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INTERNATIONAL STANDARD

Semiconductor devices – Semiconductor devices for energy harvesting and generation –
Part 6: Test and evaluation methods for vertical contact mode triboelectric energy harvesting devices

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The text of this standard is based on the following documents:

FDIS	Report on voting
47/2573/FDIS	47/2585/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62830 series, published under the general title *Semiconductor devices – Semiconductor devices for energy harvesting and generation,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
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SEMICONDUCTOR DEVICES – SEMICONDUCTOR DEVICES FOR ENERGY HARVESTING AND GENERATION –

Part 6: Test and evaluation methods for vertical contact mode triboelectric energy harvesting devices

1 Scope

This part of IEC 62830 defines terms, definitions, symbols, and specifies configurations and test methods to be used to evaluate and determine the performance characteristics of vertical contact mode triboelectric energy harvesting devices for practical use. This document is applicable to energy harvesting devices as power sources for wearable devices and wireless sensors used in healthcare monitoring, consumer electronics, general industries, military and aerospace applications without any limitations on device technology and size.

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 terminological databases for use in standardization at the following addresses:

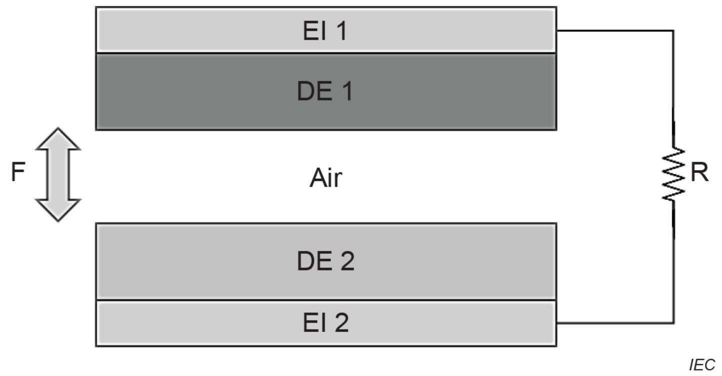
- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1 General terms

3.1.1
vertical contact
physical touching of two objects having relative movement at right angles to their planes at the point of contact

Note 1 to entry: A vertical contact mode triboelectric energy harvester which converts physical contact to electricity and is comprised of dielectric materials, surface electrode, external load, and air gap between dielectric materials, is shown in Figure 1.

Note 2 to entry: The theories for four working modes of a contact triboelectric energy harvester are shown in Figure 2.



Key

Configuration of energy harvester

EI 1, EI 2 electrode

DE 1, DE 2 dielectric material

Components to operate an energy harvester

F pressing and releasing force

R external load

Figure 1 – Vertical contact mode triboelectric energy harvester

3.1.2
nanogenerator
type of technology that converts mechanical/thermal energy as produced by small-scale physical change into electricity

3.2 Triboelectric transducer

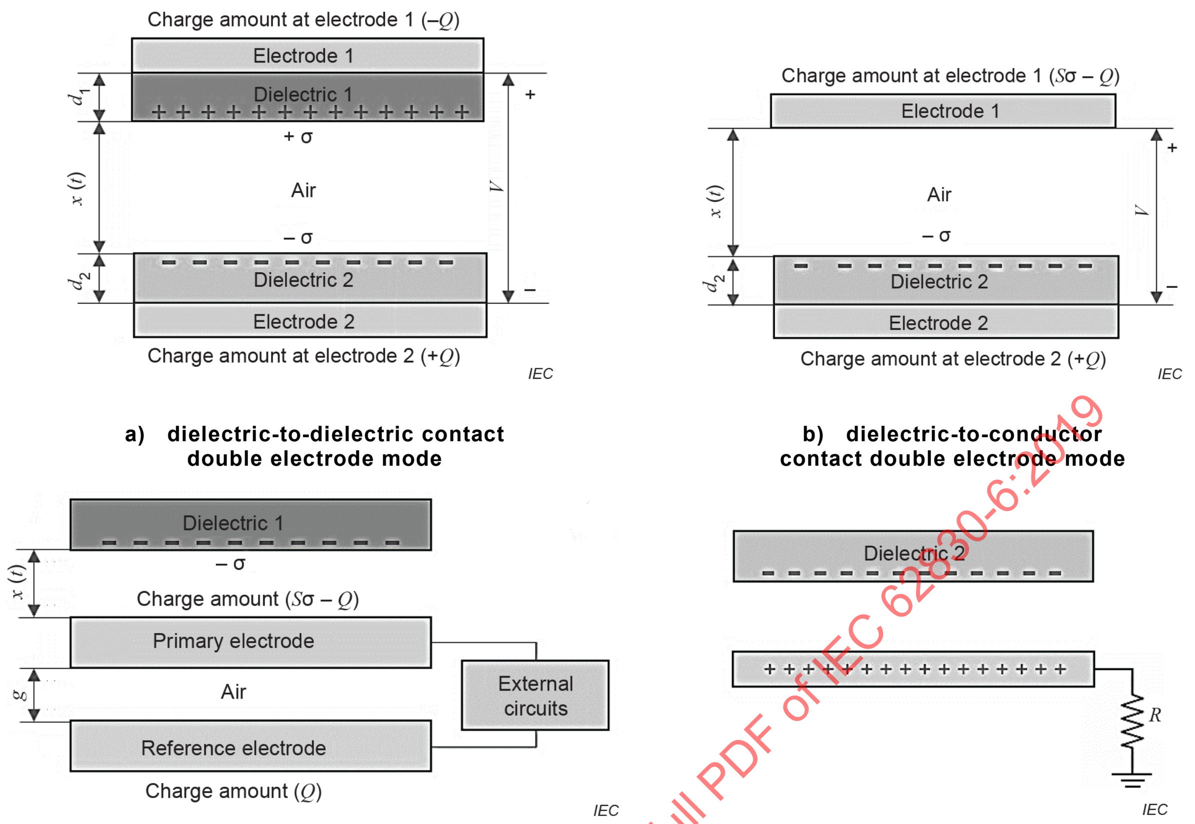
3.2.1
contact based energy harvester
energy transducer that transforms physical energy due to deceleration/acceleration of the moving contact into electrical energy

