impact of a voltage dip, the ITIC curve for minimum immunity objectives concerning dips of this equipment can be obtained by voltage dip tests.

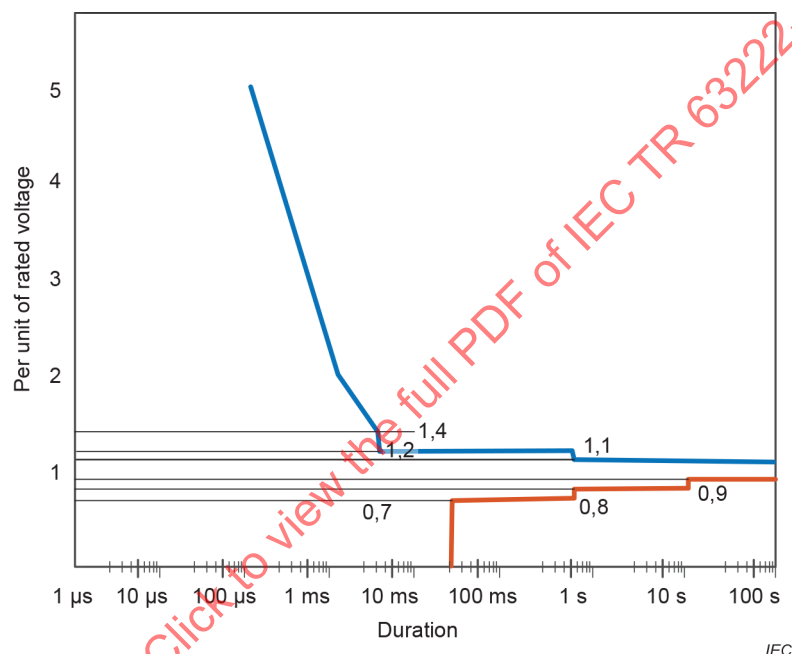


Figure 12 – ITIC (CBEMA) curve for equipment connected to 120 V 60 Hz systems

6.1.3.4 Power drive systems

Power drive systems (PDS) are sensitive to voltage dips. The effects of voltage dips and short interruptions can be quite complex because the component parts must be considered as well as the complete assembly. Such systems generally contain a power converter/inverter, adjustable speed drive (ASD), motor, control element and a number of auxiliary components. The effect on the control element is critical, since it has the function of managing the response of the other elements to the voltage dip or short interruption. The reduction in voltage results in a reduction in the power that can be transferred to the motor and driven equipment, leading to a loss of control. Voltage dips also cause decreased DC-bus voltage in the ASD (controller or protection trip) and increased AC currents during the dip or the post dip (over current trip or fuse blowing). Regenerative converters might be sensitive or require special management, especially the voltage dip or short interruption that occurs during reversed power flow.

To evaluate the impact of voltage dip, the ITIC curve for minimum immunity objectives concerning dips of this equipment can be obtained by voltage dip tests in the above evaluation process.

6.1.3.5 Lighting

High-pressure discharge lamps are extinguished by voltage dips that reduce the voltage to less than 90 % of the nominal value. As a result of the consequent cooling and loss of pressure, they may require several minutes to restart.

To evaluate the impact of voltage dips, the ITIC curve for minimum immunity objectives concerning dips in this equipment can be obtained by voltage dip tests in the above evaluation process.

6.1.4 Useful impacts assessment indices

6.1.4.1 User Equipment Dip Sensitivity Index

There is an uncertainty involved with equipment sensitivity as equipment may not have a single sensitivity curve but a family of curves inside the region of uncertainty associated with the equipment type. The variation in equipment sensitivity can be represented in terms of a univariate random variable (T) in subregion A, a univariate random variable (V) in subregion B, and a bivariate random variable (T, V) in subregion C (Figure 13) where T and V are assumed to be two statistically independent discrete random variables. T is the voltage duration-threshold varying between $T_{\min}$ and $T_{\max}$ (determined by the protection settings) and V is the voltage magnitude-threshold varying between $V_{\min}$ and $V_{\max}$. Therefore, if $p_X(T)$ and $p_Y(V)$ are the probability distribution functions for random variables T and V , respectively, then the joint probability distribution function for the bivariate random variable (T, V) in subregion C is given by the Bayes rule as follows:

$$p_{XY}(T, V) = p_X(T)p_Y(V);$$

$$T_{\min} \leq T \leq T_{\max}, V_{\min} \leq V \leq V_{\max} \quad (16)$$

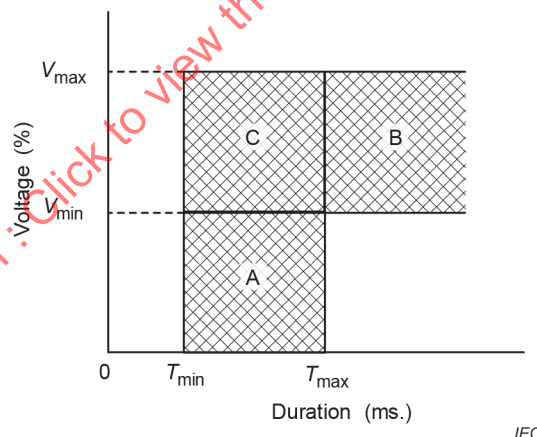


Figure 13 – Region of uncertainty for sensitivity curves of equipment

6.1.4.2 User Process Dip Trips Probability Index

The quantification of expected process trips due to voltage dips over a specified period of time requires knowledge of the mutual connection of the sensitive equipment that controls the process. Sometimes, the tripping of a single piece of equipment may disrupt a complete industrial process (i.e. it is a non-redundant system from a reliability point of view), all of the participating equipment is assumed to be connected in series. The process may be disrupted only if more than one piece of equipment fails/trips (i.e. sufficient redundancy is present, as represented by the parallel connection of the participating equipment). Therefore, the response of a complete process to the voltage dip will depend on the response of the individual equipment/ equipment types participating in the process. The overall probability of the process trip can be determined by knowing the probability of the trip of the individual equipment and

their mutual connections. In general, the probability of a process trip $P_{\text{trip}}(T, V)$ can be written as:

$$P_{\text{trip}} = 1 - \left[\prod_{i=1}^m \left(1 - \prod_{j=1}^n P_{i,j} \right) \right] \quad (17)$$

Where m is the number of series-connected equipment/equipment groups and n is the number of parallel-connected equipment in the i_{th} equipment group. $P_{i,j}$ is the cumulative probability of tripping of the j^{th} equipment of the i^{th} serially connected equipment group.

6.1.4.3 Expected Process Dip Trips Number Index

After calculating the probability distribution functions as discussed above, considering one type of equipment sensitivity at a time, the expected number of process trips are determined as follows:

$$\text{Total process trips} = \sum_T \sum_V P_{\text{trip}}(T, V) \times N(T, V) \quad (18)$$

Where $P_{\text{trip}}(T, V)$ is the trip probability of the process against the voltage dips with dip magnitude V and dip duration T , and $N(T, V)$ is the number of such voltage dips expected at the specified site over a specified period of time.

6.1.4.4 Severity Index

When the dip event is specified in terms of dip magnitude and duration, the effect of the dip on equipment cannot be estimated without prior information about the equipment's voltage tolerance characteristic.

Realising the need for a more general solution, the concept of the voltage dip Magnitude Severity Index (MSI) and Duration Severity Index (DSI) is introduced. Instead of using the magnitude and duration of voltage dips to assess equipment behavior, the magnitude and duration of the voltage dip are first translated into the corresponding MSI and DSI. Different severity indices are thus generated for a given voltage dip for different equipment types. From the equipment point of view, the severity indices give a more sensible representation of voltage dips as they link them to the probability of the failure of the equipment.

MSI and DSI are equipment-level representations of voltage dips. They are based on the fact that voltage dips with a magnitude larger than V_{max} or duration shorter than T_{min} will not cause equipment failure, while dips with a magnitude lower than V_{min} and duration longer than T_{max} will cause equipment failure. The equipment failure probabilities for a voltage dip in these two areas are deterministic, 0 and 1 respectively, and therefore require no further evaluation. The main concern is equipment behaviour for voltage dips that fall into the area of sensitivity curve uncertainty. Using a scale of 0 to 100, with 0 as minimum severity and 100 as maximum severity, assessment of equipment behavior towards voltage dips can be simplified through the implementation of MSI and DSI:

$$\text{DSI} = \begin{cases} 0 & , d < T_{\text{min}} \\ (d - T_{\text{min}}) \times \left(\frac{100}{T_{\text{max}} - T_{\text{min}}} \right) & , T_{\text{min}} \leq d \leq T_{\text{max}} \\ 100 & , d > T_{\text{max}} \end{cases} \quad (19)$$

$$MSI = \begin{cases} 0 & , m > V_{\max} \\ (V_{\max} - m) \times \left(\frac{100}{V_{\max} - V_{\min}} \right) & , V_{\min} \leq m \leq V_{\max} \\ 100 & , m < V_{\min} \end{cases} \quad (20)$$

where d represents the duration of voltage dip. The Combined Severity Index (MDSI) integrates DSI and MSI into a single index to imply the impact of voltage dips and short interruptions as a function of both duration and magnitude severity. Basically, the value of voltage dip combined severity index MDSI translates physical dip characteristics into the level of severity posed by the disturbance:

$$MDSI = \frac{MSI \times DSI}{100} \quad (21)$$

6.1.4.5 Customer Outage Costs (COC) Index

The COC at a load point j supplying ny sectors can be calculated as follows:

$$COC_j = \left(\sum_{y=1}^{ny} E_{jy} \right) \times C_j(r_j) \times \lambda_j \quad (22)$$

Where E_{jy} is the annual energy consumed by sector y ; r_j is the duration of interruption; $C_j(r_j)$ the cost per unit of electricity for duration r_j ; λ is the system fault rate.

A summation of the COC at all of the relevant load points b of a service gives the annual COC due to supply interruptions SCOC as follows:

$$SCOC = \sum_{j \in b} COC_j \quad (23)$$

6.2 The impact of voltage swell

6.2.1 General

Similarly, Table 10 provides and collects information about evaluating the impact of voltage swells on particular devices and power system.

Table 10 – reference documents on impact of voltage swell

Equipment		Impact description	Reference
Electric equipment	Wind turbine	• Lose the decoupling control • Unbalanced power transmission • Over-voltage of DC regulated capacitor • Run off the grid • Mechanical vibration	Ref. [72] P447
	Grid-connected inverter of photovoltaic power station	• The energy flows back from the net side to the machine side • Inverter running out of linear working area • The inverter operates in over modulation working area • The control margin of the system decreases • The inverter run off the grid	Ref. [73] P1
Power system	Renewable energy resource system	• Affect the operation of wind turbine • Affect the grid-connected inverter of photovoltaic power station • The wind farm operating off the grid • The photovoltaic power station operating off the grid	Ref. [74] P447
Numbers in square brackets refer to the bibliography.			

6.2.2 Impact on power system

6.2.2.1 Wind farm

The short circuit fault of electrical equipment is the inducement to the accidents of wind turbines operating off the grid. The lack of LVRT capability of wind turbines in wind farms is one of the reasons for wind turbines off the grid. At the same time, the failure of automatic switching and rapid adjustment of reactive power compensation devices in time leads to the rise of grid voltage in the residual wind farms. The lack of HVRT capability of wind turbines eventually aggravates the evolution of wind turbine off-grid accidents.

6.2.2.2 Photovoltaic power station

When a voltage swell occurs, an over-modulation problem may occur during the HVRT period of the photovoltaic inverter, causing the inverter to go off grid and the photovoltaic power station to go off grid.

6.2.3 Effects on some electrical equipment

6.2.3.1 Wind turbine

Due to its small converter capacity, constant frequency operation under speed change situations, decoupling control of active and reactive power, wide speed range and other advantages, the doubly fed induction generator is widely used in wind generation.

