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Characterization of Energy Harvesting systems from AC power lines

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***Abstract* – In recent years, energy supply has been a worldwide issue. The energy demand has increased enormously and involves all the main areas: industrial, automotive, health, monitoring, home-system, etc. Therefore, using renewable energy sources or other techniques becomes essential to produce energy. Energy harvesting systems are an indispensable alternative for converting ambient energy from the surrounding environment into electrical energy in powering autonomous electronic devices or circuits. This paper presents the characterization of energy harvesting systems for high voltage power lines. The system can recover energy from a source (DC or AC) to supply a load and manage the excess energy to a storage system. Some tests have been performed, and results have been discussed mainly from the energy point of view and self-consumption.**

I. INTRODUCTION

In recent years, there has been an increase in research aimed at recovering any energy that is daily dispersed in the environment and could be reused to meet specific purposes by creating electrical and electronic systems and devices [1]. Energy Harvesting indicates all the techniques used by electronic devices designed to obtain the necessary energy directly from the environment in which they operate [2]. Due to the scarcity of sources and the worsening of environmental pollution, sustainable energy development continues to attract increasing attention. In recent years, research has been explored, providing new approaches for the production of energy from renewable sources such as wind energy [3], thermal energy [4], solar energy [5], mechanical energy [6], and vibration energy [7], etc. The energy produced by this equipment could be used to power the sensors in a large-scale project that involves monitoring the structural health of bridges, tunnels, and buildings and monitoring energy consumption by implanted utilities, medical devices, and IoT systems [8] - [10]. In all these applications, energy harvesting plays a role of fundamental importance as it would allow continuity in operation. It converts non-electrical energy into electrical energy to power the device directly or by storing it in batteries or other storage systems that can operate the sensors. In this way, a self-recharging system is created, and maintenance interventions to be carried out are reduced. This can be advantageous in cases where the replacement of batteries is frequent or not accessible or in any case where the monitoring must take place without interruption of the service. For example, to monitor infrastructures, detect consumption, or monitor the state of health of a patient. In health applications [11], it is necessary to have a sensor suitable for monitoring the state of health, which a battery must power. When the battery runs out, it must be replaced, and this requires an intervention that is not always possible for the patient. Using a system that uses energy harvesting technology, monitoring occurs continuously without external interventions. This architecture can be applied in any field where: i) the device cannot be powered by a direct energy source and, therefore, the use of energy accumulators is required; ii) the replacement of the accumulators requires an intervention that can be carried out by specialized personnel; iii) it is necessary to provide continuous monitoring. For example, another field of application concerns the measurement systems of electricity consumption on power lines transmission lines where sensors can be used to collect information and monitor users' consumption and measure all magnetoelectric parameters such as voltage, current and magnetic field [12]. In such a system, the battery cannot maintain a permanent power supply for the sensors, leading to the sensors' replacement. However, sensors are often located in remote areas, in adverse work environments that reduce battery life, and in places where it is economically disadvantageous to replace them. For these reasons, it is crucial to collect energy from the surrounding environment to obtain a self-powered sensor to solve these problems.

II. CONSIDERATION ON ENERGY HARVESTING SYSTEM FROM AC POWER NETWORK

Conductors in power systems such as overhead lines, cables, and busbars usually carry a large mains frequency load current. In addition, a magnetic field H at the same frequency is also associated with this current. Over time, the variability of the electric and magnetic fields can generate an induced voltage on a coil that can be coupled through electromagnetic induction. The energy collected essentially takes place via an inductor, i.e., a Micro Energy Harvesting (MEH) [13], also called an Inductive Energy Harvester (IEH). The induced alternating voltages will subsequently be adapted to power the electronics using energy management and conversion module so that it is possible to obtain a stable low voltage direct current (DC) capable of supplying the connected loads. Conventionally, the power management module integrates surge protection, rectification, filtering, DC-DC conversion and other submodules. According to the different application modes of the front-end, the MEH can be divided into two categories: high potential MEH and low potential MEH as shown in Fig 1.

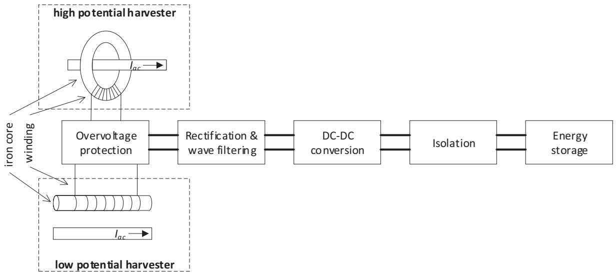


Fig. 1. High and low potential MEH block diagram.