3.2.2
triboelectric effect
type of contact electrification in which certain materials become electrically charged after they come into frictional contact and separation action with a different material

3.2.3
triboelectric series
list of materials, some of which have a greater tendency to become positive (+) and the others have a greater tendency to become negative (−)

3.2.4
triboelectric transducer
energy converter to generate electricity from mechanical energy by means of triboelectric effect

3.2.5
surface roughness
quantified surface texture by the deviations in the direction of the normal vector of a real surface from its ideal form



a) **dielectric-to-dielectric contact double electrode mode**

b) **dielectric-to-conductor contact double electrode mode**

c) **dielectric-to-primary conductor contact single electrode mode**

d) **dielectric-to-conductor contact single electrode mode**

Key

Parameters of basic operation

d	dielectric thickness	Q	transferred charge
$x(t)$	gap between dielectric materials	V	potential difference
σ	charge	g	gap between two electrodes

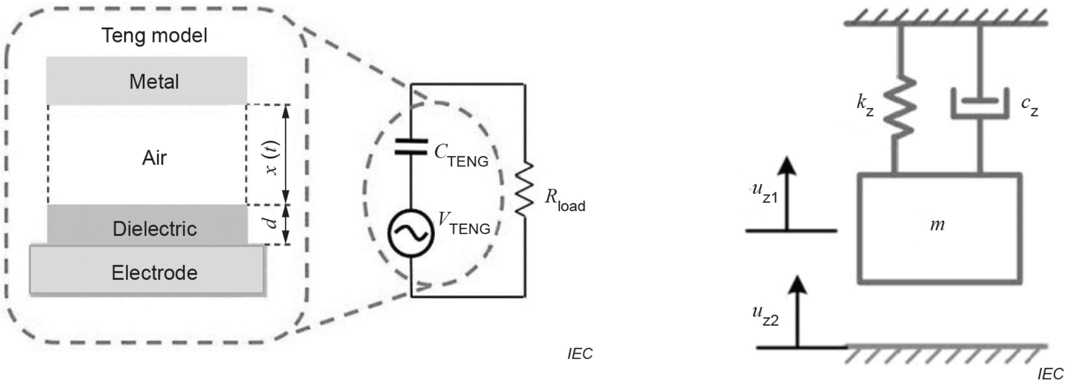
NOTE: The two major vertical contact modes, i.e. double electrode mode and single electrode mode, are described in Annex A (informative).

Figure 2 – Fundamental theories of four working modes of vertical contact mode triboelectric energy harvester

3.3 Characteristic parameters

3.3.1
equivalent circuit
arrangement of ideal circuit elements that has circuit parameters, over a range of interest, electrically equivalent to those of a particular circuit or device

Note 1 to entry: A vertical contact mode triboelectric energy harvester can be shown into parts as shown in Figure 3. The equivalent circuit consists of capacitance C which stores the charge as $+Q$ and $-Q$, open-circuit voltage source V_{oc} and external load R.



a) b)

Key parameters

C_{TENG}	capacitance	R_{load}	external load
d	dielectric thickness	V_{TENG}	open-circuit voltage
TENG	Tribo-electric nano-generator	$x(t)$	gap between dielectric materials
m	movable mass	k_{z}	spring
c_{z}	damper	u_{z1}, u_{z2}	substrates

Figure 3 – Equivalent circuit of triboelectric energy harvester

3.3.2
optimum load impedance
R_{opt}
value of load impedance at which the load absorbs the maximum energy

3.3.3
contact area
area of physical contact of one object with the other object

Note 1 to entry: When two objects touch, a certain portion of their surface areas will be in contact with each other. The contact area is the fraction of this area that consists of the atoms of one object in contact with the atoms of the other object. Because objects are never perfectly flat due to asperities, the actual contact area (on a microscopic scale) is usually much less than the contact area apparent on a macroscopic scale. The contact area can depend on the normal force between the two objects due to deformation.