When the grid voltage is disturbed by a temporary rise, the stator flux will generate a positive (forced) component, negative (asymmetric temporary rise) component and DC (free) component, which will generate over-voltage at the DFIG rotor side. The rotor over-voltage causes RSC to lose the decoupling control of DFIG. At the same time, the unbalanced power transmission

between RSC and GSC will further lead to the over-voltage of the DC regulated capacitor between the two converters. Finally, DFIG will run off the grid under the swell disturbance.

6.2.3.2 Grid-connected inverter of photovoltaic power station

The voltage swell makes the energy flow back from the grid side to the generator side, and the inverter breaks away from the linear working area into the over modulation working area, which makes the control margin of the system decrease. It is easy to trigger the system over-voltage and over-current protection, resulting in the inverter off grid.

6.3 The impact of transient over-voltage

6.3.1 General

Transient over-voltage is often associated with transient events. The amplitude of voltage during this period depends on the transient stability of the system and the efficiency of isolating the fault. Flash-over and partial discharge are often observed during transient over-voltage and hence the insulation aging of equipment will be affected. Transient over-voltage may damage electrical equipment's key components and affect their performance after events. Reference documents for impact evaluation of transient over-voltages are listed in Table 11.

Table 11 – Reference documents for impact evaluation of transient over-voltages

Equipment		Impact description	Reference
Electrical equipment	Synchronous generator	Under-excitation limit control (UCL)	Ref. [65] P1863
	Transformers	- Terminals of power transformers are exposed on transient voltages with various shapes and maximal values - Transient over-voltages impact power transformer insulation systems in spite of used over-voltage protection	Ref. [66] P1
	Wind turbine generators	WTGS might trip due to over-voltage protection	Ref. [67] P81
	HVDC	The transient over-voltages which occur during fault conditions on the DC side of a HVDC link will affect the line insulation	Ref. [68] P1
	Reactive power compensation equipment	- Explosion - Burning - Other accidents	Ref. [69] P1
Power system	Insulation aging	- Partial discharges - Insulation aging - Not easily predictable	Ref. [70] P2354
	Flash-over and partial discharge	- Accelerate the aging process - Generate a number of by-products (all types of gas, mechanical particles, etc)	Ref. [71] P1

Numbers in square brackets refer to the bibliography.

6.3.2 Impact on power system equipment

6.3.2.1 Insulation aging

In the design stage, it is difficult to forecast the impact of transients and recurring transients on cable insulation life. If transient over-voltages last a short time, but are repeated frequently during insulation system life, voltage waveform are modified from the sinusoidal typical design reference. Life can be shortened due to both the life law and the inception/modification of the

most important insulation aging mechanism triggered by electric fields, namely partial discharges.

The assessment of the effect of transient over-voltage on insulation can be carried out by using a standard test waveform.

6.3.2.2 Flashover and partial discharge

High-voltage equipment insulation is the most complex and most important part of the equipment. Insulation maintenance and inspection is an important task for reliable device operation. When transient over-voltage occurs and affects operating devices, an intense partial discharge phenomenon occurs in the insulation. In insulation, partial discharges are one of the key ongoing processes, which accelerate the aging process and generate a number of by-products (all types of gas, mechanical particles, etc.).

The assessment of the effect of transient over-voltage on flash-over and partial discharge can be carried out by using standard test waveform.

6.3.3 Effects on some electrical equipment

6.3.3.1 Synchronous generator

In addition to pre-set voltage level control, several other control functions can be performed by synchronous generator excitation systems in electric power plants. The maximum stator current limiter, maximum field current limiter, volt per hertz limiter and under-excitation limit control (UCL) are among them.

6.3.3.2 Transformer

Terminals of power transformers in electrical power systems are exposed to transient voltages with various shapes and maximal values. Voltage waves can pass through the transformer windings and be transferred to other coupled windings at different voltage levels. Transient over-voltages impact power transformer insulation systems. Over-voltage protections are able to reduce peak voltages and discharge energy to preventing malfunctions and accelerated aging. The analysis of over-voltages in winding insulation systems is critical for the proper and reliable operation of transformers.

The assessment of the effect of transient over-voltage on the transformer can be carried out by using standard test waveform.

6.3.3.3 HVDC

High voltage direct current (HVDC) plays the role of the present and future protagonist in electrical power transmission. For symmetrical monopole systems, one of the main issues concerning HVDC systems is the effect of the transient overvoltage which occur during fault conditions on the DC side.

The most meaningful new developments brought by CIGRE TB 496 concern long-term ageing tests on extruded polymer DC cables.

6.3.3.4 Reactive power compensation equipment

The parallel capacitor reactive power compensation system is a main reactive power compensation device at all voltage levels of the power system, especially the distribution system. In system operation, reactive power compensation capacitors cause explosions, burning, and other accidents as a result of a variety of transient over-voltages and over-currents, which disrupt power system operation.

The assessment of the effect of transient over-voltage on reactive power compensation equipment can be carried out by using standard test waveform.

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Annex A (informative)

Case analysis: Voltage deviation impact on power loss

A.1 Loss of low voltage distribution network

A.1.1 Transformer iron loss

The relationship between voltage deviation and transformer iron loss is

$$P_{fe} = \left(\frac{U_1}{U_{TN}} \right)^2 P_0 = \left(\frac{U_N}{U_{TN}} \right)^2 (\beta_1 + 1)^2 P_0 \quad (\text{A.1})$$

where P_{fe} is the actual iron loss of the transformer (MW) at voltage U_1 (kV), P_0 is the rated iron loss of the transformer (MW), and U_{TN} is the rated voltage (kV).

The additional loss of transformer iron loss caused by voltage deviation is:

$$\Delta P_{fe} = (\beta_1^2 + 2\beta_1) \left(\frac{U_N}{U_{TN}} \right)^2 P_0 \quad (\text{A.2})$$

It can be seen from Equation (A.2) that the additional iron loss of the transformer is related to the voltage deviation and the rated iron loss. When the voltage deviation is positive, the additional iron loss of the transformer is non-linearly and positively correlated with the absolute value of the voltage deviation. Otherwise, the additional loss of the transformer is non-linearly and negatively correlated with the absolute value of the voltage deviation.

A.1.2 Transformer copper loss

The impacts of voltage deviation on transformer copper loss depend on the connection load model types, namely constant power load, constant impedance load and constant current load. The equivalent circuit diagram for analysis shown as in Figure A.1 (R and L are connection line resistance and reactance).

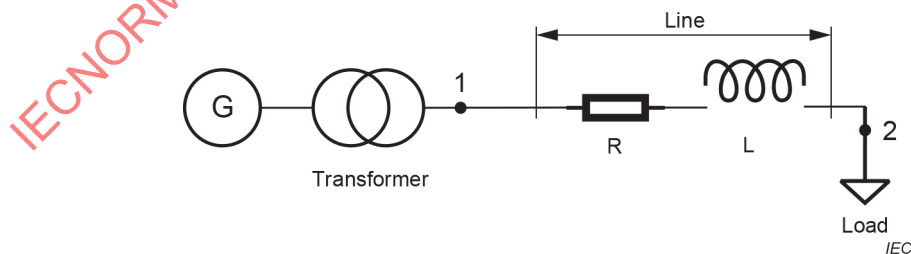


Figure A.1 – Equivalent circuit diagram of low voltage distribution network

1) Constant power load

As shown in Figure A.1, when the load type in the system is only a constant power load, the copper loss in the distribution network is

$$P_C = \frac{P^2 + Q^2}{U_2^2} R_C = \frac{P^2 + Q^2}{(\beta_2 + 1)^2 U_N^2} R_C \quad (\text{A.3})$$

where P_C is copper loss (MW), P is the equivalent load active power at the end of the line (MW), Q is the equivalent load reactive power at the end of the line (Mvar), and R_C is the total resistance of the high and low voltage windings of the transformer (Ω).

Load rate

$$LR = \frac{\sqrt{P^2 + Q^2}}{S_N} \times 100 \% \quad (\text{A.4})$$

where LR is the load rate and S_N is the rated capacity of the low voltage distribution network (the rated capacity of the transformer).

Bringing the Formula (A.4) into the Equation (A.3), the additional copper loss caused by the voltage deviation can be obtained as

$$\Delta P_C = - \frac{S_N^2 (\beta_2^2 + 2\beta_2) LR^2}{U_N^2 (\beta_2 + 1)^2} R_C \quad (\text{A.5})$$

It can be seen from the Equation (A.5) that when only a constant power load is connected to the system, the additional copper loss is related to the voltage deviation. When the voltage deviation is positive, the additional copper loss is negatively correlated with the absolute value of the voltage deviation. Otherwise, the additional copper loss is positively correlated with the absolute value of the voltage deviation.

2) Constant impedance load

When the load type connected to the system is only a constant impedance load, the copper loss in the distribution network is:

$$P_C = \frac{U_2^2}{Z_f^2} R_C = \frac{(\beta_2 + 1)^2 U_N^2}{Z_f^2} R_C \quad (\text{A.6})$$

where Z_f is the impedance of the load (Ω).

The additional copper loss caused by the voltage deviation is:

$$\Delta P_C = \frac{(\beta_2^2 + 2\beta_2) U_N^2}{Z_f^2} R_C \quad (\text{A.7})$$

It can be seen from the Equation (A.7) that when only a constant impedance load is connected to the system, the additional copper loss is related to the voltage deviation. When the voltage deviation is positive, the additional copper loss is positively correlated with the absolute value of the voltage deviation; otherwise, the additional copper loss is negatively correlated with the absolute value of the voltage deviation.

3) Constant current load

When the load type connected to the system is only a constant current load, the copper loss in the distribution network is

$$P_C = 3I^2 R_C \quad (\text{A.8})$$

where I is the load current (kA), R_C is the total resistance of the high and low voltage windings of the transformer (Ω)

It can be seen from the Equation (A.8) that when only a constant current load is connected to the system, the copper loss is independent of the voltage deviation.

4) Integrated load

An integrated load refers to a load that includes constant impedance (z), constant current (I) and constant power (P). When the type of load connected to the system is an integrated load, the copper loss in the distribution network is

$$P_C = \frac{\left[F_{Zp}(\beta_2 + 1)^2 - F_{Ip}(\beta_2 + 1)F_{Pp} \right]^2 P_0^2 + \left[F_{Zq}(\beta_2 + 1)^2 - F_{Iq}(\beta_2 + 1)F_{Pq} \right] 2Q_0^2}{(\beta_2 + 1)^2 U_N^2} R_C \quad (A.9)$$

In the Equation (A.9), F_{Zp} (F_{Zq}), F_{Ip} (F_{Iq}), and F_{Pp} (F_{Pq}) are the active (reactive) proportional coefficients of three types of loads: constant impedance (Z), constant current (I), and constant power (P). P_0 is the active power of the load at the rated voltage, and Q_0 is the reactive power of the load at the rated voltage.

The additional copper loss caused by the voltage deviation is:

$$\Delta P_C = \frac{\left[(\beta_2^4 + 4\beta_2^3 + 5\beta_2^2 + 2\beta_2) F_{Zp}^2 - (\beta_2^2 + 2\beta_2) F_{Pp}^2 + 2(\beta_2^3 + \beta_2^2 + \beta_2) F_{Zp}F_{Ip} - 2(\beta_2^2 + \beta_2) F_{Ip}F_{Pp} \right] P_0^2}{(\beta_2 + 1)^2 U_N^2} R_C$$

$$+ \frac{\left[(\beta_2^4 + 4\beta_2^3 + 5\beta_2^2 + 2\beta_2) F_{Zq}^2 - (\beta_2^2 + 2\beta_2) F_{Pq}^2 + 2(\beta_2^3 + \beta_2^2 + \beta_2) F_{Zq}F_{Iq} - 2(\beta_2^2 + \beta_2) F_{Iq}F_{Pq} \right] Q_0^2}{(\beta_2 + 1)^2 U_N^2} R_C \quad (A.10)$$

It can be known from the Equation (A.10) that when the integrated load is connected to the system, other factors are unchanged, The influence of the voltage deviation on the additional copper loss of the low voltage distribution network is related to the ZIP load proportional coefficients.