A. Low potential MEH

In this case, the autonomous energy collector is formed by an iron core and a coil. It is positioned away from the HV conductors. There are no installation problems for low potential MEH as long as there is still a variable *H* field distribution in the space where the MEH is present. Conventionally, the collector has low potential as it will not be installed directly on the HV side; therefore, it is also known as the low potential MEH method. The advantage of the low potential MEH is greater installation flexibility which provides greater applicability to different scenarios. Theoretically, it can be used for sensors or systems suitable for monitoring the operating parameters involved as long as the magnetic field is present and the energy supplied by MEH is sufficient, even if the power is low. However, it isn't easy to measure [14]. Furthermore, in a low potential MEH device, the coil can be miniaturized, which can also be compatible with the fabrication of microelectromechanical systems (MEMS). In a low potential MEH device, since the parasitic *H* field is commonly weak, the most critical considerations are focused on designing the coil to improve its performance.

B. High potential MEH

Unlike the low potential MEH, the coil structure of the high potential MEH is of the ring type. In this way, the iron core closed in a ring is clamped on the section of a conductor carried by the current. As a result, the radial *H*-field generated by the current can be recovered in the iron core by the secondary induced voltage. Due to the high permeability of the iron core, the energy density of the high potential MEH is relatively large. Therefore, this type of MEH configuration is also called high potential magnetic field energy harvesting and can be mainly used for devices with transmission line monitoring purposes. The most significant advantage of high potential MEH is that the recovered power is significant; therefore, the application can require energy consumption even on several watts, such as, for example, video monitoring of the conditions of high voltage transmission lines, etc. Also, the state of power produced is stable as long as the line is powered, which is always significant as condition monitoring is only needed when the line is in service. The devices used for energy harvesting in the case of high potential MEH are usually: improved Rogowski coil, current limiting current transformer (CT), and compensating CT [15].

III. SETUP OF MEASUREMENT SYSTEM

The present paper characterizes energy harvesting systems for low potential and high potential MEH. The measurement setup is reported in Fig. 2 where: 1) e-peas AEM30940 energy harvesting has been adopted for managing the flow energy; 2) AGILENT 6613C supplies energy to AEM30940; 3) NiMH (Nickel-Metal-Hydride) rechargeable battery was used as a storage element; 4) via a mechanical switch, an external load of 90 Ω emulates an external system to supply; 5) Yokogawa WT3000 measures the input power from the AGILENT 6613C, the output power over the load and the bi-directional power on the NiMH rechargeable battery; 6) all the measurement has been stored and analyzed on a LabVIEW user interface.

The main parts of the measurement system are reported in detail in the following sections.

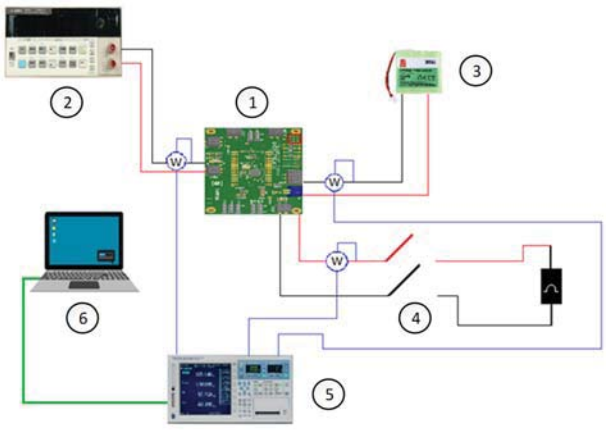


Fig. 2. Measurement system.

A. AEM30940

The AEM30940 is an integrated circuit that manages the energy produced by a piezoelectric generator, a turbine microgenerator, or any high-frequency RF input to store the energy in a rechargeable element and simultaneously power two low power loads with independent regulated voltages. The AEM30940 extends battery life and is used in a wide range of applications such as industrial monitoring, home automation, transportation and smart farming. The AEM30940 collects available input energy by absorbing up to 110 mA. It integrates an ultra-low-power boost converter to charge an energy storage element, such as a lithium-ion battery, thin-film battery, supercapacitor, or conventional capacitor. The boost converter works with input voltages in the range of 50 mV to 5 V. This device can start operating with empty storage elements, an input voltage of just 380mV, and an input power of only 3 µW. It features a system capable of powering a low voltage device at 1.2 V or 1.8 V (such as a microcontroller) and a high voltage device from 1.8 V to 4.1 V (such as a radio transceiver) simultaneously. LDO (Low Drop-Out) regulators drive both low noise and high stability. Various operating modes can be configured via pins by setting predefined conditions for the energy storage element (overload or over-discharging voltages) and selecting the voltage of the high voltage supply and the low voltage supply. In addition, special modes can be obtained by using some external resistors for the operational configuration of the device [16].

