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Design Considerations for Current Transformer Based Energy Harvesting for Electronics Attached to Electric Motor

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***Abstract*—Energy harvesting or scavenging from environment is being researched intensively. The main motivation of the research is to develop a maintenance free energy source for ubiquitous electronics, such as wireless sensors or sensor networks. The on-line condition monitoring of electric motors requires also sensors that are installed at the motor. In this case, the energy required by sensors could be harvested from a magnetic field. In this article, current transformer based energy harvesting is considered. A switch-mode power supply utilizing current transformer is designed. It is tested in laboratory with the mains supply and variable speed drive. According to the tests carried out, the current transformer based power sources are a feasible alternative to supply the electronics attached to an electric motor.**

***Index Terms*—Condition monitoring, current transformers electrical drives, energy harvesting.**

I. Introduction

Energy harvesting or scavenging from environment is being researched intensively. The main motivation of the research is to provide an energy source for pervasive wireless sensor networks used in diverse application environments, such as, domestic, industrial, and military. According to [1], some of the possible energy sources are thermal differences, ambient light, radiation, airflow, ambient radio frequency, and mechanical vibrations. Energy harvesting technologies and their characteristics are described and analyzed for example in [2]-[7]. The performance of some harvesting methods is presented in Table I. These methods are generally capable of producing energy for low-power wireless sensors, which have duty-cycle less than 1% (sensor active time/total time).

According to [8], reliable on-line condition monitoring of electrical motors requires sensors installed at the motor. In addition, a network or a bus connection is required for information exchange. A possible method for data transmission is power line communication, which is described and analyzed for instance in [9]. Compared to ubiquitous wireless sensor networks, such as home automation networks, generally more energy is required both for sensing and communication in electric motor on-line condition monitoring. The most significant factors affecting this are: different typical measurements (temperature vs. vibration), data transmission rate (bps vs. kbps), data transmission distance (meters vs. tens of meters). Due to this, a different approach for energy harvesting is required.

TABLE I
ENERGY HARVESTING METHODS AND DEMONSTRATED CABABILITIES [1].

Harvesting method	Performance
Ambient radio frequency	< 1 μW/cm^2
Ambient light	100 mW/cm^2 (directed toward bright sun) 100 μW/cm^2 (illuminated office)
Thermoelectric (ΔT = 5°C)	60 μW/cm^2
Mechanical vibration	4 μW/cm^3 (human motion, f ~ Hz) 800 μW/cm^3 (machines, f ~ kHz)
Ambient airflow	1 mW/cm^2

In the case of electrical motors a feasible energy source is the alternating magnetic field around a phase conductor, from which energy can be harvested for example with a current transformer. Current transformers are generally used as current measurement instruments. The main design principles of those are linearity and sufficient secondary load ability [10]. However, current transformers can also be used as power supplies for electronics attached to an electric motor. The electronics is typically used both for sensing and communications. Typical applications for the electronics are vibration, acoustic emission, temperature, and rotation speed measurements. In these applications current transformer based power supplies have benefits compared to voltage transformer based power supplies. The power supply can be installed on-line without electrical installation work. The current transformer is galvanically isolated from the mains voltage. Hence, the malfunction of the power supply does not degrade the reliability of the monitored system. The current transformer, as well as voltage transformer, tolerates harsh environmental conditions without degradation in performance. In this application, the current transformer's non-linearity is not a problem. Also, the core saturation can utilized to limit transformer's secondary voltage.

With the current transformer, the energy from magnetic field can be harvested efficiently and utilizing

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low cost materials, such as grain oriented silicon steel cores. This results in a low-cost and compact size power supply. Estimated achievable power densities of current transformer based power supplies with toroid cores and with different diameters D (center-to-center) as a function of primary current are presented in Fig. 1. According to Fig. 1, the method provides significantly more power in the same area or volume than the other harvesting methods presented in Table I. The maximum current in Fig. 1, 100 A, equals to the nominal phase current of an low voltage induction motor (55 kW, 3-phase, 400V / 50 Hz).

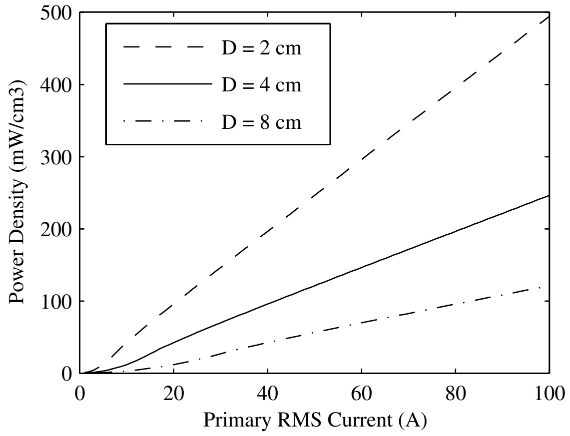

Fig.1. Estimated maximum power densities of ring core based power supplies as a function of primary current. The curves are estimated for three toroid core diameters (center-to-center). The magnetic characteristics of the core material are: B_{sat} = 1.4 T, μ_r = 9500. The supply frequency f is 50 Hz.