As can be seen from the foregoing, the constant current load has no effect on the additional copper loss caused by the voltage deviation. It can be seen from the equation (A.10) that when the additional copper loss is zero the relationship between the ratio of the constant impedance load to the constant power load and the voltage deviation is as shown in Figure A.2.

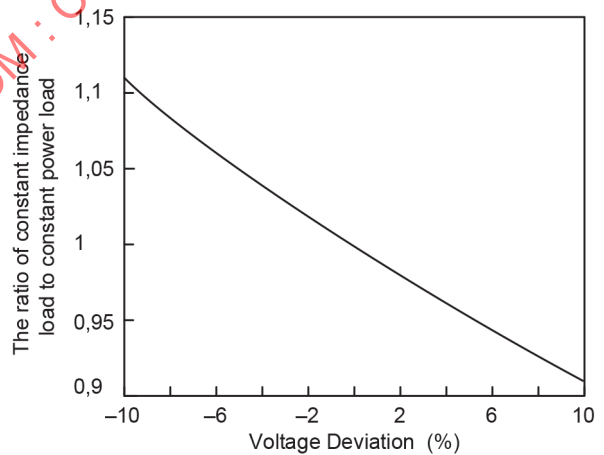


Figure A.2 – The relationship between the ratio of constant impedance load to constant power load and voltage deviation in the connected system when the additional copper loss is 0

As shown in Figure A.2, when the voltage deviation is between -10 % and 10 %, the ratio of the constant impedance load to the constant power load is between 1,11 and 0,9. If the size

of the constant impedance load is close to the constant power load, voltage deviation will have little effect on the additional transformer copper loss.

Assume that the transformer iron loss is constant and the load type and size can be adjusted. When the power supply in the normal operation is positive voltage deviation, adjusting the ratio of constant impedance load to constant power load below the curve of Figure A.2 can reduce the network loss. When the power supply in normal operation is negative voltage deviation, adjusting the ratio of constant impedance load to constant power load above the curve of Figure A.2 can reduce the network loss. That is to say, the appropriate voltage operation level within the allowable range of voltage deviation can be selected according to the load type ratio to reduce the network loss.

A.2 LED Lights

In order to analyze the load characteristics of LED lamps and ensure the authenticity and reliability of experimental data, several different types of LED lamps are selected for experiments. Table A.1 shows the four common household LED lamps on the market. It is typical to select these four kinds of LED lamps for testing, and the test results can represent the performance of common household LED lamps at present.

Table A.1 – Test object parameters

Number	Name	Rated power
1	LED down-light	3W
2	LED ceiling lamp	3W
3	LED chip	12W
4	LED tube lamp	14W

In the experiment, a power analyzer is used to obtain the AC load characteristics of an LED lamp, which is the voltage, current, power and relevant information like waveform.

Four kinds of LED lights are connected to the AC power supply respectively, to ensure that all the experimental conditions are the same. The voltage regulator is used to adjust the AC input voltage. Voltage change step is 10 V, 10 groups of data are recorded for each LED lamp.

Table A.2 lists the recorded data for fluorescent lamps as an example. The U-I and P-U curves of each LED lamp are shown in Figure A.3 and Figure A.4. It seems that these types of LED keep constant power under the tested voltage deviation.

Table A.2 – Raw data of fluorescent lamp under AC power supply

U/V	I/A	P/W
160	0,1 445	13,625
170	0,1 377	13,564
180	0,1 316	13,587
190	0,1 262	13,576
200	0,1 217	13,609
210	0,1 175	13,653
220	0,1 137	13,676
230	0,1 105	13,746
240	0,1 078	13,803
250	0,1 054	13,853

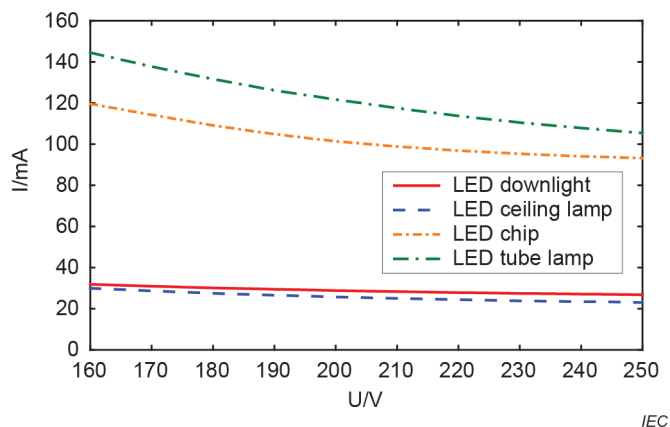


Figure A.3 – U-I curves of four LED lamps

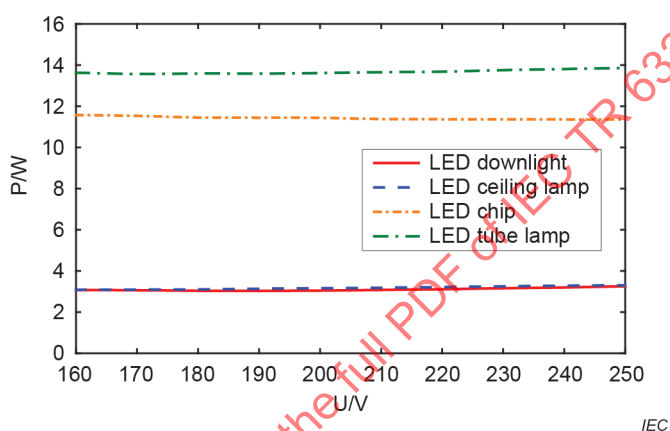


Figure A.4 – P-U curves of four LED lamps

Annex B (informative)

Case analysis: Voltage unbalance impact

B.1 Three-phase unbalance leads to voltage deviation

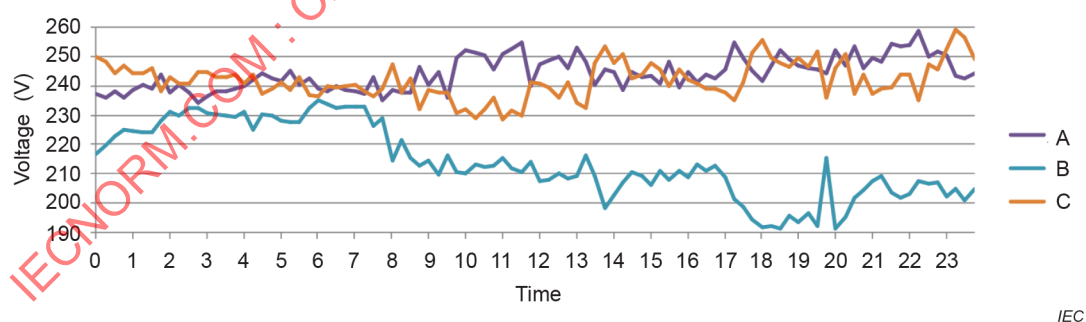
For a rural supply network in China, a Yyn0 type transformer is used for supplying 116 rural local customers. The voltage ratio is 10 kV/380 V (see Figure B.1).



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Figure B.1 – Guowan #2 station

Figure B.2 and Figure B.3 show 24-hour voltage and power curves. Figure B.2 indicates that the maximum phase voltage is 259.1V while the minimum phase voltage is 194V. It is obvious that the three phase voltages are unbalanced, and the three-phase power is also unbalanced.



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Figure B.2 – Voltage curve of Guowan #2 station on January 27

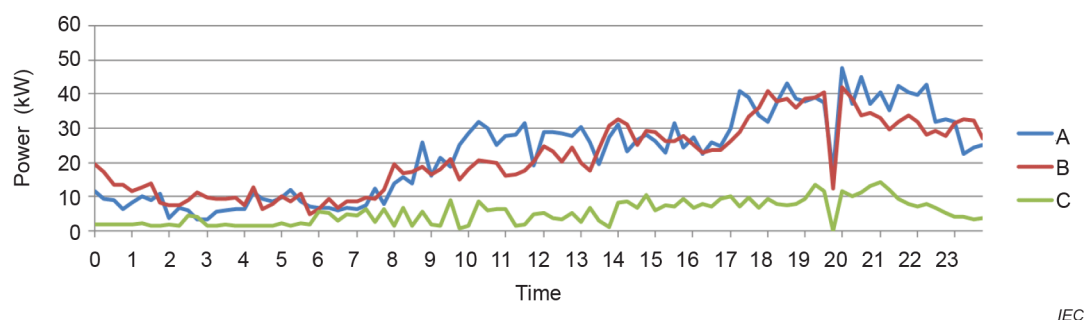


Figure B.3 – Three – phase power curve of Guowan #2 station on January 27

A simulation based on the ATP-EMTP tool was made for comparison Yyn0 with Dyn11 transformer configuration (Figure B.1). The results in Table B.1 demonstrate that transformer connection type can be used to improve voltage balance and further voltage deviation.

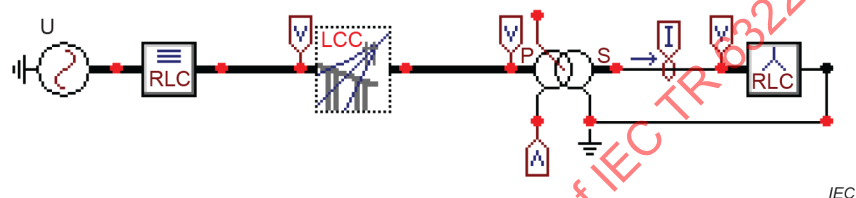


Figure B.4 – Simulation model

Table B.1 – Simulation results of output voltage

No.	Active power/kW			Output voltage of transformer/V						The neutral voltage of Yyn0-type transformer/V
	Phase A	Phase B	Phase C	Yyn0			Dyn11			
				Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	
1	10	10	10	224,4	224,5	224,5	224,7	224,8	224,7	0,22
2	12	8	10	218,9	226	228,4	223,5	225,9	224,6	112,3
3	15	5	10	210,9	228,7	234,5	221,8	227,7	224,7	306
4	18	2	10	203	231,7	240,5	220	229,5	224,7	489

B.2 Increases the loss of power network

The main purpose of this clause is to characterize the impact of unbalance on network losses. Three LV networks are used with load capacity of 6 kVA, 18 kVA and 180 kVA, and Q/P ratio is set to be 0,2.

The unbalance factor here is defined in Formula (B.1) based on the three phase active power, it is different from the classic definition defined by IEC TS 62749 (the ratio between negative and positive component magnitude).

$$D(\%) = 1 - [p \times \alpha + (1 - p) \times \beta] \quad (\text{B.1})$$

Where $\alpha = L''/L'$, $\beta = L'''/L'$, L' , L'' and L''' are the largest load, middle load and smallest load of the three phase, L' , L'' and L''' are measured at the transformer secondary, and $p=0,45$ (empirically determined). α and β are weighted by factor p and $1-p$ respectively.

Table B.2, Table B.3 and Table B.4 show the distribution of three phases loads, the corresponding unbalances index and the losses obtained for each case. The total three phase load in each case is kept constant to facilitate the interpretation of three-phase unbalance impact on losses. Figure B.5 is based on Table B.2, Table B.3 and Table B.4. It is clear that, for the same total load, the losses increase with the unbalance level.

