Development of an Electromagnetic Energy Harvesting System Based on a Current Transformer for use in Industrial Electric Motors

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***Abstract*—Predictive maintenance systems for industrial electric motors are being developed using electronic sensors and wireless communication systems incorporated into ultra-low consumption electronic circuits. If the electronic circuit is ultra-low consumption, a simple low-capacity rechargeable battery can power the system for years. However, the use of batteries on a large scale contributes to environmental pollution. To eliminate the use of batteries, several energy harvesting techniques are being used to make the electronic sensors self-sustaining. In this sense, this paper presents the development of an electromagnetic energy harvesting system based on an off-the-shelf Current Transformer (CT), with the energy management done via Integrated Circuit (IC), for use in an Internet of Things (IoT) vibration monitoring system for industrial electric motors. A process was carried out to maximize energy generation through the design of a resonant frequency tuning capacitor, optimization of the electronic circuit for energy harvesting by adjusting a shunt resistor, and energy management based on the LTC3108 IC. The resulting energy harvesting system could generate a maximum output power of 1.657 mW, representing a percentage difference of +590.42 % of the system load power consumption, it is equivalent to about 6.90 times more than the necessary to make the IoT device energetically autonomous.**

***Index Terms*—Energy Harvesting, Current Transformer, EMF, Ultra Low-Power.**

I. Introduction

Approximately 70% of all electricity consumed by the industry in Brazil is used by electric motors, this represents about 24.5% of the total consumption, or 113.8 billion kWh [1]. Electric motors are essential elements for the industry so extending the useful life of these devices contributes to the performance of the industrial sector.

Predictive maintenance systems can extend the useful life of equipment, as they allow the projection of the lifetime and occurrence of other events. These systems reduce costs with maintenance or interruption of production lines [2]. Predictive maintenance systems are among the most important technologies promoted by the Industry 4.0 [3]. Their characteristics can vary depending on power, application, and equipment dimensions. In general, accelerometers can be used to monitor useful life, since healthy electric motors exhibit vibration patterns that change as it fails [3].

In an industrial environment, machinery is often monitored by multiple sensors to minimize the impact of failures. Several researchers have investigated the use of Micro-Electro-Mechanical Systems (MEMS) accelerometers as the Internet of Things (IoT) devices combined with wireless communication networks for vibration measurement of electrical machines [4]–[8]. MEMS have been widely used due to their small size, low cost, and low energy consumption, if compared to piezoelectric accelerometers. The IoT has enabled greater flexibility and freedom to maintain continuous real-time monitoring of electrical machines and can be used to monitor and diagnose the performance of induction motors [4], [7], [9]–[12] and wind turbines [13]. In addition to vibration, parameters such as current, voltage, temperature, power factor and frequency [9], [14] can be monitored. The acquired data is then sent wirelessly to a more powerful computer, where it can be stored and analysed.

The energy consumption of vibration monitoring systems varies mainly depending on the technology used for data communication [15]. In general, electronic circuits with ultra-low consumption are powered by small lithium batteries or via energy harvesting techniques. However, the lithium battery must be seen not only as an energy source, but also as a residue of potential toxicity that threatens the environment and biodiversity after the end of its useful life [16], [17]. In [18] the researchers explain that each battery improperly disposed of in the environment contaminates about one square meter of land.

On the other hand, energy harvest can minimize environmental impacts and reduce costs, representing a significant technological innovation [19]–[21]. Since it is a topic of great economic relevance, modern electric motors are increasingly energy efficient. Often, the greater the power demand of a motor, the better its cooling, stability, and containment of Electromagnetic Fields (EMF). A motor can give off EMF through the cables that connect it to the mains or due to the containment imperfections of the fields on its core. It is possible to harvest these EMFs to generate electrical power

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through Current Transformers (CT) that loop the electrical cables [22] or by precisely positioned coils along the electric motor [23]. Energy harvest using CTs has a greater capacity as electrical cables do not have EMF retention systems like electric motors; however, it is not always possible to access the power cables of large motors, which favours the use of coils placed over the motor. However, the use of coils also presents some drawbacks, as often these are hand-made (inductance may vary during the manufacturing process) and it can be difficult to place them on some electric motors in industrial environments due to vibrations that can cause accidental displacement of the coils.