The block diagram is shown below.

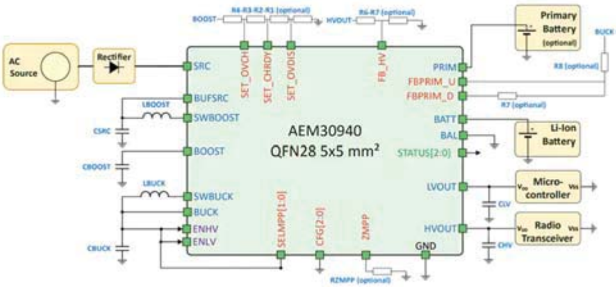


Fig. 3. AEM30940 block diagram.

B. Storage element

A NiMH (Nickel-Metal-Hydride) rechargeable battery was used as a storage element. The nickel-metal hydride accumulator is a type of rechargeable battery in which the cathode is made up of nickel oxyhydroxide (NiOOH), while the anode is made up of a composite hydride of metals, typically mixtures of lanthanides and nickel or other metals of the first series transition and/or aluminum.

NiMH batteries generally work with devices that require moderate power currents, such as digital cameras, cell phones, and consumer electronics.

The main characteristics are: i) technology: NiMH; ii) rated voltage: 3.6 V; nominal energy storage capacity cells type: 2/3AAA; dimensions: 30x30x10 mm;

C. Yokogawa WT3000

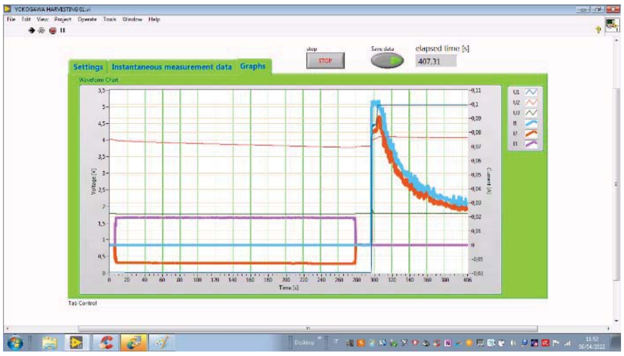
Precision Power Analyzer Yokogawa WT3000 has been adopted to measure the input power from the AGILENT 6613C, the output power to a load, and the bi-directional power of the NiMH rechargeable battery. The Yokogawa WT3000 has a power accuracy of ±0.02% reading, DC and 0.1 Hz to1 MHz measurement bandwidths, and up to four input elements.

D. Load

The load used to test the energy harvesting system is a resistive load where the resistance value was obtained considering that the AEM30940low voltage output channel is 1.8 V with a maximum current of 20 mA for the selected configuration. Therefore, a 90 Ω resistance was used. It was decided to use four 90 Ω resistors by connecting them in parallel and then putting them in series To dissipate the maximum deliverable current value. Even if the total resistance is 90 Ω, the energy dissipated on the load for every resistor is reduced to a quarter.

E. LabVIEW

The NI LabVIEW environment has been adopted for acquiring, processing, and saving the measurements. LabVIEW is a development environment for applications mainly oriented to data acquisition and electronic instrumentation management and the analysis and processing of signals. An ad-hoc software has been developed which collects Yokogawa WT3000 measurement data, displays the data in the UI, and saves the data in a CSV file for export to other software, as reported in the following figure.



elapsed time [s] 407,31

Fig. 3. The developed UI based on LabVIEW.

IV. TESTS

Different operating conditions have been considered. In detail: i) the behavior of the energy harvesting system in the presence or absence of the source has been examined; ii) the voltage and current values was measured for every element connected to the energy harvesting system, as well as iii) the different behavior of the energy harvesting system for different values of the input voltage. These tests were carried out by connecting and disconnecting the load to the AEM30940. The connection and disconnection of the load are made possible through a mechanical switch. The developed software in LabVIEW has been used to save the measurement data of Yokogawa WT3000 by sampling the data every 100 ms.

