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Semiconductor devices – Semiconductor devices for energy harvesting and generation –
Part 7: Linear sliding mode triboelectric energy harvesting

Dispositifs à semiconducteurs – Dispositifs à semiconducteurs pour récupération et génération d'énergie –
Partie 7: Récupération d'énergie triboélectrique en mode de coulissement linéaire

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Part 7: Linear sliding mode triboelectric energy harvesting

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The text of this International Standard is based on the following documents:

FDIS	Report on voting
47/2676/FDIS	47/2686/RVD

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

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

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SEMICONDUCTOR DEVICES – SEMICONDUCTOR DEVICES FOR ENERGY HARVESTING AND GENERATION –

Part 7: Linear sliding mode triboelectric energy harvesting

1 Scope

This part of IEC 62830 defines terms, definitions, symbols, configurations, and test methods that can be used to evaluate and determine the performance characteristics of linear sliding mode triboelectric energy harvesting devices for practical use. This document is applicable to energy harvesting devices for consumer, 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
linear sliding
physical sliding of one material on another material in horizontal direction

3.1.2
sliding-based energy harvester
energy transducer that transforms physical sliding energy into electrical energy

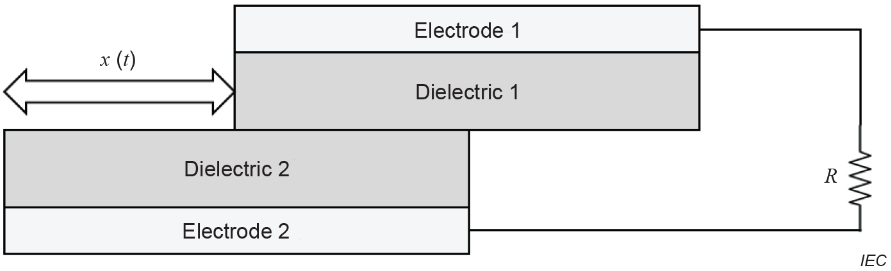
Note 1 to entry: A linear sliding mode triboelectric energy harvester to convert linear sliding to electricity comprises dielectric materials, a surface electrode, an external load, and a relative displacement between dielectric materials as shown in Figure 1. The sliding makes the two dielectric material surfaces come into physical touch, and relative displacement makes the gap between those two materials. The top and bottom electrodes on the two dielectric materials harvest charges generated from the coupling of triboelectrification and electrostatic induction. The triboelectric charges are generated by the charge transfer between two thin organic/inorganic films that exhibit distinct surface electron affinity, and the potential difference results from the separation of the triboelectric charges; under short-circuit conditions, electrons are driven to flow between two electrodes attached on the back side of the films through the load in order to balance the potential difference resulting from mechanical action.

3.2 Triboelectric transducer

3.2.1
triboelectric effect
type of contact electrification in which certain materials become electrically charged after they come into frictional contact with a different material

3.2.2
triboelectric series
list that ranks various materials according to their tendency to gain or lose electrons

3.2.3
triboelectric transducer
energy converter to generate electricity from mechanical energy by means of the triboelectric effect



Key

Configuration of energy harvester

$x(t)$ displacement

R external load

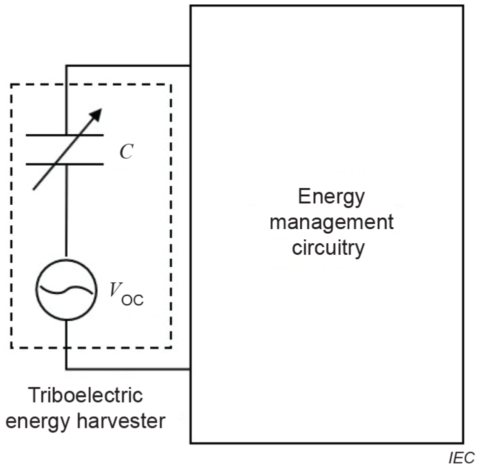
Figure 1 – Schematic of linear sliding mode triboelectric energy harvester

Note 1 to entry: A linear sliding mode triboelectric energy harvester can be divided into parts as shown in Figure 1. The equivalent circuit consists of capacitance C which stores charge as $+Q$ and $-Q$, open-circuit voltage source V_{oc} and external load R. Considering the materials to be used as the pair of the triboelectric layers, the sliding mode triboelectric nanogenerator (TENG) has two types: dielectric-to-dielectric and conductor-to-dielectric. The fundamentals of these two types are reported under Annex A.