The paper is organized as follows. In Section II, the characteristics of a current transformer as a power supply are discussed. The design of a switch-mode power supply for a current transformer is presented in Section III. In Section IV, laboratory measurements are carried out and measurement data are analyzed. The paper is finished with a concluding section.

II. Current Transformer as Power Supply

An equivalent circuit of an ideal current transformer is presented in Fig. 2. Leakage inductances, coil resistances and core losses are assumed to be insignificant. The secondary winding of the current transformer is terminated by a load resistor. In this particular application, there is always a single turn in a primary winding.

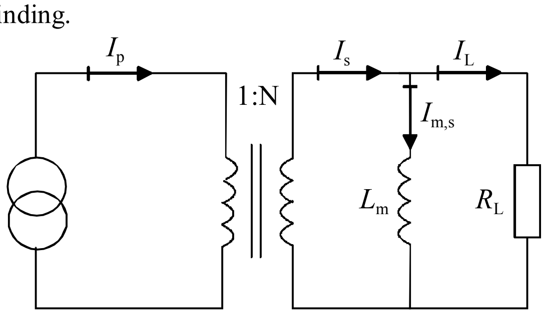

Fig.2. Equivalent circuit of an ideal current transformer.

The current transformer operates with the ampere turn balance:

$$I_p = N \cdot I_s , \tag{1}$$

where I_p is the primary current, I_s the secondary current and N the number of secondary winding turns. Both currents are assumed to be sinusoidal and represent as RMS values. The secondary current of the current transformer can be written:

$$I_s = \sqrt{I_{m,s}^{\ 2} + I_L^{\ 2}} , \tag{2}$$

where $I_{m,s}$ denotes magnetizing current and I_L the load current, respectively. The equation for the secondary voltage U_s can be written based on the equivalent circuit (Fig. 2):

$$U_s = R_L I_L = \omega L_{m,s} I_{m,s} , \tag{3}$$

where R_L is the load resistance, $L_{m,s}$ the magnetizing inductance from the transformer secondary side, and ω the angular frequency. Power P_L delivered to the load resistance can be written:

$$P_L = U_s I_L = \omega L_{m,s} I_{m,s} I_L . \tag{4}$$

The magnetizing inductance is a parameter that is defined in the design phase. It is a key element defining the power available to the load. The magnetizing inductance depends on several factors, such as the core dimensions, the core material magnetic characteristics, the core flux density and the number of turns in the secondary winding. In the case of toroid core without an air gap, the magnetizing inductance is given by:

$$L_{m,s} = \frac{\mu_0 \mu_r A_e N^2}{\pi D} , \tag{5}$$

where A_e denotes the effective core area, N is the number of secondary winding turns, and D the center-to-center diameter of the core. The constants μ_0 and μ_r represent permeability of vacuum and the relative permeability of the transformer core material. The maximum output voltage is limited by the transformer core saturation flux density B_{sat}. The maximum allowed magnetizing current can be written:

$$I_{m,s,max} = \frac{B_{sat} \pi D}{\mu_0 \mu_r N} . \tag{6}$$

In this case, it is assumed that the loading of the current transformer secondary does not affect the primary current. Practically, the current transformer generates additional serial impedance to the phase conductor of a motor cable. If the primary RMS current is 100 A and the secondary load power 10 W, the resulting voltage drop due to the additional serial impedance is about 0.1 V. This can be considered insignificant, since it is less than 0.1 % of phase voltage (400 V). In order to reduce the amount of required core material, the current transformer core diameter should be designed as small as practically possible (Eq. 4, Eq. 5).

III. Design of Switch-mode Power Converter

The current transformer is an AC current source. In this specific application it can also be considered to be a constant (RMS) current source. In general, low power electronics is supplied with a DC voltage source. Hence, a power converter is required to regulate the AC current, produced by the transformer, to a suitable DC voltage.

The schematic of the designed switch-mode power converter is presented in Fig. 3. The current transformer produces an AC load current, which is determined by the primary current, the secondary winding turns N, and required secondary voltage U_s (Eq. 4, Eq. 5). The secondary current is rectified by a diode bride rectifier D_1. An n-type MOSFET Q_1 (Metal-Oxide Field Effect Transistor) is used as the switching element of a power supply. It controls the route of the current that is produced by the current transformer. If the output voltage level V_{dc} is sufficient, the transistor Q_1 is switched on. Otherwise, Q_1 is kept off. In this case, the current transformer output current is used to load the capacitor C_{dc} and to supply current to a load connected to the power supply. The diode D_2 prevents current flow from energy storage capacitor C_{dc} to the ground through transistor Q_1.