A total of five tests have been carried out, as shown in

Table I, in detail: battery charge tests without load with 1 V and 5 V power supplies ((1) and (3)), battery discharge tests with 90 Ω load applied (2), battery charge tests with 5 V and 1 V and applied load of 90 Ω ((4) and (5)).

Table I. Tests carried out.

Test number	Type	Supply (V)	Load (Ω)
1	Charge	Low (1 V)	---
2	Discharge	---	90 Ω
3	Charge	High (5 V)	---
4	Charge	High (5 V)	90 Ω
5	Charge/ Discharge	Low (1 V)	90 Ω

A. Test n.1

In this test, the load has been disconnected from the energy harvesting system while the power supply of the source is 1 V. The recorded values are shown in Figure 4. The starting voltage of the battery is approximately 3.6 V. Subsequently; the input voltage has connected to the AEM30940 board with a value of 1 V. The storage element begins to charge exponentially, reaching an asymptotic voltage value of about 4.1 V while the current value towards the storage system remains almost constant.

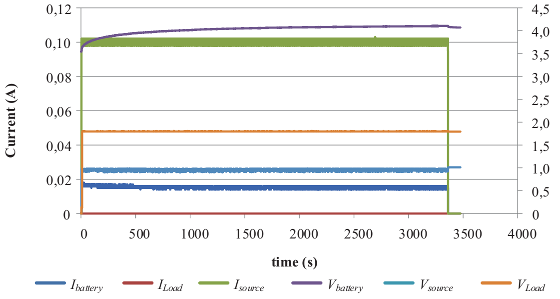


Fig. 4. Measurement results on test n.1.

B. Test n.2

In the second test, the load was connected to the harvester system. First, the power source was interrupted; then, starting from the maximum voltage accumulated in the battery during the charge transient (about 4.2 V), the resistance was connected, closing the mechanical switch. The data acquisition phase began immediately afterward. The battery voltage decreases slightly linearly during the discharge process, while the voltage on the load is constant. Finally, the current delivered to the load is relatively stable (see Figure 5).

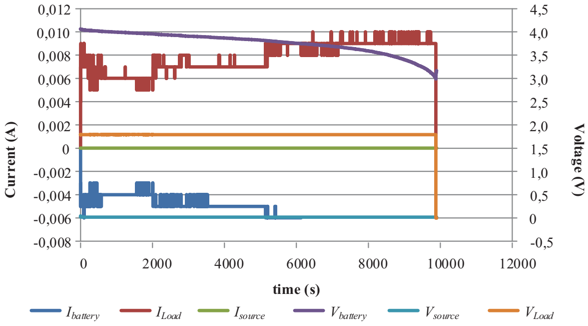


Fig. 5. Measurement results on test n.2.

C. Test n.3

In the third test, the harvester system was powered with a voltage of 5 V corresponding to the maximum input value while the load remained disconnected. As a result, the input supply presents a value higher than the maximum battery voltage. In addition, the current values of either the battery or the input source have a behavior that decays exponentially, unlike Test n.1 where the current values remain practically constant for the entire test duration.

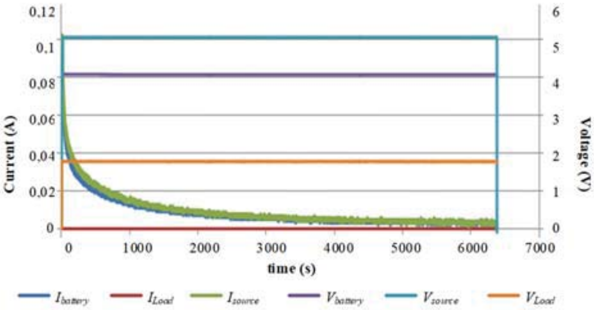


Fig. 6. Measurement results on test n.3.

D. Test n.4

In the fourth test, the harvester system has an input source voltage of 5 V, and the load is connected to the board. The maximum voltage that can be accumulated on the battery is reached in a very short time. The current either of the battery or the source decreases exponentially. There is a greater slope of the battery current ($I_{battery}$) than that of the source (I_{source}) while the current of load (I_{load}) remains constant, absorbing the same amount of power.