3.3.4
input frequency
rate at which a repetitive force is applied

3.3.5
surface contact time
time of contact between two triboelectric surfaces

Note 1 to entry: The bigger the surface contact, the greater the net charge on the two surfaces after separation.

3.3.6
relative humidity range
range of humidity as measured on the enclosure over which the energy harvester will not sustain permanent damage though not necessarily functioning within the certain tolerances

3.3.7
temperature range
range of temperature as measured on the enclosure over which the energy harvester will not sustain permanent damage though not necessarily functioning within the specified tolerances

4 Essential ratings and characteristics

4.1 Identification and type

The energy harvester shall be clearly and durably marked in the order given below:

a) year and week (or month) of manufacture;
b) manufacturer's name or trademark;
c) terminal identification (optional);
d) serial number;
e) factory identification code (optional).

4.2 Limiting values and operating conditions

The characteristic parameters should be listed as shown in Table 1. The manufacturer shall clearly announce the operating conditions and their limitation for energy harvesting. The limiting value is the maximum operating cycle to ensure the operation of the vertical contact mode energy harvester for power generation without any damage. Some mandatory input parameters, such as applied force, input frequency, number of cycles and internal impedance of the harvester shall be recorded. Some optional input parameters, such as surface roughness, material strain, capacitance, and dimension of the harvester shall also be recorded. Some mandatory output parameters are open-circuit voltage, short-circuit current, output voltage (for matching load), output current (for matching load), charge transfer between electrodes, and optimum load impedance. Some optional output parameters, such as rectified voltage and current, capacitor charging voltage, and reliability shall also be recorded.

Table 1 – Specification parameters for vertical contact mode triboelectric energy harvester

Parameters	Symbol	Min.	Max.	Unit	Measuring conditions

4.3 Additional information

Some additional information should be given such as equivalent circuits, handling precautions, physical information (outline dimensions, terminals, etc.), accessories, installation guide, package information, PCB interface and mounting information, and other information.

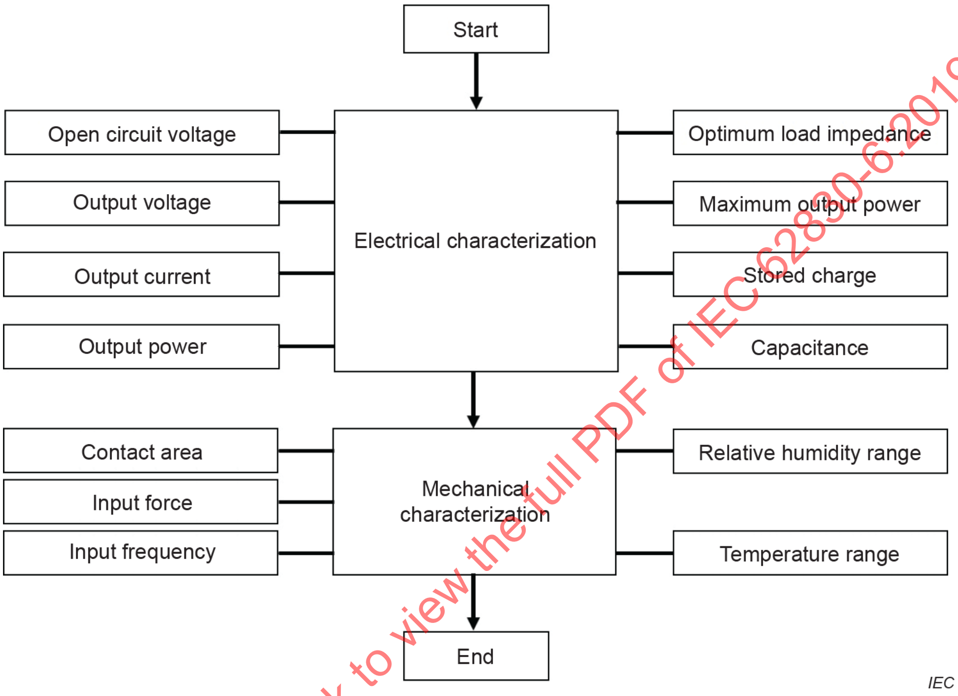
5 Test method

5.1 General

Basically, general test procedures for a contact-based energy harvester are performed as shown in Figure 4. After the energy harvester has been mounted on a test fixture, the harvester is characterized by using an electrometer and force gauge. To measure and characterize these devices accurately, ultra-high-impedance meters should be used.

Before connecting the energy harvester to the test fixture, measuring meters shall be calibrated. After calibration, a test cable is connected to the energy harvester test fixture mounted on an actuator or force gauge. The output voltage or current reading on the display of the meters is carefully taken, together with induced excitation which is measured by the force sensor. The measurement method is common and independent of the materials or the dimension of the device.

NOTE After mounting the energy harvester on an actuator, the electrical characteristics are measured by using a meter or equivalent equipment. If the measurements are satisfactory, the reliability test for the temperature range with thermal cycling and mechanical failure with various excitation is performed for commercial use.