3.3 Characteristic parameters

3.3.1
equivalent circuit
electrical circuit block diagram that has the same output voltage from relative displacement-based linear sliding mode triboelectric energy harvester in the immediate neighborhood of the acting force

Note 1 to entry: An equivalent circuit diagram of linear sliding mode triboelectric energy harvester is shown in Figure 2.



Key parameters

C capacitance

V_{oc} open-circuit voltage

Figure 2 – Equivalent circuit diagram of linear sliding mode triboelectric energy harvester

3.3.2
***V*-*Q*-*x* relationship**
relationship between the triboelectric output voltage, the amount of charge transferred between electrodes and the separation distance between tribological material surfaces

Note 1 to entry: Owing to the electrical potential superposition principle, the total voltage difference between the two electrodes can be given by Formula (1):

$$V = -\frac{1}{C}Q + V_{OC} = -\frac{d_0}{w\varepsilon_0(l-x)}Q + \frac{\sigma d_0 x}{\varepsilon_0(l-x)} \quad (1)$$

where, d_0 is effective dielectric thickness, w is dielectric width, ε_o is the permittivity of the medium, σ is the surface charge density, l is the length of the dielectric material, x is the lateral separation distance, and other parameters are as defined before.

3.3.3
open-circuit voltage
V_{oc}
electrical potential difference relative to a reference node of an energy harvester when there is no external load connected to the terminal of the energy harvester

Note 1 to entry: The theoretical V_{oc} expression for the linear sliding mode triboelectric energy harvester is given by Formula (2):

$$V_{OC} = \frac{\sigma x}{\varepsilon_0(l-x)}\left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}}\right) \quad (2)$$

where, d_1 and d_2 are the dielectric thickness, ε_{r1} and ε_{r2} are the permittivity of dielectric material 1 and 2, respectively, and the other parameters are as defined before.

3.3.4
short-circuit current
I_{sc}
current measured through the terminals of the energy harvester from induced excitation without external load

Note 1 to entry: The theoretical I_{sc} expression for linear sliding mode TENG is given by Formula (3)**Error! Bookmark not defined.**:

$$I_{SC} = \sigma w \frac{dx}{dt} = \sigma w v(t) \tag{3}$$

where w is the thickness of the dielectric material, $v(t)$ is the sliding speed of the triboelectric layer, and the other parameters are as defined before.

3.3.5
output voltage
V
electrical potential difference relative to a reference node of an energy harvester when an external load is connected to the terminal of the energy harvester

3.3.6
output current
I
<energy harvester device> current through the external load connected to the terminal of an energy harvester

3.3.7
output power
P
electrical power transferred to the external load connected to the terminal of an energy harvester

Note 1 to entry: The theoretical expression for the output power of linear sliding mode TENG is given by Formula (4):

$$P = VI \tag{4}$$

3.3.8
optimal load impedance
R_{opt}
specified value of the external load for transferring the largest electrical energy from the energy harvester

3.3.9
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 because of 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 may depend on the normal force between the two objects because of deformation.

3.3.10
contact force
applied force in the normal direction to the surface owing to friction at the interface of two triboelectric material surfaces

3.3.11
displacement
x
moving distance of one material from its original position

3.3.12
sliding speed
v
displacement per unit time of one material over another material surface while maintaining continuous contact

3.3.13
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 certain tolerances

3.3.14
temperature range
range of temperatures 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 blank specification

4.1 Identification and type

The linear sliding mode triboelectric energy harvester shall be clearly and durably marked with the following information, 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

Characteristic parameters should be listed in 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 linear sliding mode energy harvester for power generation without any damage.

Table 1 – Specification parameters for linear sliding mode triboelectric energy harvesters

Parameter	Symbol	Min.	Max.	Unit	Measuring conditions
Insert name of characteristic parameters					