**Table B.2 – Load distribution (L1, L2 and L3)
and unbalance index D (%) for the 6 KVA network**

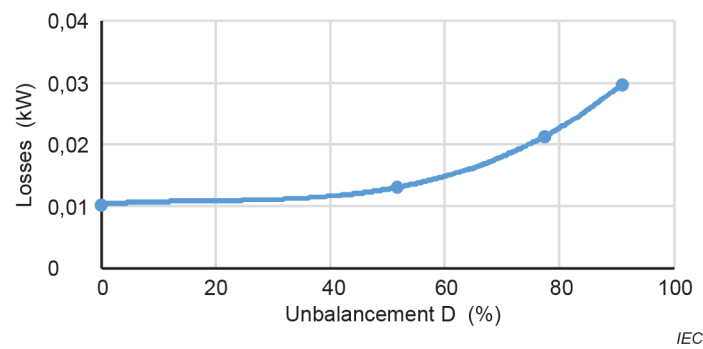
Case	L1	L2	L3	D(%)	Loss(kW)
1	2	2	2	0	0,010
2	3	2	1	52	0,013
3	4	2	0	78	0,021
4	5	1	0	91	0,030

**Table B.3 – Load distribution (L1, L2 and L3)
and unbalance index D (%) for the 18 KVA network**

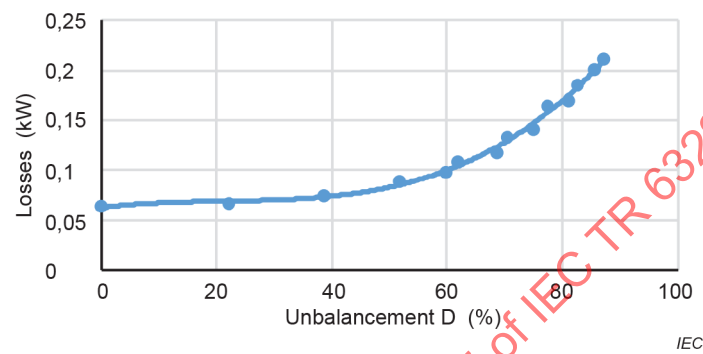
Case	L1	L2	L3	D(%)	Loss(kW)
1	6	6	6	0	0,063
2	7	6	5	22	0,066
3	8	6	4	39	0,074
4	9	6	3	52	0,089
5	10	4	4	60	0,097
6	10	6	2	62	0,108
7	11	4	3	69	0,117
8	11	6	1	70	0,134
9	12	3	3	75	0,140
10	12	6	0	78	0,165
11	13	3	2	81	0,169
12	13	5	0	83	0,185
13	14	2	2	86	0,201

**Table B.4 – Load distribution (L1, L2 and L3)
and unbalance index D (%) for the 180 KVA network**

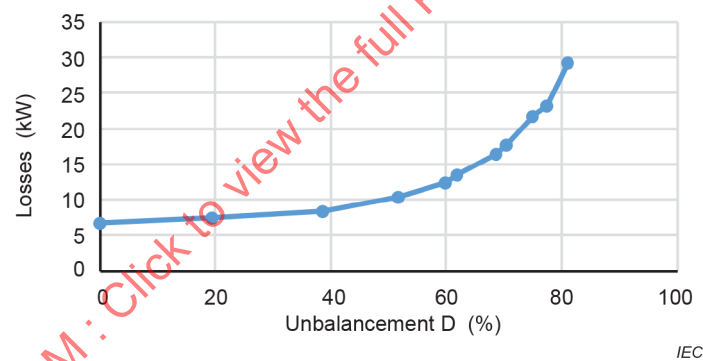
Case	L1	L2	L3	D(%)	Loss(kW)
1	60	60	60	0	6,623
2	80	60	40	39	8,275
3	90	60	30	52	10,393
4	100	40	40	60	12,452
5	100	60	20	62	13,472
6	110	40	30	69	16,337
7	110	60	10	70	17,661
8	120	30	30	75	21,678
9	120	60	0	78	23,216
10	130	30	20	81	29,246



a) Network 6 kVA



b) Network 18 kVA



c) Network 180 kVA

Figure B.5 – Losses vs. unbalance factor

Annex C (informative)

Case analysis: flicker and rapid voltage change impact

C.1 The impact of RVC on induction motor

1) Reduce the energy efficiency of induction motor

A simulation shows that the energy efficiency of the induction motor is inversely proportional to the square of the voltage amplitude and inversely proportional to the square of the voltage fluctuation frequency.

- The impact of fluctuating amplitude on energy efficiency

It is known that flicker at about 8,8 Hz is the most sensitive for human beings. For RVC at this frequency, the energy efficiency with voltage changes amplitude variation is shown in Figure C.1.

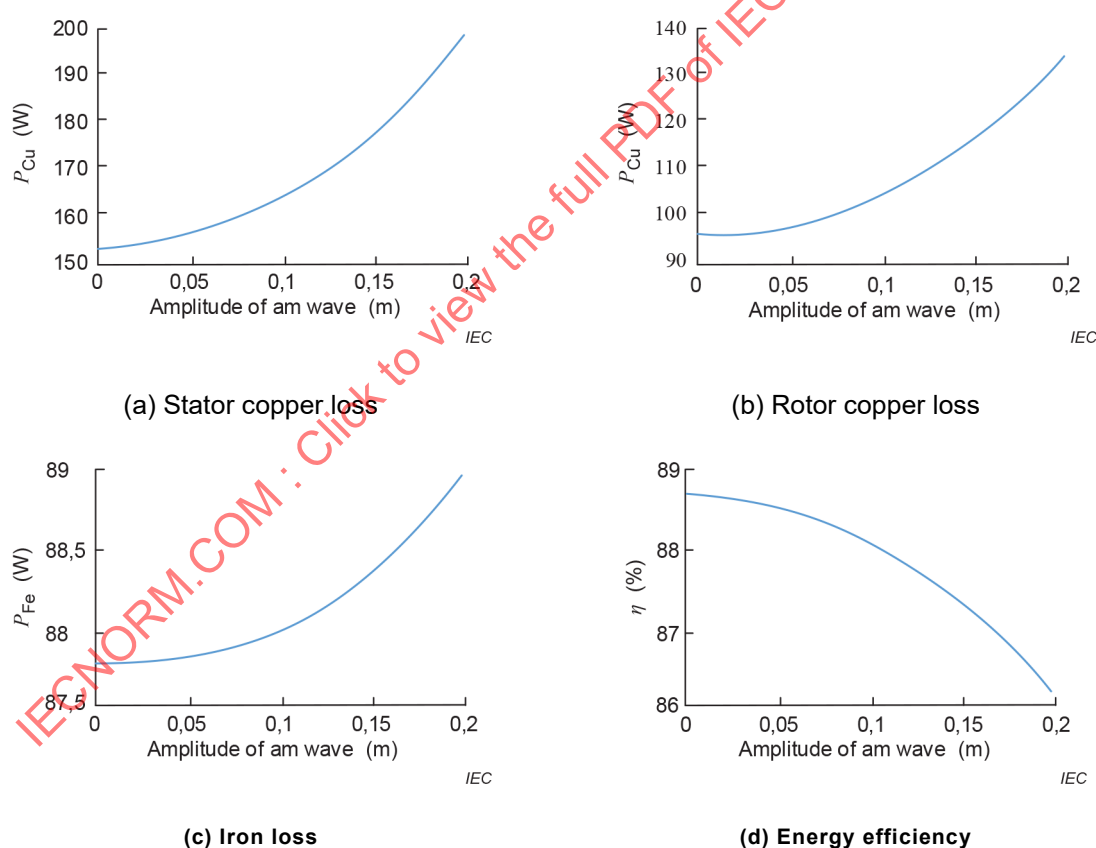


**Figure C.1 – Energy efficiency indexes of A phase
when the frequency of am wave is 8,8 Hz**

As seen from Formula (C.1), when the fluctuation frequency is constant, the motor energy efficiency will gradually decrease with the increase of fluctuation amplitude. This is because the amplitude of the inter-harmonic increases leading to the winding current increase as well as the loss increasing; while the alternating frequency of ferromagnetic flux remains unchanged, the magnetic flux amplitude increases slightly due to the increase of inter-harmonic excitation current, and the iron consumption also shows an increasing trend, but it is not obvious.

Combined with simulation data, when the fluctuation frequency is 8,8Hz, the impact of voltage fluctuation amplitude on motor energy efficiency can be expressed as:

$$\eta = -0,6175 \times m_{vf}^2 + 88,66 \% \quad (C.1)$$

It can be seen that the energy efficiency of the asynchronous engine attenuates in the form of a quadratic function with the increase of fluctuation amplitude under the condition of constant fluctuation frequency.

- The impact of fluctuating frequency on energy efficiency

Under the condition that the amplitude modulation is 10 % (the relative voltage variation is 20 %), the energy efficiency with voltage changes frequency variation is shown in Figure C.2.

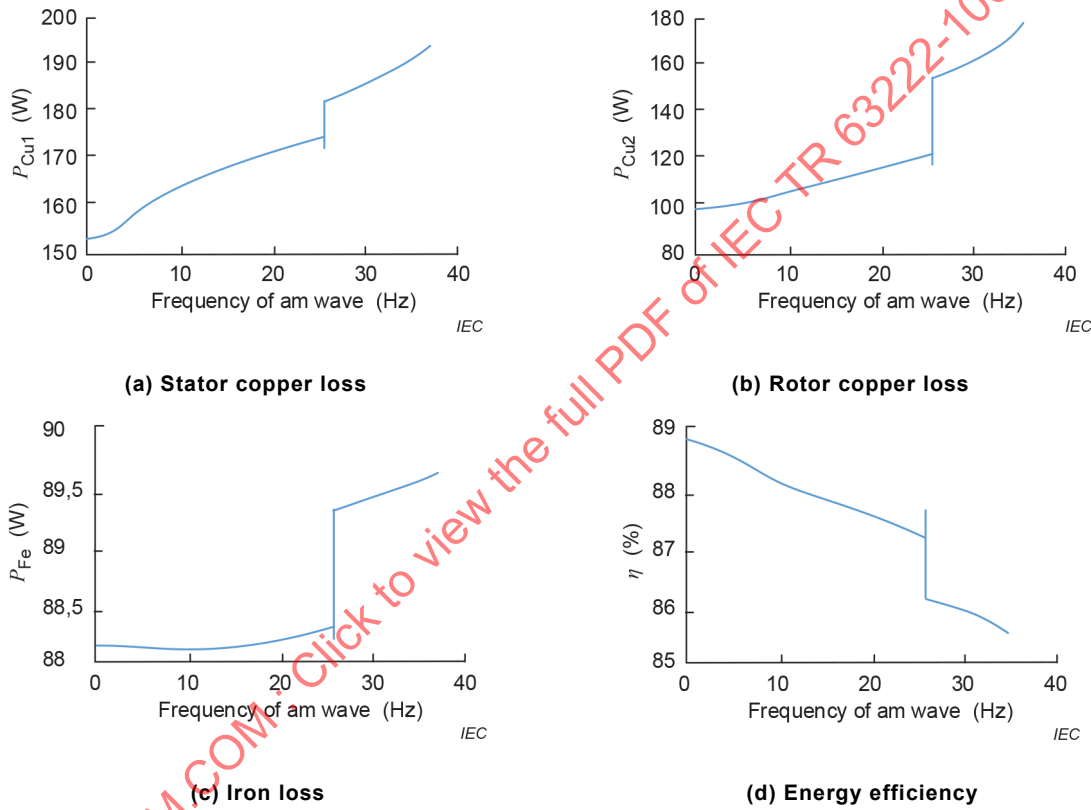


Figure C.2 – Energy efficiency indexes of A phase when the amplitude modulation is 10 % (based on 50Hz system)

When the amplitude modulation is 10 %, through data fitting, the impact of voltage fluctuation frequency on motor energy efficiency can be expressed in the following three stages:

$$\eta = \begin{cases} -0,0005765f + 88,66 \% & 0 \leq f < 25 \\ 87,51\% & f = 25 \\ -0,0007603f + 88,15 \% & 25 < f \leq 35 \end{cases} \quad (C.2)$$

It can be seen that for asynchronous motor, the energy efficiency attenuates in the form of linear function with an increase of fluctuation frequency under condition of the fluctuation amplitude is unchanged, and 25 Hz is the sudden point of energy efficiency.