Key

Procedure	**Reference subclause**	**Procedure**	**Reference subclause**
Start		Maximum output power	**5.2.8**
Electrical characterization		Stored charge	**5.2.9**
		Capacitance	**5.2.10**
Open-circuit voltage	**5.2.2**	Mechanical characterization	
		Contact area	**3.3.3 and 5.3.2**
Output voltage	**5.2.4**	Input force	**5.3.3**
Output current	**5.2.5**	Input frequency	**3.3.4 and 5.3.4**
Output power	**5.2.6**	Relative humidity range	**3.3.6 and 5.3.5**
Optimum load impedance	**3.3.2 and 5.2.7**	Temperature range	**3.3.7 and 5.3.6**

Figure 4 – Measurement procedure of vertical contact mode triboelectric energy harvester

5.2 Electrical characteristics

5.2.1 Test procedure

Figure 5 shows a test setup for measuring the electrical characteristics of a device under test. To measure the electrical characteristics of the energy harvester, the device shall be mounted on a linear motor or force gauge. When a continuous excitation with specified acceleration and frequency is applied to the device, an output voltage or current across an external load is measured. Before the contact-separation operation happens, the initial surface potential of the interfacing material is zero. Therefore, the output performances (voltage, current and charge) of the harvester experience unsteady change at the initial cycles of operation and then reach a stable value. This unsteady change of output lasts between the first 1 to 5 cycles of operation, based on the inherent properties of the interfacing materials. To avoid this unavoidable unsteady change, it is recommended to take the output data after the first five cycles of operation. In case a custom-made testing setup other than a linear motor or force gauge is used, some input parameters, such as input frequency, applied force, and operating cycles shall be monitored using precision sensing equipment.

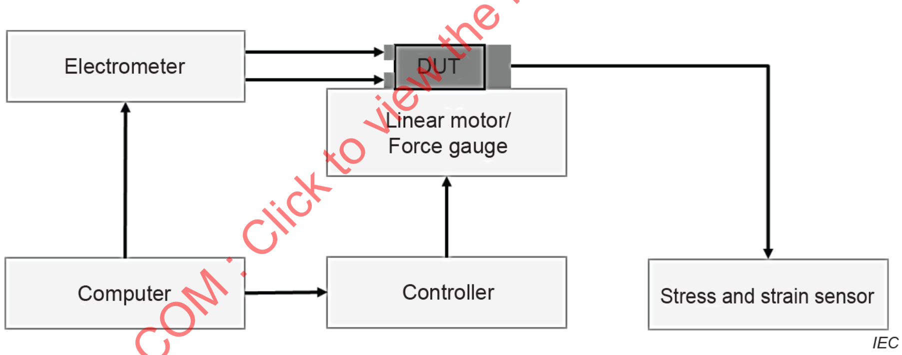
The following test procedure is performed:

a) A specified excitation is induced to the energy harvester.

b) The voltage or current across the external load which is connected to the terminals of the energy harvester is measured using a voltage or current meter.

c) The voltage and current are measured with various excitations by adjusting the parameters via computer.

d) The maximum voltage and current are derived from various external loads to find the optimal load.



Key

Input exciter and meters to monitor

DUT: device under test	energy harvester	Linear motor	to apply force as input into energy harvester
Electrometer	to detect voltage, current, amount of charge transfer and resistance	Controller	to control linear motor and force gauge
Computer	to select input excitation and to get data points	Stress and strain sensor	to monitor the stress and strain of energy harvesting device

NOTE A practical example of the test setup is shown in the Annex B.

Figure 5 – Test setup for the electrical characteristics of vertical contact mode triboelectric energy harvester

5.2.2 Open-circuit voltage

The objective of this test is to measure the instantaneous output voltage across the terminals of the energy harvester without external load. When measuring the open-circuit voltage, the input impedance of the voltage meter shall be recorded. Figure 6 shows the graphical shape of a measured instantaneous open-circuit output RMS voltage as a function of time. When measuring voltage, the input impedance of the meter shall be many decades higher than the impedance of the voltage source. For example, if the meter's input impedance is only 1 GΩ (typical of DMMs), and the source of the voltage has 10 MΩ of impedance, then the meter will introduce a 1 % error due to its relatively low input impedance. In contrast, an electrometer with 10^{14} Ω input impedance will cause only a 0,000 01 % error.