4.3 Additional information

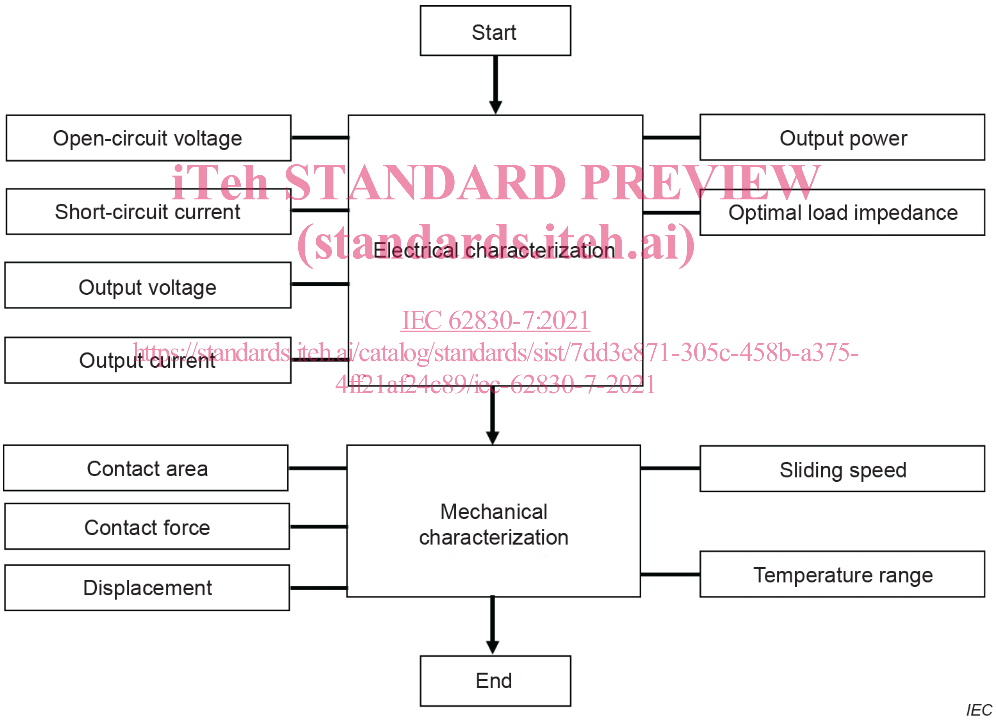
Some additional information should be given, such as equivalent circuits (relative displacement, internal impedance, output voltage, current, and power, etc.), handling precautions, physical information (outline dimensions, terminals, etc.), accessories, installation guide, package information, PCB interface and mounting information.

5 Test method

5.1 General

Basically, general test procedures for a linear sliding-based energy harvester are performed as shown in Figure 3. After the linear sliding mode triboelectric energy harvester has been mounted on a test fixture, it is measured by using an oscilloscope/electrometer and a linear variable differential transformer (LVDT). For measuring and characterizing these devices accurately, ultra-high-impedance meters should be used. Before connecting the triboelectric energy harvester to the test fixture, measuring meters shall be calibrated. After calibration, connect a test cable to the energy harvester test fixture mounted on an actuator or a force gauge. The output voltage or current reading on the display of the meters is carefully taken, together with induced linear displacement, which is measured by the LVDT.

After mounting the energy harvester on an actuator, the electrical characteristics are measured by using a meter or equivalent equipment. If the electrical characteristic measurements are satisfactory, the reliability test is performed under the relative humidity range with thermal cycling and various excitations.



Key			
Procedure	**Reference subclause**	**Procedure**	**Reference subclause**
Start			
Electrical characterization		Mechanical characterization	
Open-circuit voltage	3.3.3 and 5.2.2	Contact area	3.3.9 and 5.3.2
Short-circuit current	3.3.4 and 5.2.3	Contact force	3.3.10 and 5.3.3
Output voltage	3.3.5 and 5.2.4	Displacement	3.3.11 and 5.3.4
Output current	3.3.6 and 5.2.5	Sliding speed	3.3.12 and 5.3.5
Output power	3.3.7 and 5.2.6	Relative humidity range	3.3.13 and 5.3.6
Optimal load impedance	3.3.8 and 5.2.7	Temperature range	3.3.14 and 5.3.7