- Shorten the induction motor life

In the strong voltage fluctuation level, the motor loss will increase, thus making the motor heating. If the incremental temperature at the critical point is considered to be proportional with the incremental stator copper loss of the induction motor, the lifetime of induction motor can be estimated approximately as:

$$L_x = L_0 \times 2^{\left(\frac{T_b - R_{th} \times P_{closs}}{HIC} \right)} \quad (C.3)$$

$$P_{closs} = 3I_S^2 R_S \quad (C.4)$$

where P_{closs} is stator copper loss, I_S is stator current, R_S is stator equivalent resistance.

C.2 The impact of RVC on electrolytic capacitor lifetime

Capacitor power loss and lifetime evaluation require both modelling and experimental understanding of the capacitor characteristics. Such models must represent the key characteristics that define the lifetime parameters of the capacitor. The complex impedance of the electrolytic capacitor is described as:

$$Z_{cap} = \frac{1}{\frac{1}{R_2} + j2\pi f C_2} + R_0 + R_1 - \frac{j}{2\pi f C_1} \quad (C.5)$$

Resistance R_0 combines the resistances of foil, tabs and terminals, whilst R_1 accounts for the electrolyte. A parallel combination of R_2 and C_2 models the dielectric resistance. However, the ripple current heating occurs in the real part of the capacitor impedance. Thus, the (ESR) of electrolytic capacitor can be expressed as:

$$\begin{aligned} ESR &= \text{Real}(Z_{cap}) \\ &= \frac{R_2}{1 + (2\pi f)^2 C_2^2 R_2^2} + R_0 + R_{1base} e^{\frac{(T_{base} - T_{core})}{E}} \end{aligned} \quad (C.6)$$

The temperature dependent nature of the electrolytic resistance R_1 , is modeled with a base resistance R_{1base} , and an exponential temperature variation controlled by a temperature sensitivity factor E .

The ripple-current heating losses in the capacitor are estimated based on this model. Since aluminum electrolytic capacitors have a relatively high ESR, a large ripple current can result in high total capacitor power loss, especially under fluctuating power conditions. The increase of capacitor power loss causes a higher operating temperature inside the capacitor. The total capacitor power loss P_{loss} and capacitor core temperature T_h can be calculated by using the capacitor ripple current as:

$$P_{loss} = \sum_{n=1}^N I_{f_n}^2 ESR(f_n) \quad (C.7)$$

$$T_h = T_a + P_{loss} R_{th} \quad (C.8)$$

Since the capacitor's heating will lead to electrolytic gas escaping through the end seal, the increase of capacitor ripple current and ESR will accelerate the aging process of the capacitor. Thus, the relationship of the electrolyte volume and the ESR can be expressed by:

$$\frac{ESR}{ESR_{ini}} = \left(\frac{V_{ini}}{V} \right)^2 \quad (C.9)$$

If the electrolyte volume is reduced by 40 %, the ESR value is increased by a factor of 2,8. Under such circumstances, the electrolytic capacitor is considered to be a failure. Therefore, for electrolytic capacitor applications, higher capacitor ripple current will lead to an increased internal heating that in turn accelerates the evaporation of electrolyte and degrades the lifetime.

C.3 The experiment of the impact of voltage fluctuation on induction motor life

As an illustrative example, as shown in Figure C.3, Figure C.4 and Figure C.5, a Class F insulation Toshiba 5,5 kW, 50 Hz induction motor was simulated to estimate the induction motor lifetime subject to different voltage fluctuation conditions and various load torque levels.

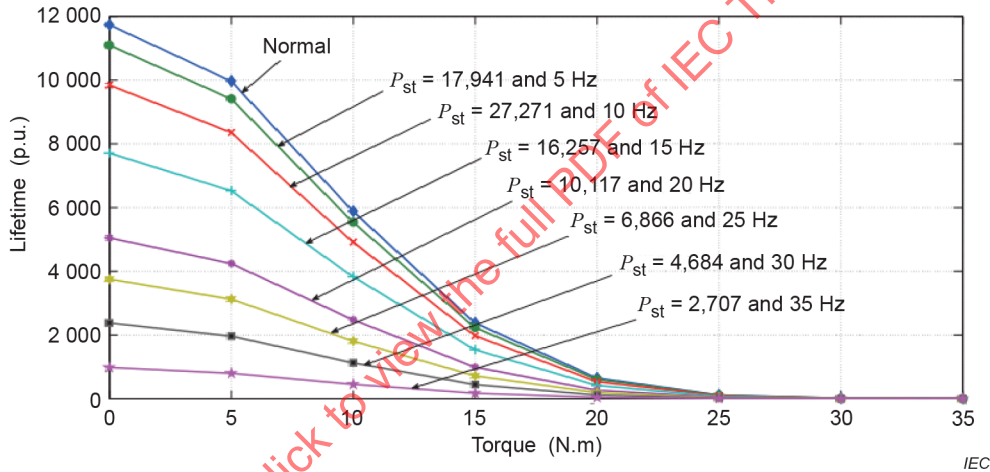


Figure C.3 – Motor lifetime estimation with load torque gradually increase subject to 10 % voltage magnitude change and different modulation frequency

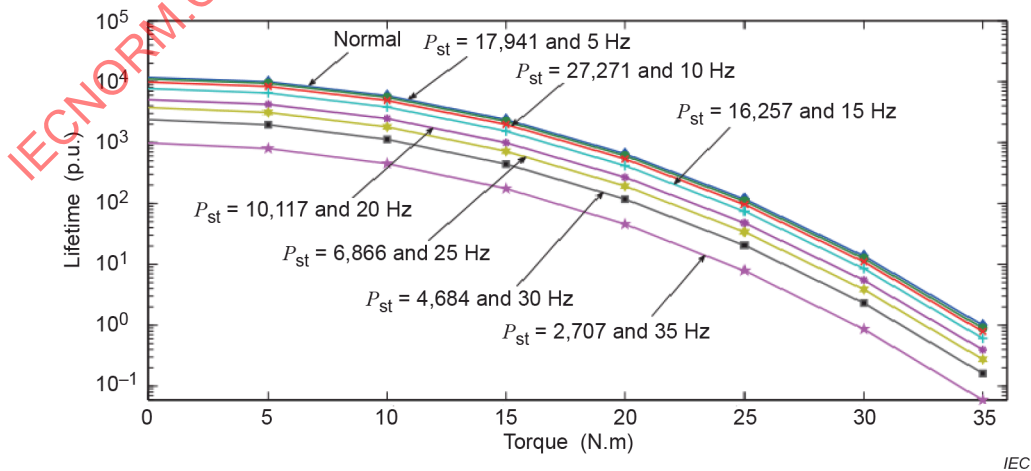


Figure C.4 – Motor lifetime estimation with load torque gradually increase subject to 10 % voltage magnitude change and different modulation frequency

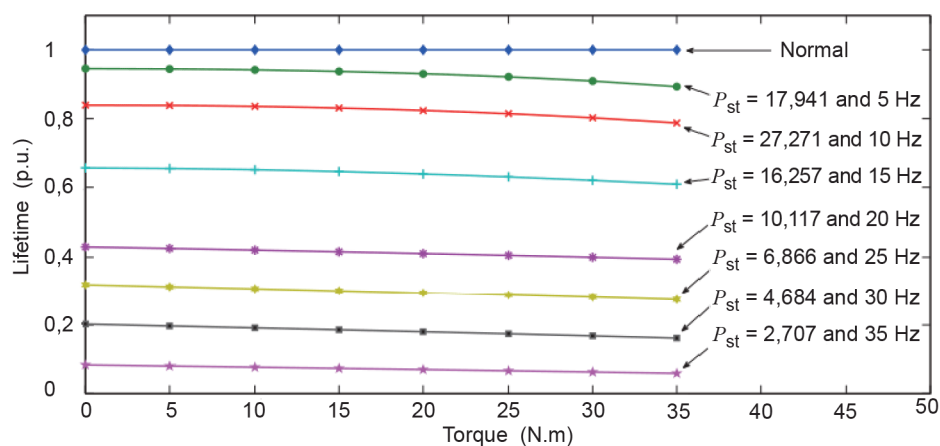
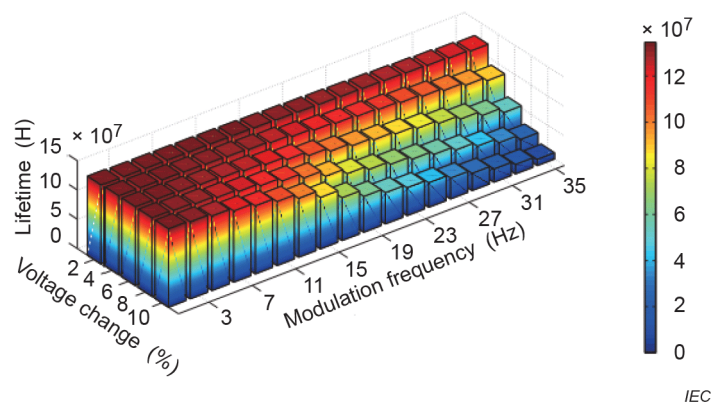
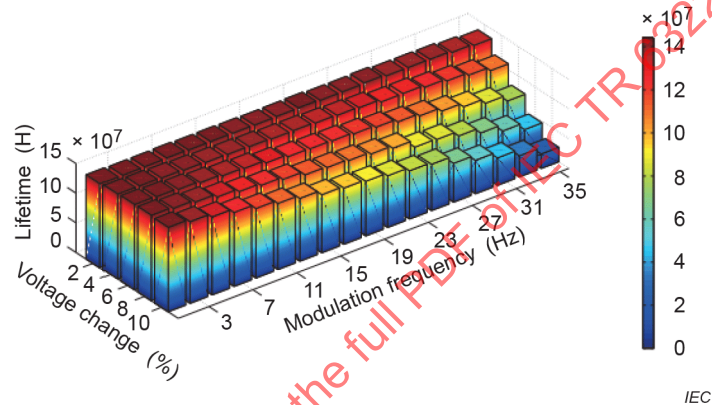


Figure C.5 – The comparison of motor lifetime between voltage fluctuations condition and normal condition

With the voltage change amplitude and modulation frequency increase, the induction motor stator current will increase rapidly, in particular the higher voltage change and higher modulation frequency range. For both light load and heavy load, the investigation details can be summarised, including the simulation results and experimental verification results. Moreover, the corresponding lifetime decrease tendency can be illustrated in Figure C.6 and Figure C.7 according to the simple lifetime estimation model which considers the hot-spot temperature increase to be directly contributed from stator copper loss without taking account of thermal dissipation, including aspects of conduction, convection and radiation effect, etc.