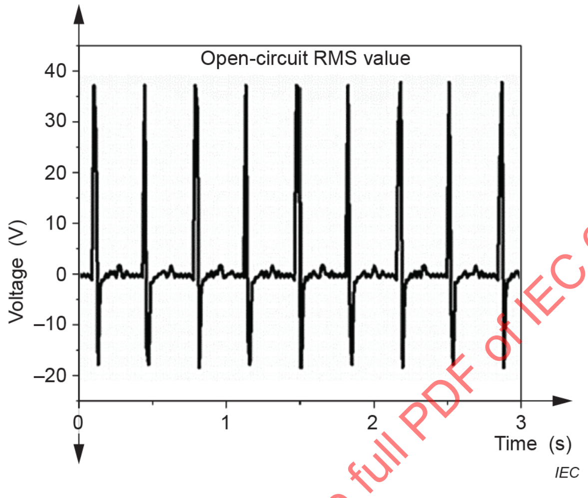


Figure 6 – Instantaneous open-circuit output voltage characteristics

5.2.3 Short-circuit current

The objective of this test is to measure the instantaneous output current measured through the terminals of the energy harvester from induced excitation without external load. When measuring the short-circuit current, the input impedance of the voltage meter shall be recorded. The output short-circuit RMS current for a contact mode triboelectric energy harvester is shown in Figure 7. It is also important for the current measurement instrumentation to have a low bias current, because any current coming out of the meter input will be forced through the source. Electrometers use active cancellation to reduce bias current to the single femtoampere level. Leakage currents are generated by stray resistance paths between the measurement circuit and nearby voltage sources. These currents can degrade the accuracy of low current measurements considerably. To reduce leakage currents, it is necessary to use good quality insulators, reduce the level of humidity in the test environment, and use guarding. Guarding also reduces the effect of shunt capacitance in the measurement circuit.

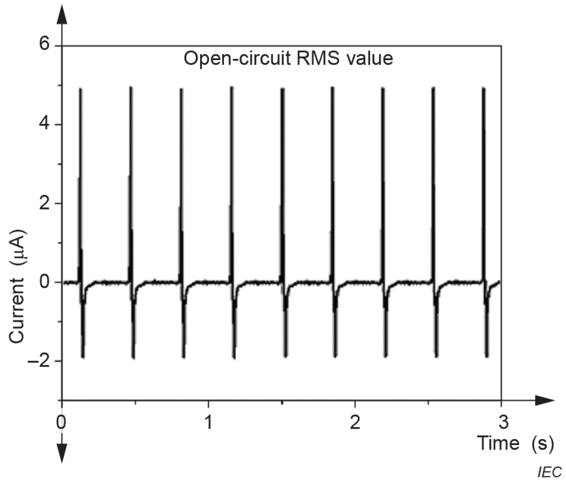


Figure 7 – Instantaneous short-circuit output current characteristics

5.2.4 Output voltage

The objective of this test is to measure the output voltage across the terminals of the energy harvester with external load and input excitation. Figure 8 shows the graphical shape of measured output voltage as a function of external resistive load connected to the terminal of the energy harvester. Due to the electrical potential superposition principle, the total voltage difference between the two electrodes can be given by

$$V(x) = -\frac{Q}{C(x)} + V_{oc}(x)$$

5.2.5 Output current

The objective of this test is to measure and evaluate the current through the specified external load connected to the terminal of the energy harvester at the specified input. Figure 8 also shows the graphical shape of the measured RMS current as a function of the output voltage of an energy harvester. The short-circuit current from the terminal of the energy harvester is the rms value of measured current when the voltage across the energy harvester is zero.

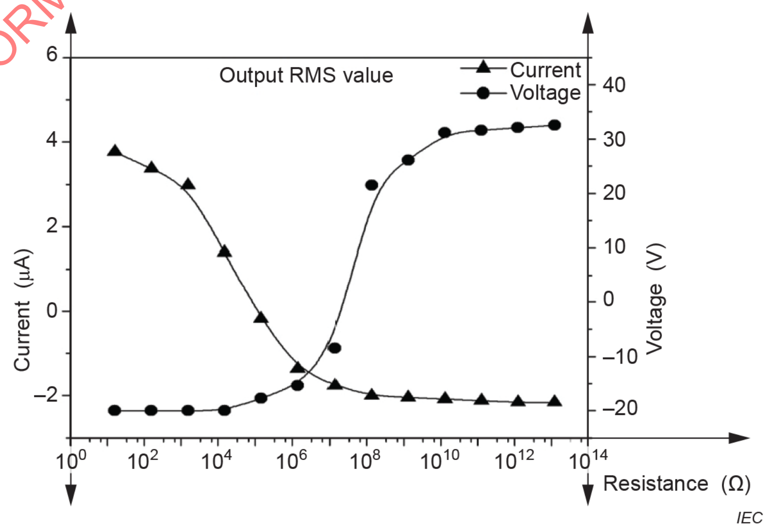


Figure 8 – Output voltage and current of triboelectric energy harvester under different loads

5.2.6 Output power

The objective of this test is to evaluate the output power from the time integration value of the measured output voltage and current of the energy harvester with external load. Figure 9 shows the graphical shape of the measured output average power as a function of the external load of an energy harvester.