This article presents the development of an electromagnetic energy harvesting system based on an off-the-shelf CT, with the energy management done using an Integrated Circuit (IC) to be used in the vibration monitoring of industrial electric motors. The sections are organized as follows: Section II presents related works; Section III describes the details of the IoT system used as a load for the energy harvesting circuit, and Section IV describes the processes of running maximization, and optimization of the energy harvesting circuit. Finally, Sections V and VI present the results and conclusions, respectively.

II. Related Works

In [24] the authors present an Ampere hour (Ah) measuring system based on a CT. It is a battery-powered ultra-low consumption circuit, consisting of a Texas Instrument MSP430 series microcontroller and a transceiver for radio communication. To measure currents, the authors used a "mini clamp" CT with a 2500:1 ratio that can measure currents up to 120 A_{RMS}. Although it is used only for the measurement of current, the off-the-shelf CT employed by the researchers presents great versatility and simplicity of installation due to the trigger in the clamp-type CT.

In [25], the author improved the system presented in [24]. In this system, the CT from the Ah meter can be used to generate electricity. To achieve energy autonomy, the author used the LTC3108 DC-DC converter, commonly used in energy harvesting applications. Even though the system achieves energy autonomy, the system still integrates batteries, due to the type of electronic instrumentation used to perform the measurements.

Unlike [25], in [26], [27] the authors describe an energy harvesting solution using CTs for Wireless Sensor Networks (WSN) used to estimate disaggregated current in large buildings. The authors used a Split-Core Current Transformer (SCCT), like the clamp-type CT, differing in the opening and closing system of the toroidal nucleus. The system was used to monitor currents between 65 and 130 A. The IoT system communicates via a ZigBee wireless network and the power management circuit is also based on the LTC3108 IC, however, unlike [25] that performs an external "OR" logic to manage the harvested energy, the authors of [26] used the independent $VOUT$ output of the LTC3108 to power the MSP430FR5739 microcontroller and the CC2530 transceiver. The terminal $VSTORE$ is electronically controlled by the microcontroller to allow not only the harvesting of energy but also the estimation of the electric current in the primary.

There are also works that avoid the use of commercial CTs, seeking energy optimization. In [28], [29], the researchers carried out the development of a power collector using a hand-built CT for industrial electric motors that draw between 20 and 100 A. In this case, the CT has two "U" shaped cores with $B_{sat} \approx 1.4\ T$ and 160 turns in the secondary winding. Even though the author used discrete components (low energy efficiency) in the development of the electronic circuit, the system achieved a maximum power of 12 W for a current of 100 A in the primary due to the manual construction of the CT. Despite the high power achieved, the system is not very versatile, as it is intrusive and requires an electrical wire to be inserted in to the collector. In [30] the authors seek to optimize energy generation through the construction of handmade CTs. The researchers developed a high-efficiency circuit management system using CTs with multiple windings to collect energy. The CTs have a relative magnetic permeability of $\mu = 4500$ and three secondary windings, with 3000, 1000 and 3000 turns, respectively. They carry an electronic circuit of discrete components to match, rectify and control the power generation on the coils in the secondary. Although the management circuit elaborated by the authors can power IoT devices with an output power of 60 mW at more than 40 m, its construction is not very versatile, needing improvements to make it viable for use on a large scale.

Regarding low-consumption circuits used in energy management, we mention the work of [31]. In that, the authors developed a self-oscillating DC-DC converter circuit using discrete components. The circuit was designed for low voltage and ultra-low power systems (4 μW – 1 mW) with high source impedance, typical of radio frequency (RF) energy harvesters. The circuit achieved up to 25 % efficiency with a voltage rise ratio of up to 9 times. In [32] the authors carried out a comparative analysis between the LTC3108, EH4295 and EH4205 DC-DC converters, which have start-up voltages of 20 mV, 60 mV and 75 mV, input resistances between 2.5 and 6.5 Ω, 700 and 1100 Ω, and 50 and 90 Ω and efficiency peaks of 40 %, 60 % and 30 %, respectively. These converters were used in a system that harvested energy from the movement of the human body through electromagnetic collectors.