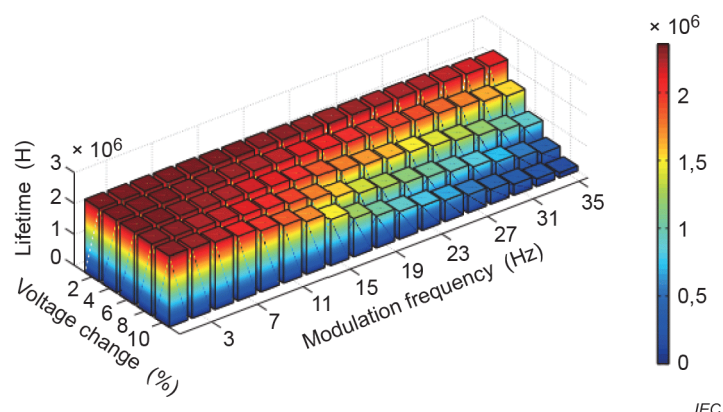


(a) Simulation result

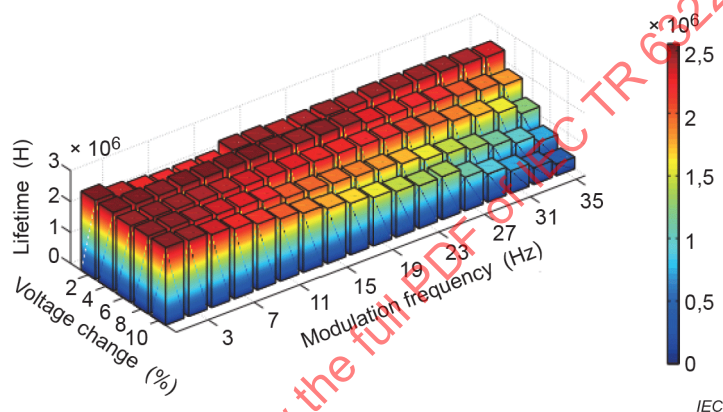


(b) Experimental result

Figure C.6 – Motor lifetime estimation with light load subject to various voltage fluctuations



(a) Simulation result



(b) Experimental result

Figure C.7 – Motor lifetime estimation with heavy load subject to various voltage fluctuations

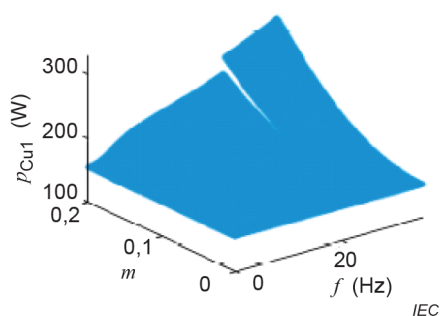
From both simulation and experiment results, the tendency can be clearly shown that with the voltage change and modulation frequency increase, the lifetime of the motor decreases dramatically, particularly under higher voltage change and higher modulation frequency conditions. For example, in the heavy load case study, a 2 % voltage change with 3 Hz modulation frequency leads to a reduction in the induction motor's lifetime to 0,998 2 p.u., and this number is down to 0,066 5 p.u. with 10 % voltage change with 35 Hz modulation frequency for simulation results. Even for experimental results, the number is 0,966 7 p.u. for 2 % voltage change with 3 Hz modulation frequency and 0,152 8 p.u. for 10 % voltage change with 35 Hz modulation frequency condition.

In addition, for light load conditions, a 2 % voltage change with 3 Hz modulation frequency reduces the induction motor's lifetime down to 0,999 p.u., and this number is 0,077 6 p.u. subject to 10 % voltage change with 35 Hz modulation frequency according to the simulation results. From experimental results, the number is 0,993 5 p.u. for 2 % voltage change with 3 Hz modulation frequency and 0,168 6 p.u. for 2 % voltage change with 3 Hz modulation frequency condition. Both simulation and experimental results indicate the fact that the higher voltage change ratio and modulation frequency will bring the induction motor lifetime steeply decline for different load levels.

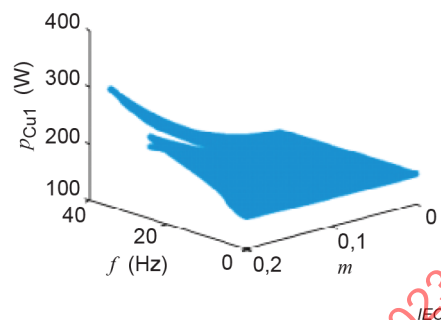
C.4 Voltage fluctuation reduces the energy efficiency

Figure C.8, Figure C.9, Figure C.10 and Figure C.11 show the three-dimensional diagram of the variation trend of stator and rotor copper consumption, iron loss and working efficiency of

asynchronous motors with voltage fluctuation. For relevant information on energy efficiency see Table C.1.

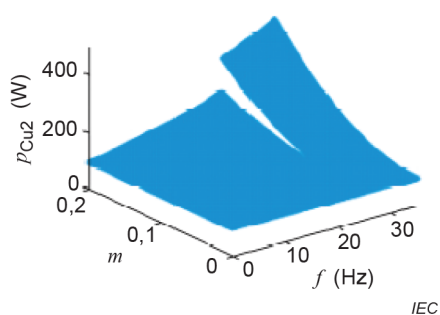


(a) Perspective 1

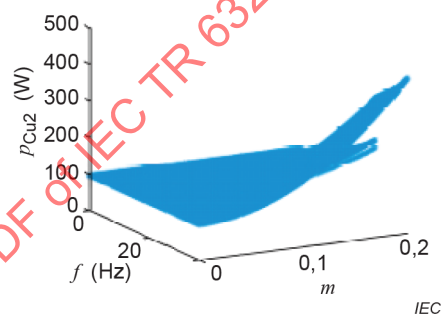


(b) Perspective 2

Figure C.8 – Three-dimensional diagram of copper loss of A phase stator

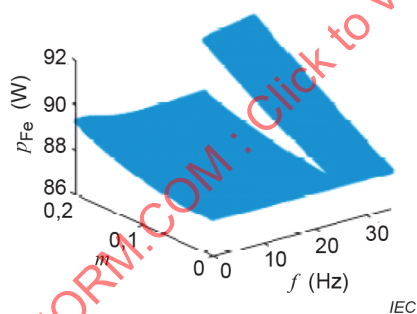


(a) Perspective 1

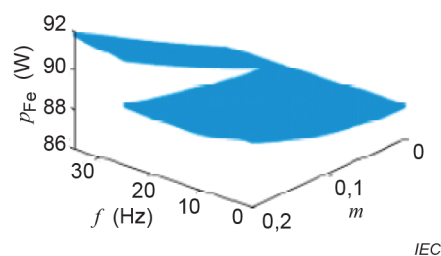


(b) Perspective 2

Figure C.9 – Three-dimensional diagram of copper loss of A phase rotor



(a) Perspective 1



(b) Perspective 2

Figure C.10 – Three-dimensional diagram of iron loss of A phase

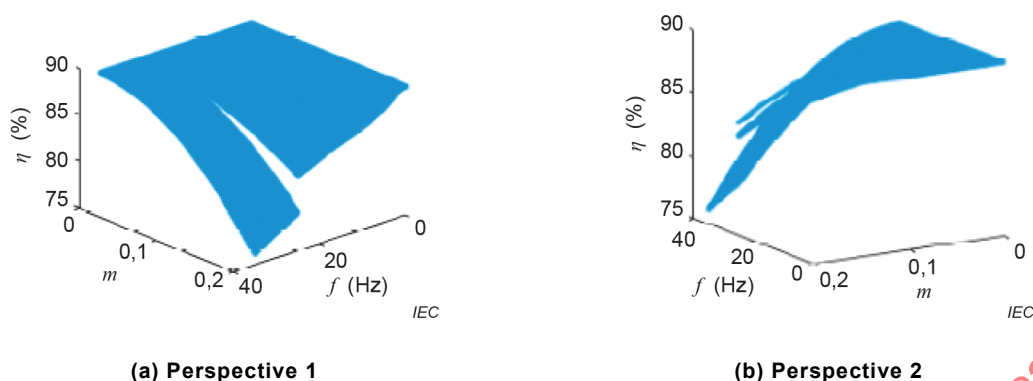


Figure C.11 – Three-dimensional diagram of energy efficiency of A phase

Table C.1 – The variation trend of motor energy efficiency η with voltage fluctuation (%)

Frequency f/Hz	Amplitude of am wave m			
	0,05	0,10	0,15	0,20
5	88,61	88,36	87,93	87,34
10	88,53	88,02	87,17	85,98
15	88,47	87,79	86,66	85,08
20	88,41	87,54	86,10	84,09
25	88,40	87,51	86,01	83,91
30	87,98	85,88	82,45	77,76
35	87,87	85,46	81,53	76,19

With the increase of the fluctuation frequency, the increased rate of copper consumption in fixed rotor of the motor increases with the increase of fluctuation amplitude, and the rate of energy efficiency decline is obviously accelerated. As shown in Table C.1, when the amplitude of a wave increases from 0,05 to 0,20, the energy efficiency decreases by 11,67 %.

With the increase of fluctuation amplitude, the constant rotor copper consumption of the motor increases with the increase of fluctuation frequency and the energy efficiency decreases. The energy efficiency decreased by 11,15 % when the amplitude was 0,2, compared with 0,74 % when the amplitude was 0,05.

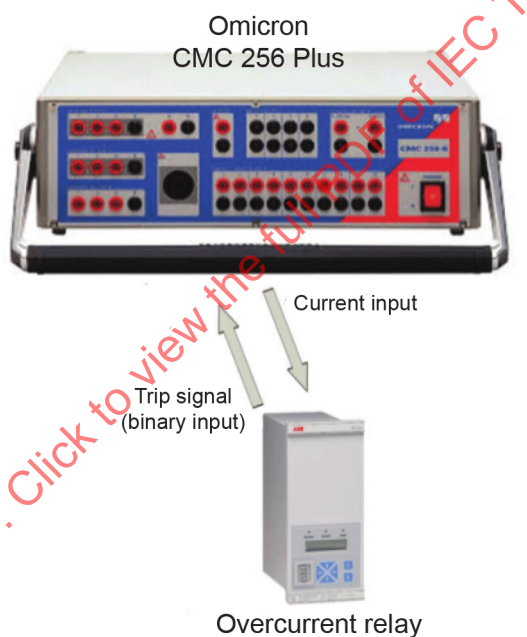
Annex D (informative)

Case analysis: Harmonic, inter-harmonic and the high frequency component impact

D.1 Harmonic impact on tripping time of relay protection device

The microprocessor based over-current relay was tested with modern relay current injection test instruments as shown in Figure D.1. Different harmonics were generated by the OMICRON 256 and were applied to the relay. To define the effects of current harmonic orders, each time the tripping times were recorded as the relay was subjected to the same current distortion for the specific harmonic order.

Figure D.2 and Table D.1 show one set of testing results, it is indicated that different harmonic order almost has the same impact on relay tripping time. Comparing the effects of fundamental current and distortion current with same amplitude shows that harmonic current will delay relay tripping.