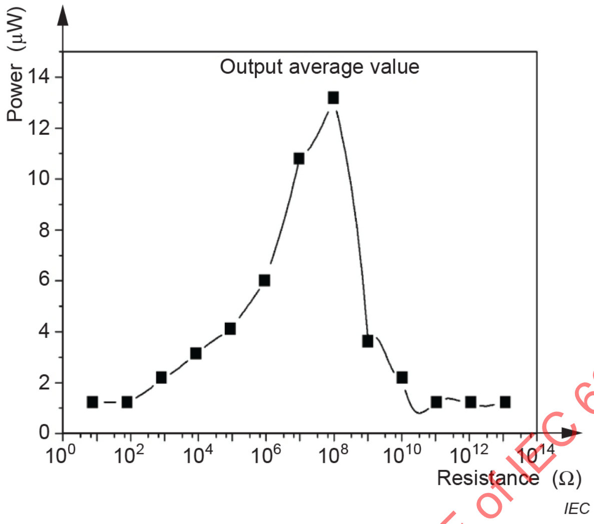


Figure 9 – Output power of triboelectric energy harvester at various external loads

5.2.7 Optimal load impedance

The objective of this test is to evaluate the optimal load impedance which is determined as the value of the external load when the output power of the energy harvester is maximized. For example, the optimum load impedance as shown in Figure 9 is 100 MΩ.

5.2.8 Maximum output power

The objective of this test is to evaluate the maximum output power which is a maximum value of output power for the matched impedance measured from an energy harvester at a certain excitation. For example, the maximum output peak power as shown in Figure 9 is 13 µW for an optimum loading resistor of 100 MΩ.

5.2.9 Stored charge

The objective of this test is to evaluate the generated charges from the energy harvester which are stored across a capacitor after being rectified by a full-wave bridge rectifier and to investigate the charging behavior of the harvester as shown in Figure 10. A programmable electrometer is used to accurately measure the stored charge in a capacitor. The charging time of a capacitor is inversely proportional to the storage capacitor value. The capacitor with the higher rating takes a longer time to be charged and discharged compared to the smaller one. The recommended value for the load capacitor is 1 000 µF.

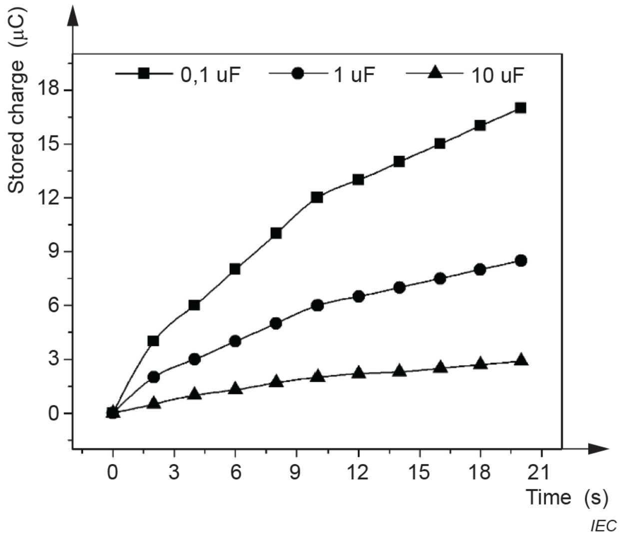


Figure 10 – Stored charging time relationship at different load capacitances of triboelectric energy harvester

5.2.10 Capacitance

The objective of this test is to evaluate the capacitance which is the ability of a system to store an electric charge. Due to the fixture of the single electrode based triboelectric energy harvester, its capacitance is nearly a constant with the increase of the gap between triboelectric materials. This is because when one dielectric material is far away from the electrodes, the influence of that material on the electric field distribution around the electrodes is small. The degradation of the output performance of a single electrode based harvester mainly comes from the electrostatic shield effect of the primary electrode. However, for the double electrode structure, its capacitance decreases quickly when the distance between the two electrodes is increasing. Capacitance trends for both the single electrode and double electrode based energy harvesters are shown in Figure 11 and the description of each type is provided in Annex A. The layer gap is the distance between two triboelectric material surfaces after being separated from the contact state.

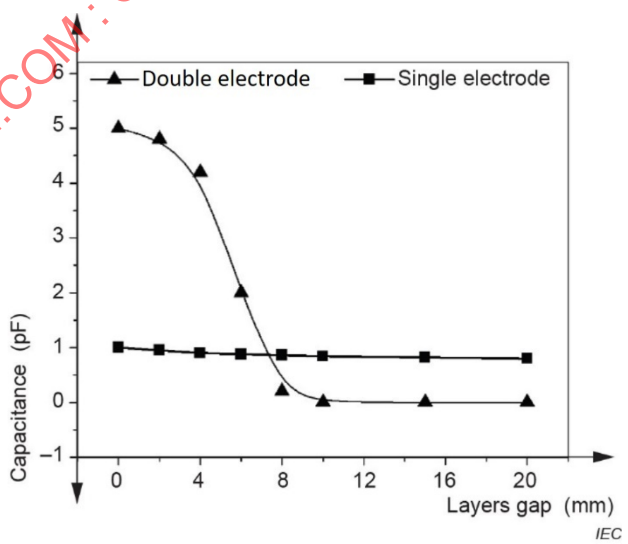


Figure 11 – Capacitance between the two electrodes of a triboelectric energy harvester