Therefore, after analysing the aforementioned works, we noted that research focused on the development of hand-built or commercial CT-based energy harvesting systems, and electronic circuits for power management based on ICs or discrete components. Authors who used hand-built CTs, that present greater power generation capacity, chose to use electronic circuits based on discrete components. These, however, may have lower energy efficiency if the Printed Circuit Board (PCB) is not properly designed. On the other hand, the authors who chose to use off-the-shelf CTs, prefered to use ICs for energy management, as these have their efficiency described in the datasheets.

In this sense, this article aims to propose the development of a system for capturing electromagnetic energy based on an off-the-shelf CT, with the energy management done with an IC, to be used in electric motors. This work's main contributions are:

- Maximise the electrical power generation by tuning the resonant frequency of an CT;
- Achieve energy optimization of the electronic circuit used in the energy management through the adjustment of a shunt resistor;
- Adaptation of IC LTC3108's traditional circuit to operate with a CT;
- Use of an off-the-shelf CT in an IoT engine vibration monitoring system that can achieve energy autonomy.

III. Vibration Monitoring System

An energy harvesting system using a CT will be employed to supply power to a vibration monitoring system of electric motors described in detail in [33]. Figure 1 presents the high-level architecture of the device.

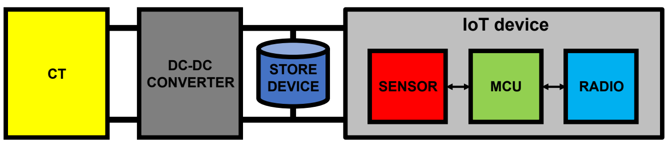


Fig. 1. High-level architecture - Autonomous IoT electric motor vibration monitoring system.

The IoT device is made of three main elements: a sensor, a microcontroller unit (MCU) and a communication radio, all operating on ultra-low power consumption.

As a sensor element, the system employs a KX134-1211 triaxial digital MEMS-type accelerometer. It has a quiescent current (I_q) of 148 μA, operating with voltage levels ranging from 1.7 V to 3.6 V. The microcontroller used was the MSP430FR5949 from Texas Instruments, like the one used by [24]–[26]. To carry out the periodic monitoring of motor vibration, the MCU alternates between active mode, with a consumption of 1.6 mA, and deep sleep mode, consuming a current of 250 nA. The change between modes of consumption occurs every 10 minutes, at which time the MCU wakes up and transmits 24 KB of data from the motor acceleration and then returns to deep sleep mode.

The data transmission is achieved via the MS50SFB1 Minew radio, which operates using the Bluetooth Low Energy (BLE) 5.0 protocol stack. The BLE module transmits at 4 dBm and operates with voltages between 1.8 V and 3.9 V, consuming a current of 5.3 mA during transmissions and 5.4 mA during data receptions. To make the device energetically self-sustainable, based on the work cycle and components' current consumption [33], we calculated that it would be necessary for the energy harvesting system to provide a minimum of 240 μW.

IV. Energy Harvesting Circuit

The electronic circuit used for energy harvesting using a CT was developed based on the operation of the LTC3108 IC [34] and is similar to the topologies described in [25], [26]. However, it differs from those as it neither needs any electronic keys in the input from terminal C_1 [25], nor a transistor to control the voltage level at the V_{STORE} terminal [26]. Both authors used the LTC3108 IC topologies because they needed to measure the primary current along with the power generation.

Due to cost reduction and energy consumption, the present work will carry out only power generation using a CT. The circuit diagram can be seen in Figure 2.

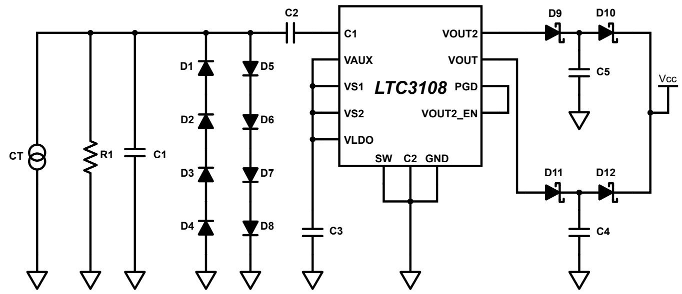


Fig. 2. Electronic circuit diagram - Energy harvesting using the LTC3108 integrated circuit.

The following subsections address the optimization process, running and management of the output voltage levels of the electronic circuit based on the LTC3108 IC.