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Figure D.1 – Test setup

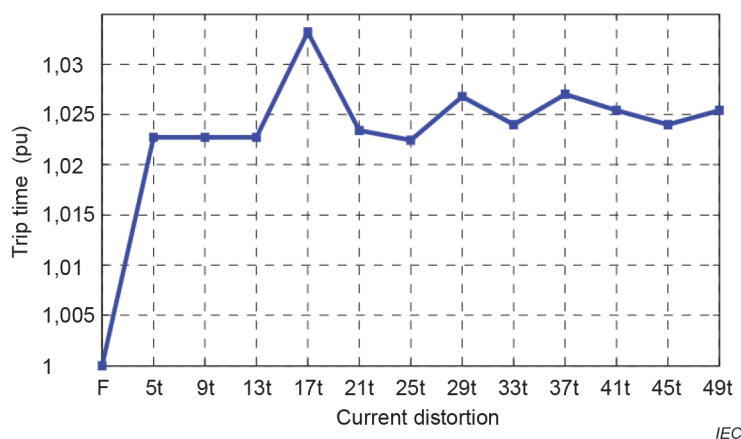


Figure D.2 – Tripping time with distortion current (each test for each order harmonic with 20% distortion)

Table D.1 – Test 1 THD=20 %

Test 1	Harmonic order	Error %	t/t _{exp}
$I_{rms} = 2 \text{ Amps}$ $T_{expected} = 2,97 \text{ seconds}$ 20 % THD	5	2,3	1,023
	9	2,3	1,023
	13	2,3	1,023
	17	3,3	1,033
	21	2,3	1,023
	25	2,2	1,022
	29	2,7	1,027
	33	2,4	1,024
	37	2,7	1,027
	41	2,5	1,025
	45	2,4	1,024
	49	2,5	1,025

D.2 The impact of harmonics on billable meters in Markal, Dist. Pune Steel Mill

The numeric meters are the most affected type of meters due to harmonic distortion. Harmonics may lead the meter records less than actual consumption. This fact was first identified at the HT metering installation of 'M/s Sant Dnyeshwar Steel Industries Ltd', Markal, Dist. Pune. 'M/s Sant Dnyeshwar Steel Industries Ltd' are the manufacturers of steel. They have a manufacturing unit at Markal near Alandi in Pune District. The contract demand was 2 MVA and connected Load was 1,8 MW. The power supply was from 220 kV Lonikand Substation by a 22 kV feeder. The energy meter meant for billing was 'L&T' make, 5 Amp HT TOD meter. During the load test, it was observed that the billed units were less than actual units.

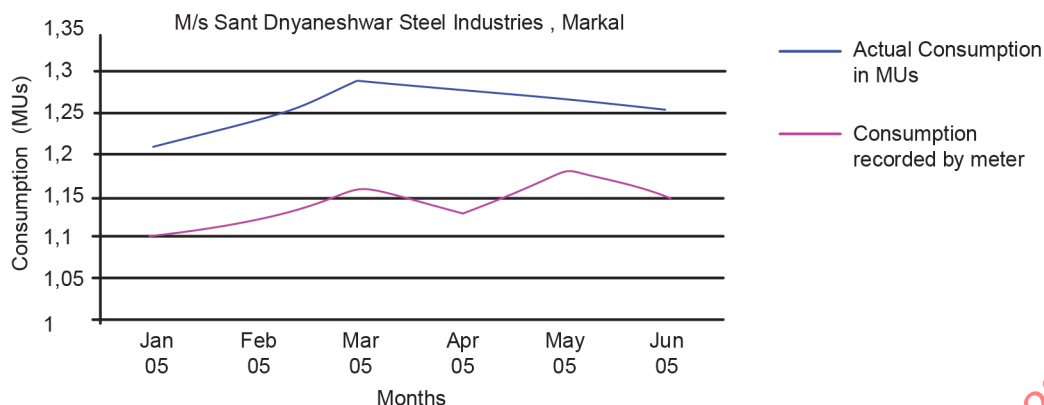


Figure D.3 – Recording kWh consumption at HT consumer metering installation

D.3 The impact of harmonics on power cable

D.3.1 Parameter aspect

- Effect of harmonics on resistance (R)

Based on the recent CIGRE technical brochure TB 766 C4/B4, Figure D.4 shows the variation in per unit resistance (ohm/km) of power cables with respect to harmonic frequency (Hz).

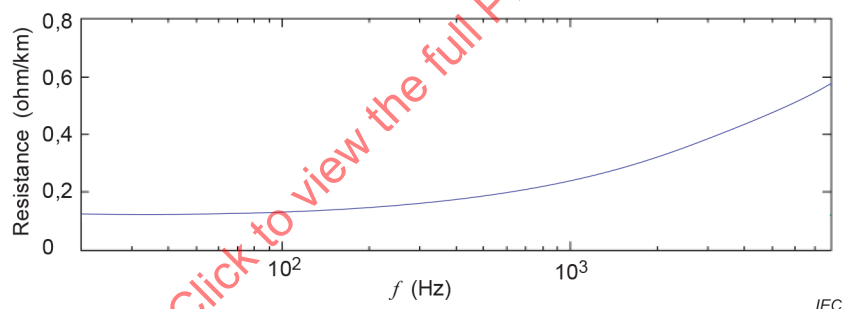


Figure D.4 – Effect of harmonics on resistance (R)

The resistance (R) of power cables increases with harmonic frequency increasing. As the conductor power loss in cables is directly proportional to its resistance (R), this impact will lead more power loss in cable and increased voltage drop across cables.

- Effect of harmonics on inductance (L)

Figure D.5 shows the variation in per unit inductance (mH/km) of power cables with respect to harmonic frequency (Hz).

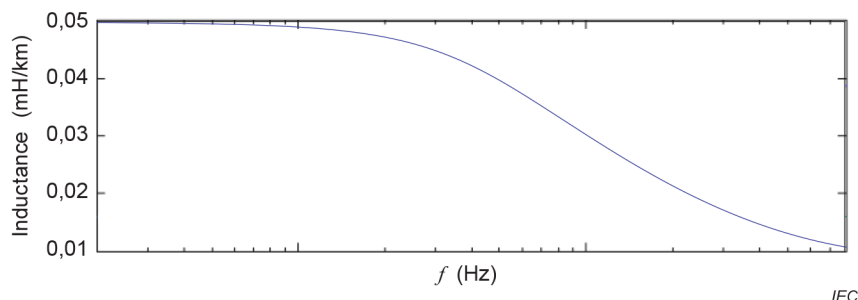


Figure D.5 – Effect of harmonics on inductance (L)

The inductance (L) of power cables decreases considerably with increase in harmonic frequency. This impact may result harmonic resonance in underground power distribution systems at specific harmonic orders.

D.3.2 Performance aspect

Four cables of different sizes but of same types were considered for investigation of threat of harmonics to underground cables. All these cables were of 3 core, 1,1 kV, sector shaped aluminium conductor type and their cross-sectional area and ampacity were 35 mm², 116 Amp, 120 mm², 225 Amp, 240 mm², 325 Amp and 400 mm², 435 Amp.

The results of these investigations into the threat of harmonics are presented in terms of the effects of harmonics on XLPE power loss, temperature rise and expected useful life of cables.

- Effect of harmonics on power loss

Figure D.6 shows the effect of harmonics on per unit power loss in underground cables.

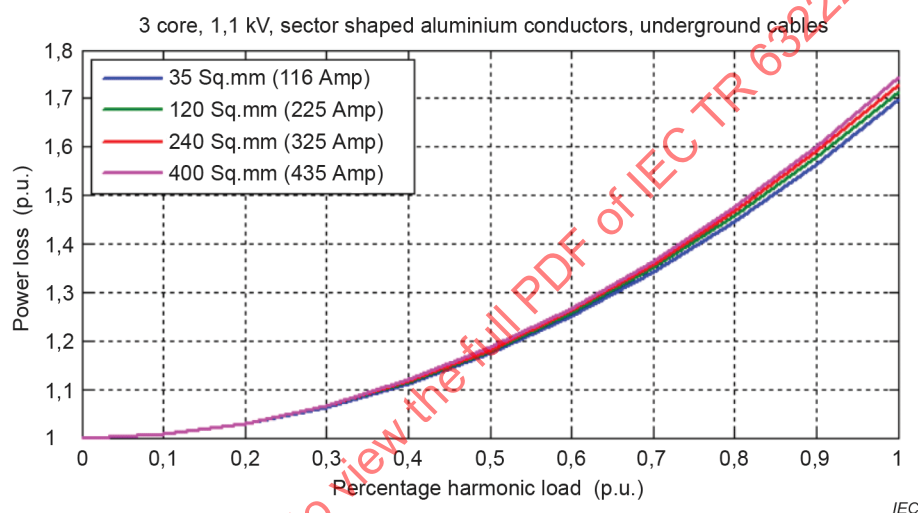


Figure D.6 – Effect of harmonics on power loss

The power loss in underground XLPE cables increases exponentially with increase in harmonics. This additional power loss due to harmonics will produce additional heat in the cables.

- Effect of harmonics on temperature rise

Figure D.7 shows the effect of harmonics on the temperature rise in underground cables.

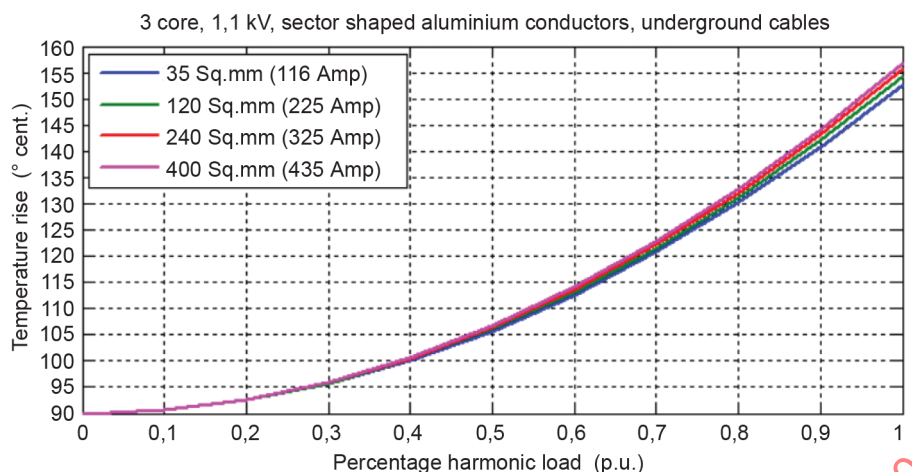


Figure D.7 – Effect of harmonics on temperature rise

The temperature rise in underground XLPE cables also increases exponentially with increase in harmonics. This increased temperature rise ultimately causes accelerated thermal aging of cables leading to possibility of premature failure of cables.

- Effect of harmonics on expected lifetime

Figure D.8 shows the effect of harmonics on expected lifetime of underground cables. The expected lifetime of underground XLPE cables decreases sharply with increase in harmonics.

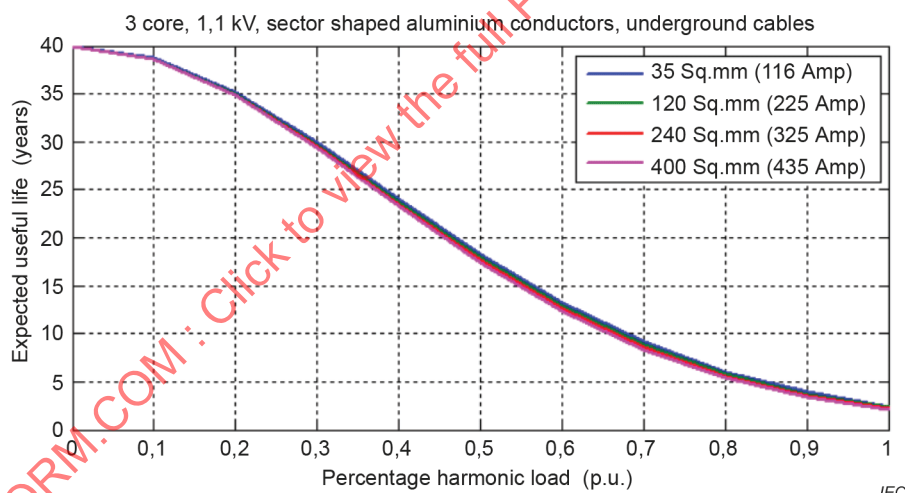


Figure D.8 – Effect of harmonics on expected lifetime

D.4 The impact of inter-harmonics on sub-synchronous oscillation of power system

Reference [55] has carefully examined a turbine generator damage accident caused by a load of a large rolling mill. The damaged generator, with a capacity of 350 MW, located in the western United States, supplied power to two 60 MVA EAFs via a three mile long 230 kV transmission line. In particular, two thyristor-controlled SVCs are installed in the steel plant to maintain system voltage stability and suppress flicker.