5.3 Mechanical characteristics

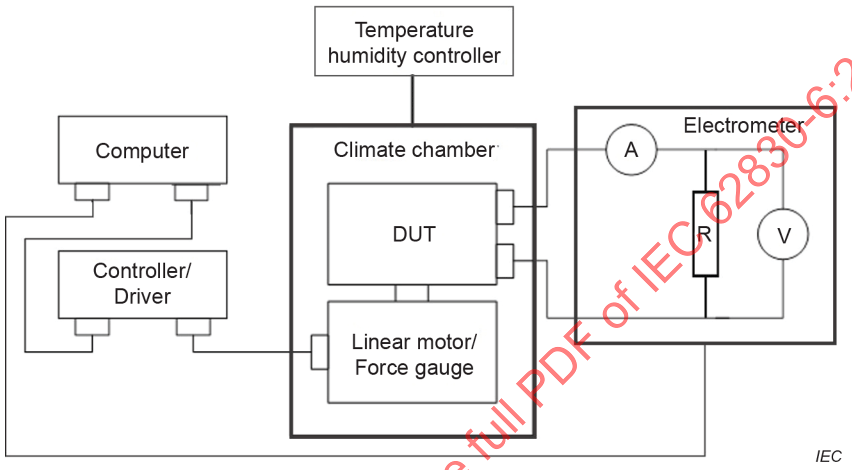
5.3.1 Test procedure

Figure 12 shows a test setup for evaluating the reliability of an energy harvester. When a continuous force is applied to the device, the output voltage or current is measured through an external load connected to the device.

To test the reliability, the following test procedure is performed:

a) An external force is applied to the energy harvester.

b) The output voltage or current of the energy harvester is measured with the meter.



Key

Component and meters to monitor		**Equipment and supplies**	
DUT: device under test	energy harvester	Liner motor/ force gauge	to supply a specified speed/ force
Voltage meter (V)	to detect a voltage across the external load	Computer	to control input parameters for liner motor, force gauge and electrometer
Ampere meter (A)	to detect a current through the external load	Temperature, humidity controller	to keep a specified temperature and humidity value of a DUT

Figure 12 – Block diagram of a test setup for evaluating the reliability of vertical contact mode triboelectric energy harvester

5.3.2 Contact area

The objective of this test is to evaluate the relationship between the electrical outputs and the area of the triboelectric surfaces. It is possible to observe the open-circuit voltage for the different values of the triboelectric surface area, which clearly demonstrates an increase of the voltage peaks with increasing contact area as shown in Figure 13.

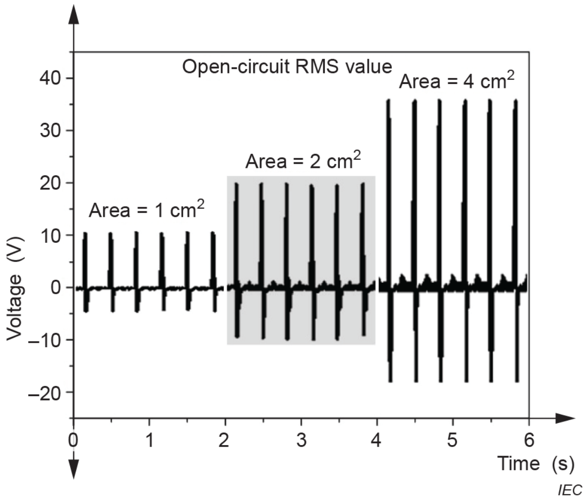


Figure 13 – Instantaneous open-circuit voltage characteristics for four different contact areas of contact mode triboelectric energy harvester

5.3.3 Input force

The objective of this test is to evaluate the reliability of the device under different input forces and constant frequency. The increase in force results in higher output performances (open-circuit RMS voltage and short-circuit RMS current) unless it gets saturated because of an increase in the surface contact area, which causes a larger surface charge density as shown in Figure 14. The minimum time required for maximum contact area between two triboelectric materials is an important parameter to determine the performance. Once complete contact is made, the applied force would not help better performance, and it should be withdrawn to reduce the surface structure. The waveform of the oscillation for voltage and current remains the same as reported in Figure 6 and Figure 7, respectively.

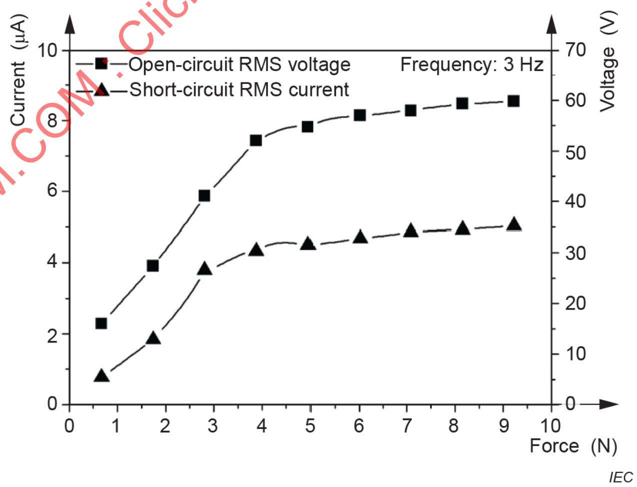


Figure 14 – Output voltage and current under different input forces on vertical contact mode triboelectric energy harvester

5.3.4 Input frequency

The objective of this test is to evaluate the reliability of the device under different input frequencies and constant force. The increase in frequency results in higher output performances (open-circuit RMS voltage and short-circuit RMS current) unless it gets saturated because of an increase in the surface contact area, which causes larger surface charge density as shown in Figure 15. The waveform of the oscillation for voltage and current remains the same as reported in Figure 6 and Figure 7, respectively.