A. Maximization of CT Power Generation

A CT generates electricity through the phenomenon of electromagnetic induction in electrical conductors. The variation of the magnetic flux that intercepts the CT, induces an electric current in the CT in the opposite direction of the electrical current that originated the magnetic flux, seeking to annul it. By adding a resistor across the CT terminals, the current from the CT flows through the resistor, generating a difference in potential. Due to its composition (wound wire), a CT has a high inductance value, which in Alternating Current (AC) circuits has an inductive reactance (X_L) which should not be neglected, as it contributes to the increase of electrical impedance (Z). Thus, a power generation via an inductive resistive CT (known as an RL circuit) circuit will generate power, but the X_L will reduce the generation efficiency.

To maximize the CT´s energy generation, it is necessary to eliminate the imaginary component (generated by the CT inductance) of Z. To do this, we just inserted a capacitor in the circuit, so that its capacitive reactance (X_C) became equal to the value of X_L, constituting an RLC circuit operating in resonance. Since the current in the primary is alternate (AC), with a frequency of 60 Hz (Brazil), it is possible to determine the value of the capacitor that cancels out the inductive component of Z using Equation 1:

$$f_r = \frac{1}{2\pi\sqrt{LC_r}} \tag{1}$$

where L is the CT inductance, C_r is the resonance tuning capacitor capacitance and f_r is the resonance frequency which, in this case, corresponds to 60 Hz. When a circuit operates at resonance, another design requirement must be considered, the quality factor Q, which value can be determined by Equation 2:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{2}$$

where R is the circuit electrical resistance, defined as shunt resistance (R_{shunt}). The higher the value of Q, the higher the value of the current delivered to the load, but the lower will be the AC signal bandwidth (BW) generated by the CT, so that any variation in the nominal values of the components of an RLC circuit with high Q implies a reduction of the generation performance. The RLC circuit to be tuned is represented in Figure 2 by the CT, R_1 and C_1. Therefore, both C_r and R_{shunt} must be properly chosen to guarantee the maximization of the CT´s energy generation.

B. The Input Voltage Protection Circuit on the LTC3108 Integrated Circuit

Since the CT-induced voltage generation is proportional to the electrical current of the primary, for high-power industrial electric motors, the current value of the primary can be high (greater than 100 A_{RMS}), promoting high values of induced voltage. The maximum input voltage level allowed on the terminal C_1 of the LTC3108 is 6 V. Higher voltage values can damage the IC.

Diodes were used to protect the input of the LTC3108 IC. The diodes D_1, D_2, D_3 and D_4 were inserted to cut the undervoltage of the negative half-cycles of the sinusoid generated by the CT. Symmetrically the diodes D_5, D_6, D_7 and D_8 were also inserted to cut the overvoltage of the positive half-cycles of the sinusoid. All the diodes used in the clipper circuit are rectifier type, with high direct voltage drops (V_D). We decided to use two BAV99 switching diodes, as they have 2 diodes internally connected in series to the encapsulation with $V_D \approx 0.715$ V per diode.

C. The LTC3108 Integrated Circuit

The LTC3108 IC can operate with several power harvesting solutions. In this work, the LTC3108 IC was configured to operate with a CT. In that case, the terminals SW and $C2$ must be grounded since the input voltage is already AC type.

The LTC3108 IC maximum output voltage level can be controlled through the terminals $VS1$ and $VS2$, ranging from 2.35 V to 5 V. The voltage level was set to 5 V output by connecting $VS1$ and $VS2$ to the terminal $VAUX$. To reduce the consumption of I_q on the LTC3108 IC as much as possible, and so promoting energy optimization, we turned off the Very Low Dropout voltage regulator (VLDO) internal to the LTC3108 IC, connecting the $VLDO$ terminal to the $VAUX$. Instead of using the LTC3108 VLDO, the TPS7A0225 VLDO was used, which has 2.5 V, I_q of 25 nA and dropout of 270 mV (max) to 200 mA. Therefore, the energy harvesting circuit charges the output capacitor up to 5 V, and the IoT device already starts to operate normally after 2.75 V (max). The rest of the energy is stored in the supercapacitor in order to keep the IoT device operating for long periods of energy collection absence.