After the accident, the working group, through careful testing and analysis, found that there is an inter-harmonic frequency component in the current spectrum of the system periodically, and the source of the inter-harmonic current signal can be traced back to one of the two control loops of the SVC device in the nearby steel plant. The control loop becomes unstable when the

steel plant is in a low power working environment. The extremely high response rate of the control loop leads to the amplitude modulation of the 60Hz fundamental wave. The results of the modulation are inter-harmonic frequency components. The typical inter-harmonic current signals of 55Hz and 65Hz are generated. The inter-harmonic signals of 65Hz do not appear outside the triangle connection of SVC, and only 55Hz inter-harmonic signals are detected at the generator terminal. After analysis, the working group concluded that: the 55Hz inter-harmonic component appears in the three-phase current of the system, and fluctuates between 54 Hz and 58 Hz with the different working conditions of the steel plant. Because the inter-harmonic component of the inverse rotation coincides with the natural frequency of the sixth mode of the generator rotor shaft system, the torsional vibration of the rotor shaft system is excited. The torsional vibration stress level of the rotor shaft system becomes very high in a short time, which directly leads to the shaft damage.

However, the amplitude of the 55 Hz inter-harmonic current signal which excites the torsional vibration of the shaft system is very small, which only accounts for 1 % of the positive sequence fundamental load current of the generator.

After finding out the truth of the accident, the working group reset the response rate of the control circuit, which destroyed the excitation conditions of the shaft torsional vibration, and the torsional stress level of the generator shaft system also returned to the safe value. The engineering example mentioned above is a typical example of sub-synchronous oscillation of power systems caused by inter-harmonics.

Therefore, in reference [55], the working group called for: "special attention [to] be paid to the inter-harmonics generated by cycloconverter and electric arc furnace during operation. These inter-harmonics can stimulate torsional vibration of turbo-generator shafting, and the resulting shafting stress level will even exceed the high cycle fatigue limit of shafting. In contrast, harmonics have not received special attention because mechanical resonance may be avoided near the corresponding harmonic frequency points when designing mechanical equipment".

Annex E (informative)

Case: Voltage dip impact

E.1 Voltage dip sensitive equipment tolerance test

E.1.1 Alternating current contactor (ACC) voltage dip tolerance results

Three contactors from different manufacturers were tested (Table E.1), considering the impact of point on wave (POW) and phase Angle jump (PAJ) on ACC.

Table E.1 – Tested ACC

Serial number	The manufacturer	main contact terminal current
C1	Siemens	16A
C2	Schneider	25A
C3	ABB	26A

1) The test results

- POW impact

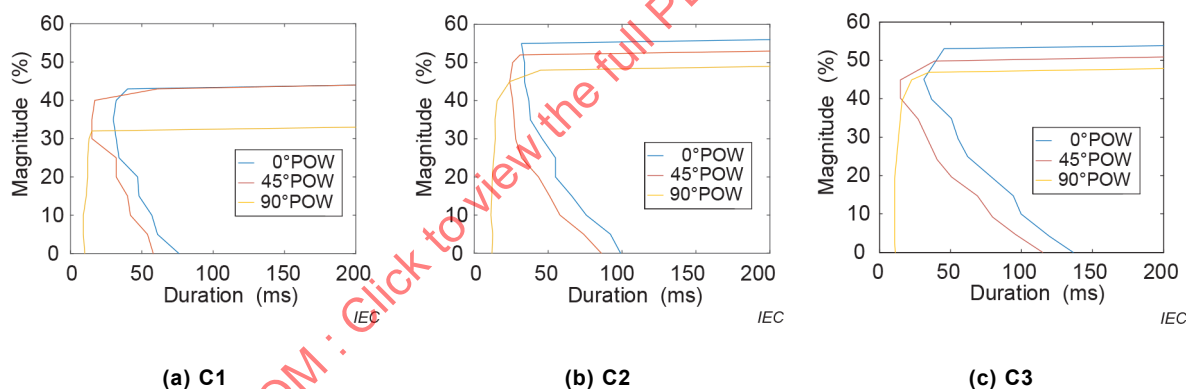


Figure E.1 – VTC (voltage tolerance curve) under different POW

The influence of POW on ACC has a strict half-wave symmetry and an approximate quarter-cycle wave symmetry, this test only tested and analyzed the conditions from 0° to 90°. It can be seen from Figure E.1 that POW has a great influence on the ACC's transient tolerance.

When POW is close to 0°, ACC is more sensitive to the magnitude characteristics of the dip, but its tolerance for the duration of the dip is strong. With the increase in the temporary drop value, its tolerance has a strong-weak-strong non-monotonic relationship. When the POW is close to 90°, ACC is more sensitive to the short duration of the dip, and its tolerance to low magnitude dip is not enhanced. The reason for the above phenomenon is related to the remanence of the coil at the moment of the dip, which leads to the difference in the duration of the electromagnetic transient process and the difference in the release time of the iron core.

- PAJ impact

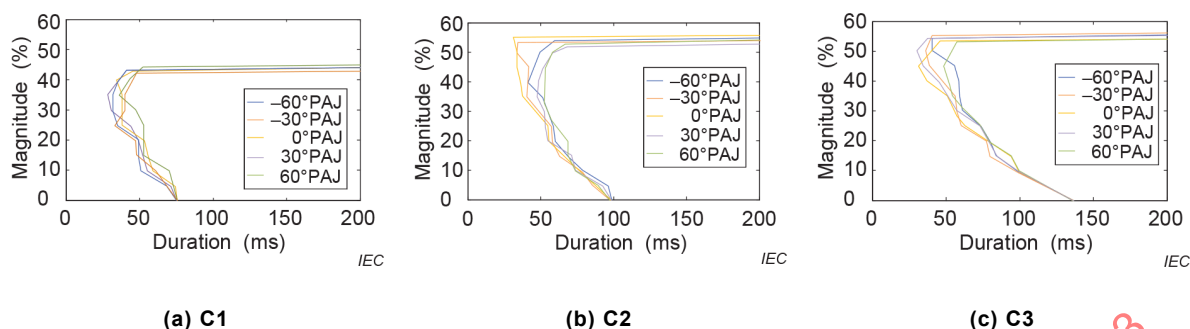


Figure E.2 – VTC (voltage tolerance curve) under different PAJ

The essence of the phase angle jump is that the system side impedance ratio is different from the fault resistance ratio. When the system side impedance ratio is less than the fault point impedance ratio, the jump angle is negative. According to the relevant data, the jump angle in the actual system is generally a negative value, and not less than -60° , and a few faults will lead to the jump at a positive angle, such as a fault at the cable connection. Therefore, this study tested the influence of -60 to 60° PAJ on ACC transient tolerance.

According to the test results in Figure E.2, it can be found that the jump has no significant influence on the critical tolerance magnitude of the equipment. For the duration, with the decrease in the temporary decrease value, the influence degree of PAJ shows a trend of decreasing. Theoretically, the PAJ index mainly affects the position of the instantaneous voltage waveform after the occurrence of the dip. Different positions will bring slight differences in the electromagnetic transient process, and the lower the temporary drop value is, the smaller the difference will be. When the theoretical temporary drop value is 0, there will be no waveform position characteristics, so the PAJ has no impact on the tolerance of the ACC. This reflects the fact that the PAJ has a limited influence over it, which is not as obvious as the POW.

2) Conclusion

Multiple features of the voltage dip impact were analyzed. The VTC (voltage tolerance curve) under different POW and different PAJ are plotted by experiments, and compared with the theoretical analysis, which verifies the correctness of the theory. The specific conclusions are as follows:

- The longer the duration of the dip, the greater the impact on the equipment.
- The essence of POW's influence on ACC is the initial value of the transient current. Different POW leads to different initial values of transient components of magnetic flux, which further leads to different initial values of transient components of electromagnetic force and different duration of a transient process.
- In the range of 0 to 90° , the influence of PAJ on ACC is to some extent the magnitude difference of current or magnetic flux caused by the instantaneous jump, which determines the different transient duration of PAJ. However, the magnitude difference due to the jump (which is related to the magnitude of the waveform during the dip) is small. It cannot determine the initial value of the instantaneous current when the fault occurs, so its influence is not obvious in the POW.
- The influence of the voltage recovery stage on ACC is the magnetizing inrush current generated at the moment of recovery. The inrush current size depends on the waveform point and jump angle during recovery. The effect of this current on the immunity of equipment is small, but the potential harm could be paid attention to.
- Reducing the number of coil turns can increase the endurance of ACC in normal working state. However, increasing the number of coil turns can enhance the immunity in ACC transient process, which can be contradicted by the idea of additional module switching. The short-circuit ring material also has a significant impact on the performance of ACC, and reasonable material selection can improve the immunity of ACC. ACC can also be improved by using a restorative spring with a lower stiffness coefficient.

E.1.2 PLC voltage dip tolerance test and test results

1) The test equipment

The test equipment includes 5 PLC of different brands, and the specific parameters are shown in Table E.2.

Table E.2 – Tested PLC equipment

Brand Number	Parameter
P1	The power supply voltage: 100V to 240V, relay output, 6 input terminals, 4 output terminals
P2	The power supply voltage: 100V to 240V, relay output, 24 input terminals, 16 output terminals
P3	The power supply voltage: 100V to 240V, relay output, 6 input terminals, 4 output terminals
P4	The power supply voltage: 100V to 240V, relay output, 6 input terminals, 4 output terminals
P5	The power supply voltage: 100V to 240V, relay output, 9 input terminals, 7 output terminals

2) The test results

- Different types of PLC tolerance test results

According to the requirements of the test, considering only the voltage temporary drop value and duration of the temporary drop, the voltage tolerance curve of each type of PLC is obtained as shown in Figure E.3.

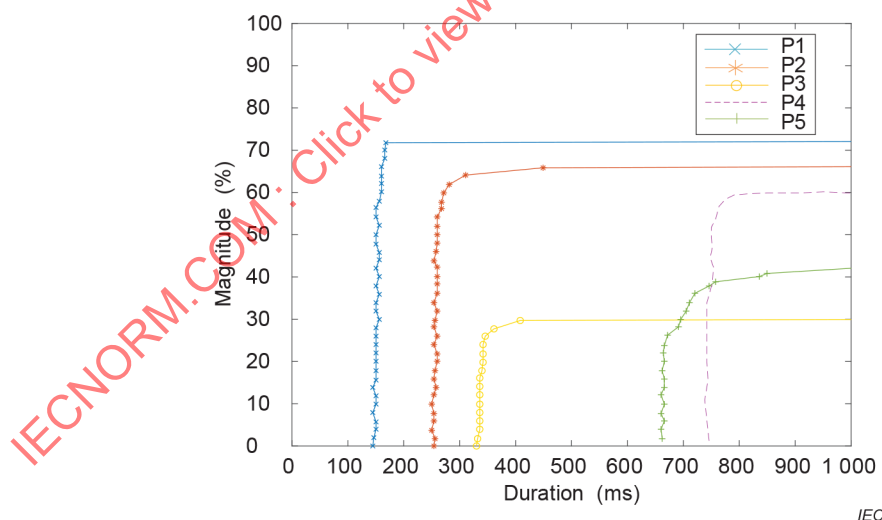


Figure E.3 – Voltage tolerance curve of each PLC

The voltage dip sensitivity of most PLCs is different, and the shape of the sensitivity curve is approximately rectangular.

According to the PLC wide supply voltage range, the PLC itself is able to be immune to transient drop events with a temporary drop value of above 85 %. As can be seen from Figure E.3, P1 to P5 are able to withstand the temporary drop events with a temporary drop value of more than 85 %. When suffering from a short interruption, P1 can only maintain an operation of about 145 ms, while other PLCs can continue to operate for more than 200 ms.