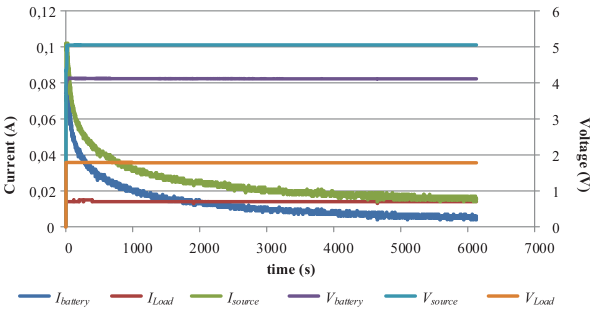


Fig. 7. Measurement results on test n.4.

E. Test n.5

In the fifth and last test, the response of the harvester system was measured during a charge, with a constant power supply at 1 V and a subsequent discharge. The test simulates the availability of energy from the input source for a certain time while it is missing. With a supply voltage of 1 V, the charge on the battery increases from 3.5 V to 3.9 V. Subsequently, the supply of energy is interrupted causing the charge accumulated by the battery to be discharged on the load. It is noted that the current absorbed by the load remains constant, and the board continues to supply energy to the load without interruption, guaranteeing continuity of service with the presence of the battery. Furthermore, the battery voltage (Vbattery) decreases during discharge until it reaches a minimum voltage value (2.8 V); then, the discharge stops. The load is no longer powered as the board disables the output voltage, and the battery voltage value returns to approximately 3.6 V.

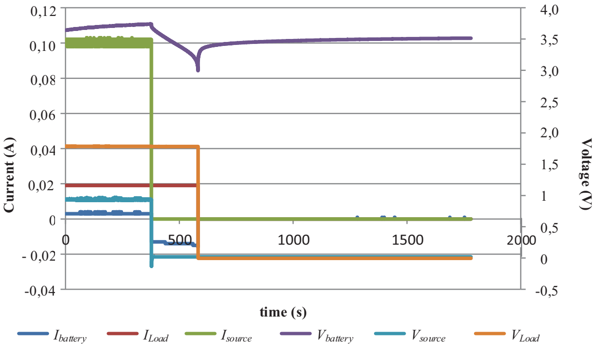


Fig. 8. Measurement results on test n.5.

V. RESULTS

The maximum voltage on the storage element was obtained by powering the system at 5V, corresponding to the maximum applicable input voltage on the board. The value of 4.35V is never exceeded; the voltage remains around 4.1 V in the other tests with an input supply voltage of 1V. During the charging phase, $V_{battery}$ tends to a value of 4.07 V or 4.35V (depending on the input source voltage). With a 1 V input source, the boost converter stops to recharge the battery when the voltage level reaches a value of 4.1 V. On the contrary, with a 5 V input source, a higher value has been reached.

When charging with a 1V input source supply, the voltage on the battery increases at a constant current (see Test 1 and Test 4). On the contrary, in the tests with a 5 V input supply, the charge takes place differently: the voltage increases and the current remains constant until the voltage on the battery reaches its maximum value, after which a reduction in the current is registered (see Test 2 and Test 4).

Finally, the following tables show the energy values recorded during the charging phase at 1V and 5V voltage with and without the connected load.

Table II. Energy comparison in mWh without a load connected.

	Supply (1 V)	Supply (5 V)
Source	89.44	85.82
Battery	57.34	61.29

Table III. Energy comparison in mWh with a load connected.

	Supply (1 V)	Supply (5 V)
Source	113.82	221.54
Battery	31.68	97.02
Load	27.57	42.68

Table II shows that the self-consumption amount regarding the energy supplied by the source without a load connected is 35.89% and 28.58% for the charging phase at 1 V and 5 V, respectively. While in Table III, the self-consumption amount respect on the energy supplied by the source with a load connected is 47.93% and 33.95% for charging phase at 1 V and 5 V, respectively. The results show the conversion efficiency is higher during the charging phase at 5 V, and in any case, the load connected to the energy system decreases the performance by 5%.

VI. CONCLUSIONS

This paper characterized an energy harvesting system in different operating configurations by changing the input supply values and connecting and disconnecting a load.

Using a LabVIEW-based UI that control the measurement performed by the Yokogawa WT3000, currents and voltages of input and output elements connected to the energy harvesting system have been measured and saved. The results show that the system's response under test presented an acceptable behavior, unwanted responses were found only for voltage values close to the operating ranges.

The conversion efficiency depends on the load connected and the supply voltage but can be considered about the 30% of the energy supplied by the input source.

The wide range of applications that these devices will have in the future and the enormous utility they can provide in various fields is expected to develop increasingly sophisticated and functional Harvesting devices.

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