The LTC3108 IC has two output terminals, terminals $VOUT$ and $VOUT2$. The $VOUT$ is the main circuit output since $VOUT2$ is only enabled if the terminals PGD and $VOUT2_EN$ are short-circuited, as seen in Figure 2. In this way, both output terminals will be used to power energy storage devices (third block of Figure 1).

D. The OR Logic

As described previously, $VOUT$ and $VOUT2$ are used to power energy storage devices. Capacitors were used to store energy to avoid the use of lithium batteries. As described in [34], the terminal of PGD only changes logic level when the voltage output $VOUT$ reaches the value programmed by the terminals $VS1$ and $VS2$, in this case, 5 V. Therefore, $VOUT$ starts charging capacitor C_4 first. Once $VOUT$ reaches 5 V, $VOUT2$ starts charging capacitor C_5. Due to this charging sequence and, due to the device´s ultra-low power consumption, capacitor C_4 can have a minimum capacitance and so leave the MCU turned on in LPM3.5 mode. In LPM3.5 mode the MCU is in deep sleep state and is activated by an interrupt signal via Real-Time Clock (RTC). In this state, the core supply voltage regulator is completely disabled. Thus, the CPU and all digital modules including RAM are unpowered. In this case, the typical electrical current consumption of the MCU is about 250 nA. A 1 to 10 μF capacitor is enough, and in this case, a 10 μF Multilayer Ceramic Capacitor (MLCC) was chosen. The capacitor C_5, on the other hand, must have high capacitance, to be used during BLE data transmissions. For a power consumption of 240 μW, C_5 must be a 5.5 V supercapacitor and have a minimum capacitance of 120 mF.

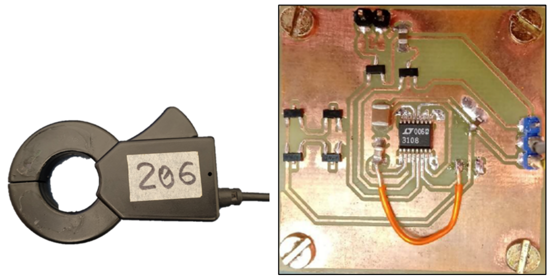
To keep the V_{CC} voltage constant for the IoT device, an "OR" logic was implemented between $VOUT$ and $VOUT2$. Thus, the terminal with the highest voltage will be the terminal that will feed the load. However, unlike the diodes used in the clipper circuit, the diodes on the "OR" logic circuit must have low V_D values and reverse current (I_R). In this case, two BAR43S diodes were chosen, as they have two Schottky diodes internally connected in series, with $V_D \approx 0.35$ V and $I_R = 500$ nA.

V. RESULTS

To maximize energy generation, the CT inductance was measured. To do that, we used the model LCTC-0250 [35], a mini-clamp type CT, with a ratio of 2500:1 and a maximum current of 120 A. Using the LCR Meter 4284A from Hewlett Packard (HP), we found the inductance of the CT as $L = 6,467$ H. According to Equation 1, we calculated the frequency tuning capacitor capacitance $C_r = 1.088$ μF.

Figure 3(a) shows the CT model used and Figure 3(b) presents the prototype of the PCB built to carry out the experiments in the laboratory. We connected in parallel a 1 μF capacitor with an 82 nF capacitor to approach the ideal value of C_r.

After building the PCB and connecting it to the CT, we optimized the energy harvesting circuit. This process consisted of determining the R_{shunt} under the best conditions in Equation 2. To find the R_{shunt} value, a test was set up in the Laboratory of Solutions in Electronics and Radiofrequency (LSERF) at the School of Electrical and Computer Engineering (FEEC) at Unicamp, as seen in Figure 4.



(a) (b)

Fig. 3. Electronic circuit prototype: (a) CT model LCTC-0250 used, (b) PCB built.

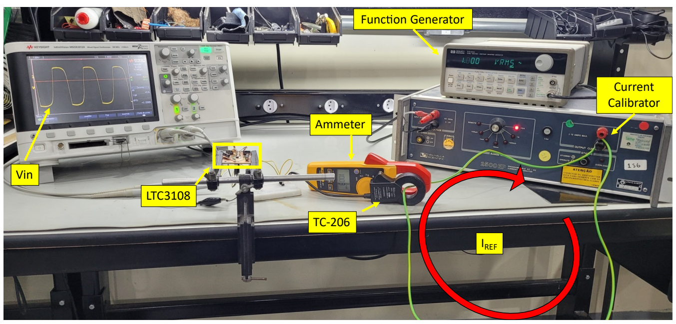


Fig. 4. Energy harvesting circuit test setup showing the equipment used.