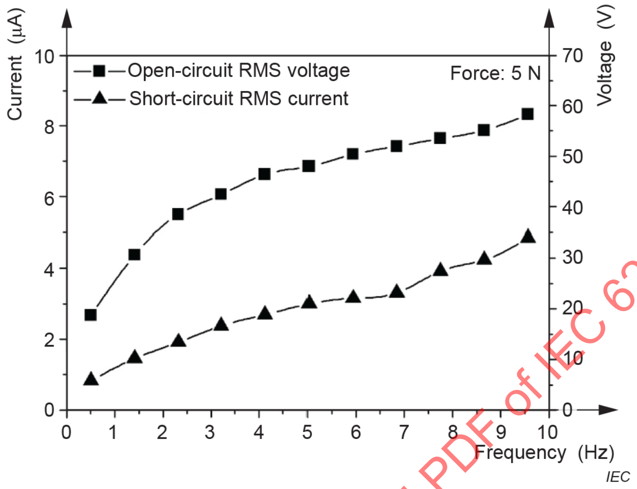


Figure 15 – Output voltage and current under different working frequencies on vertical contact mode triboelectric energy harvester

5.3.5 Relative humidity range

The test is performed in the humidity cycling test chamber with specific temperature, while the device was put inside the chamber and the performance was observed remotely. The performance characteristics are monitored by a humidity measuring meter. At a given temperature, an increase in the relative humidity causes unsteady decrease in the output RMS voltage generated due to triboelectrification, as shown in Figure 16. The output performance of the device decreases rapidly with relative humidity on a hydrophilic surface but it is less significant for a hydrophobic surface. The device performance degrades exponentially at a relative humidity higher than 80 % and therefore, it is not recommended to be used.

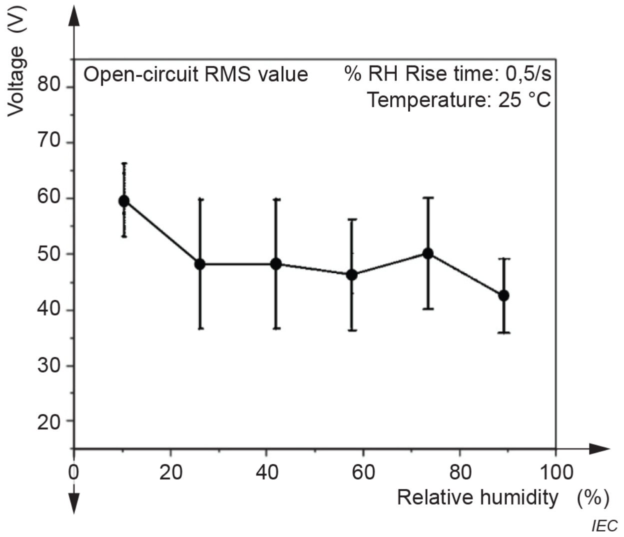


Figure 16 – Triboelectric output voltage as a function of relative humidity

5.3.6 Temperature range

The objective of this test is to evaluate the reliability of the device by a low/high temperature cycling test inside a high precision climate chamber. The temperature range should be specified from the applications. At a given relative humidity, the increase in the temperature beyond a certain limit causes a decrease in the charge generated due to triboelectrification, as shown in Figure 17.

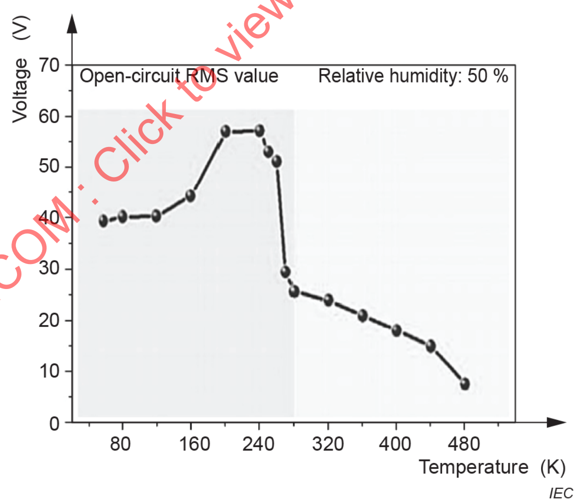


Figure 17 – Open-circuit voltage of triboelectric energy harvester at different temperatures