Figure 3 – Measurement procedure for sliding mode triboelectric energy harvester

5.2 Electrical characteristics

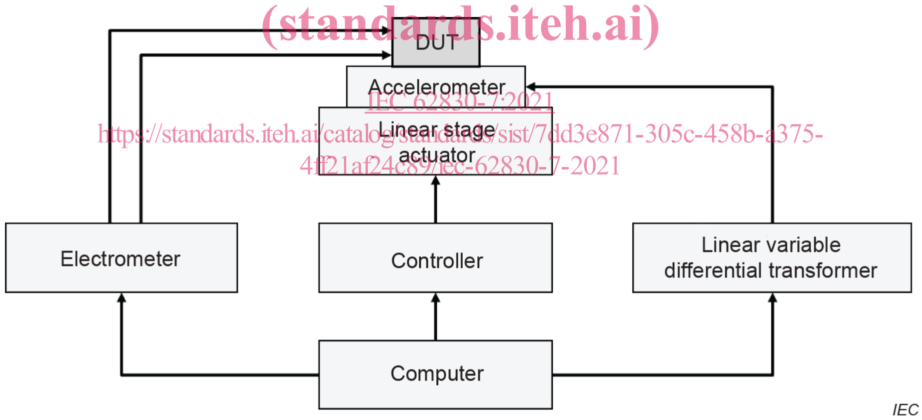
5.2.1 Test procedure

Figure 4 shows a test setup for measuring the electrical characteristics of a linear sliding mode triboelectric energy harvester. To measure the electrical characteristics of the energy harvester, the device shall be mounted on a linear stage actuator as shown in Figure 4. When a linear displacement is applied to the device, an output voltage or current across an external load is measured. The peak-to-peak value, RMS value, and frequency information for the instantaneous output waveform of the harvester can be obtained from the measuring equipment.

A description of two different linear sliding modes is given in Annex A. An example of experimental setup is described in Annex B. An example of measurement for a linear sliding mode triboelectric energy harvester is described in Annex C.

The following test procedure is performed:

1) A specified relative sliding is induced to the energy harvester.
2) 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.
3) The voltage and current are measured with various excitation by adjusting the parameters via a computer.
4) 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
Electrometer	to detect voltage, current, amount of charge transfer and resistance
Computer	to select input excitation and to get data points
Accelerometer	to measure the input excitation
Linear stage actuator	to apply linear motion as input in energy harvester
Controller	to control linear stage actuator
Linear variable differential transformer	to measure displacement between layers of energy harvesting device

Figure 4 – Test setup for the electrical characteristics of linear sliding mode triboelectric energy harvester

5.2.2 Open-circuit voltage

The objective of this test is to evaluate the instantaneous output voltage across the terminals of the energy harvester without external load. The input frequency, contact force, sliding speed, displacement, contact area, and input waveform for this measurement are 1,6 Hz, 20 N, 60 mm/s, 4 cm, 4 mm^2, and sinusoidal wave, respectively. When measuring open-circuit voltage, the input impedance of the voltage meter shall be recorded. Figure 5 shows the measured instantaneous peak-peak open-circuit output voltage profiles 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 voltage has 10 MΩ of impedance, then the meter will introduce a 1 % error owing to its relatively low input impedance. In contrast, an electrometer with 10^{14} Ω input impedance will cause only a 0,000 01 % error. Therefore, an input impedance of 10^{14} Ω is recommended for electrical measurements. Furthermore, parasitic capacitances in the system easily cause a long charging-discharging time constant. For example, if the capacitance is only 10 pF, a test resistance of 1 TΩ will result in a time constant of 10 s. Thus, a settling time of 50 s would be required for the reading to settle to within 1 % of final value. In order to minimize settling times when measuring high resistance values, shunt capacitance in the system shall be kept to an absolute minimum by keeping connecting cables as short as possible. The effect of voltage leakage and parasitic capacitance can be diminished further by shielding the cables and guarding the measurement device. Therefore, a shielded, low noise, triax cable (model 237-ALG-2 [1]) with guard mode ON on the Electrometer 6514 [2] is recommended to be used for electrical measurements.

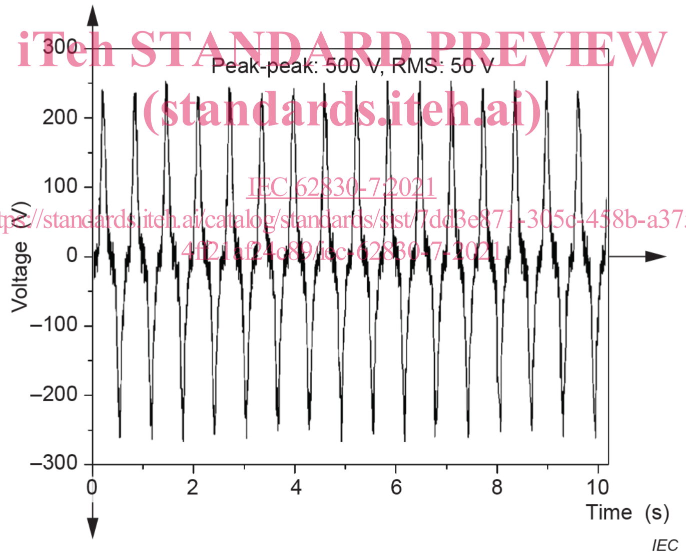


Figure 5 – Instantaneous open-circuit output voltage characteristic

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