The setup seen in Figure 4 consists of monitoring the input voltage (Vin) generated by the CT and the voltage at the high capacitance capacitor (V_{C_5}), in this case, a 1.8 mF, as a Proof of Concept (PoC). The primary current is generated using a current calibrator (Valhalla Scientific 2500EP), an instrument of high precision capable of generating a current signal of reference (I_{REF}) to power the CT used ($TC-206$).

A function generator (HP 33120A) was used to generate the 60 Hz I_{REF} sine wave pattern. We also used a digital ammeter clamp (Fluke 302) to examine the accuracy of the *RMS* current. The measured current remained within the stipulated values, with a precision of three decimals places.

Several current patterns were generated, in the range of 1-10 A, as well as in the range of 10-100 A. Figures 5 and 6 display the shapes of the sinusoids in Vin generated by the CT and measured by an oscilloscope (Keysight MSOX2012A).

As can be seen in the sinusoids presented in Figures 5 and 6, the clipper circuit protected the C_1 terminal of the LTC3108 in all cases. Furthermore, the C_r guaranteed that the sinusoid reached the maximum value in all cases.

To optimize the energy harvesting circuit, we carried out the same test for the following values of R_{shunt} (R_1 in Figure 2): 10 kΩ, 47 kΩ, 100 kΩ, 470 kΩ, 1 MΩ. Figure 7 plots the summary of the tests for the different values of R_{shunt} used.

Analysing Figures 7(a) and 7(b), we noticed that the $R_{shunt} = 1M\Omega$ is the best resistor for low currents, but it is the worst resistor for high currents. On the other hand, the $R_{shunt} = 47\ k\Omega$ has intermediate performance at low currents and has the best performance at high currents. Therefore, $R_{shunt} = 47\ k\Omega$ was considered the best candidate to operate on both current ranges.

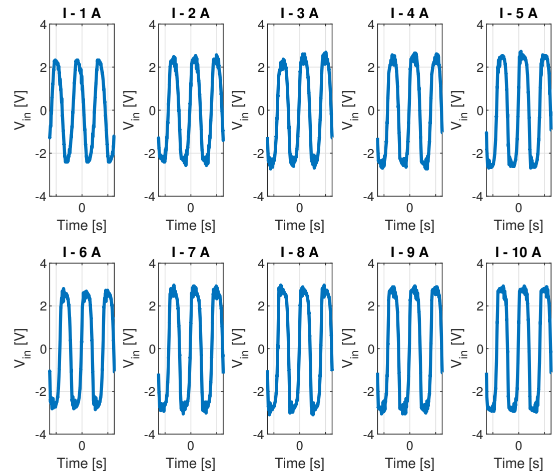


Fig. 5. Sinusoids generated by the CT, Time (s) × Vin (V): ranging from 1 to 10 A.

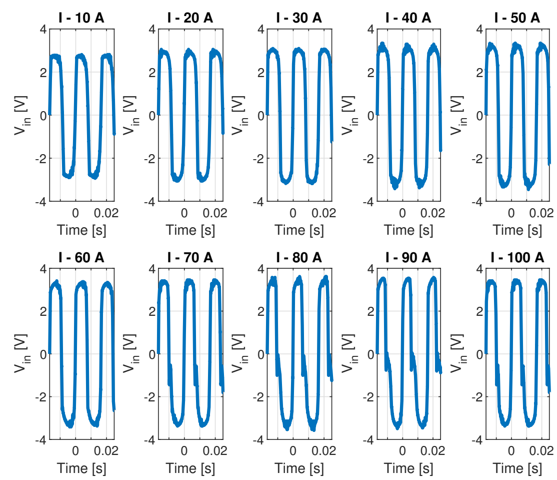
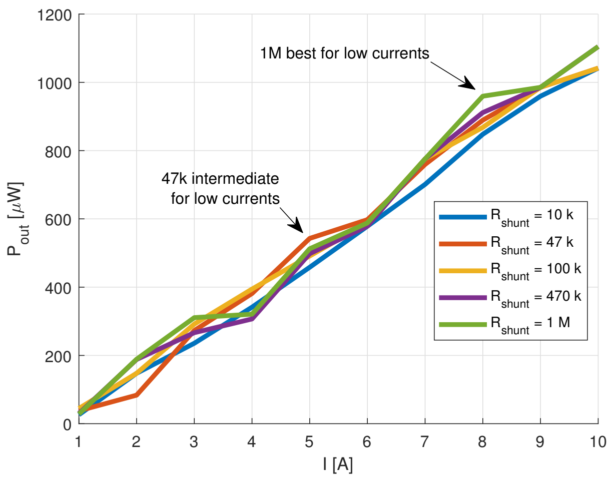


Fig. 6. Sinusoids generated by the CT, Time (s) × Vin (V): ranging from 10 to 100 A.

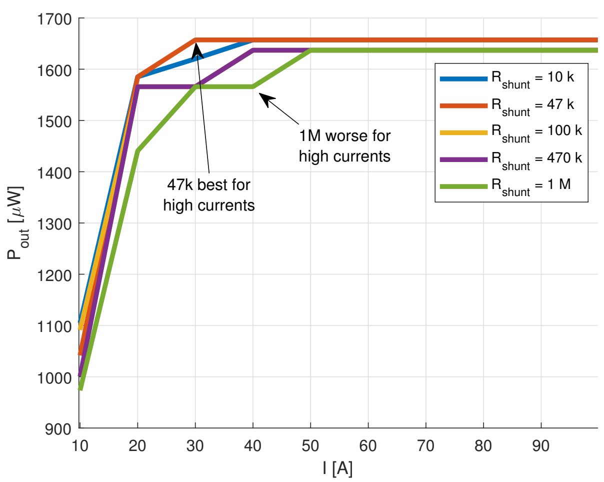
With $R_{shunt} = 47\ k\Omega$, the IoT device becomes self-sustaining from a primary current greater than 2.83 A_{RMS}, and the energy harvesting circuit via CT was able to generate a maximum output power (P_{out}) of 1.657 mW, equivalent to +590.42 % of the IoT electric motors vibration monitoring system projected consumption.

Finally, to validate the correct circuit operation, an experimental test was carried out with a 75 HP three-phase electric motor used in the system of an electrodynamic exciter at the Laboratory of Dynamic Tests (LabEDin) at Unicamp, as shown in Figure 8(a).

As seen in Figure 8(b) the motor used has a current consumption of 54.8 A per phase. When using the circuit proposed in this paper, the circuit provided a maximum power of 1.600 mW, similar to that predicted by laboratory tests, validating its correct operation.

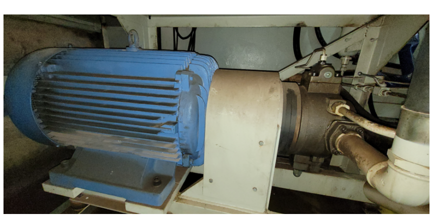


(a)

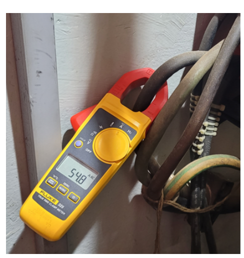


(b)

Fig. 7. Power generation via CT response curves, I (A) × P_{out} (μW): (a) ranging from 1 - 10 A and (b) ranging from 10 - 100 A.



(a)



(b)

Fig. 8. Experimental tests with a real electric motor: (a) used motor and (b) motor current consumption.

VI. Conclusions

The energy generation maximization through C_r, the optimization of the energy harvesting electronic circuit (by removing the electronic keys from the input and output of the base circuit) and the adjustment of R_{shunt}, enabled the use of an off-the-shelf CT alongside an electronic energy harvesting circuit based on IC (in this case the LTC3108).

The energy harvesting system was able to generate a P_{out} of 1.657 mW, about 6.90 times more than necessary to make the IoT device energetically autonomous.

Therefore, the electromagnetic energy harvesting system based on a CT proved practical to be used in industrial electric motors, up to 100 A_{RMS}. In future work, we intend to evaluate the performance of the energy harvesting circuit in an industrial environment, where high levels of temperature, humidity and mechanical vibration are present since such factors can influence the nominal values of passive components, as well as the I_q on the IC, causing a reduction in system performance.

Acknowledgements

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