The simple regulator circuit built using an operational amplifier Q_2 is a hysteresis comparator. It switches transistor Q_1 (on/off) based on output voltage level V_{dc}. The reference voltage to the hysteresis comparator is produced by the zener diode D_3 and the current limiting resistor R_3. The output voltage level and hysteresis is adjusted by resistors R_1, R_2, R_4, and R_5. Output voltage limits are given by:

$$V_{dc,max} = V_z \frac{(R_1 + R_2)(R_4 + R_5)}{R_2 R_5} \tag{7}$$

$$V_{dc,min} = V_z \frac{(R_1 + R_2)(R_4 + R_5)}{R_2 R_5 + R_4 (R_1 + R_2)}, \tag{8}$$

where V_z denotes the breakdown voltage of the zener diode D_3. It has been assumed that $R_1, R_2 << R_4 + R_5$.

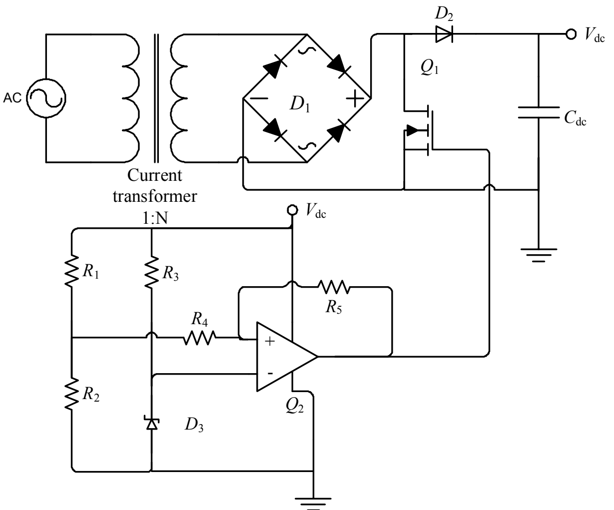

Fig. 3. Schematic of the power supply. The output voltage level V_{dc} is controlled by the transistor Q_1 and a hysteresis comparator.

IV. LABORATORY MEASUREMENTS

The current transformer and a simple switch-mode power converter were built for the laboratory measurements. The goal was to design a DC power supply with output voltage of 24 V and output power of 10 W at primary current of 100 A.

The built current transformer is illustrated in Fig. 4. The core dimensions were $A_e = 0.512 \cdot 10^{-3}$ m^2 and core length l =0.212 m (along core center line). The number of secondary winding turns was $N = 160$. The magnetic properties of the core at 50 Hz were $\mu_r \approx 9500$ and $B_{sat} \approx 1.4$ T. The values were determined by laboratory measurements. The power converter was built on a printed circuit board. The resistors and the zener diode of the converter were selected such that the converter output voltage varies between V_{dc} = 23.9-26.4 V.

Fig. 4. Current transformer installed around a phase conductor of an electric motor. The transformer core consists of two U-cores, which are manufactured from grain oriented silicon steel.

A. Measurements with 50 Hz Sinusoidal Current Supply

The performance of the current transformer based power supply was measured with a sinusoidal primary current supply. First, the maximum output power as a function of I_p was measured. A resistive load was connected to the output of the power supply. The load resistance was adjusted at each primary current level to achieve the maximal output power. The tests were carried out with a single current transformer and two identical transformers connected in parallel. The test results are illustrated in Fig. 5.

According to the measurements (Fig. 5), the output power increases linearly as a function of the primary current. The usage of two parallel transformers approximately doubles the output power. The output power with a single transformer and at 100 A primary current is approximately 12 W.

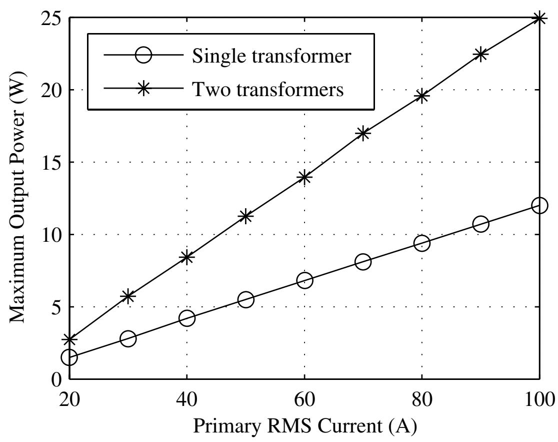

Fig. 5. Maximum output power as a function of primary current. The usage of two identical transformers in parallel doubles the output power. The supply frequency of the current transformer was 50 Hz.

The output voltage waveform of the power supply at different operation points was measured. The primary current was set to 80 A, and the load resistance was adjusted such that the maximum output power was achieved. The output voltage waveform of this test is illustrated in Fig. 6. The average output voltage is about 24 V, and the voltage ripple is about 1.5 V (peak-to-peak). The output voltage remains between the hysteresis limits (23-24.5 V) and the transistor Q_1 is not switched. Next, the load impedance was increased. The power consumption was reduced and the hysteresis comparator started to regulate the output voltage by switching the transistor Q_1. The output voltage waveform of this test is illustrated in Fig. 7. The average voltage is now about 24 V, and the voltage ripple increases to about 3 V (peak-to-peak).

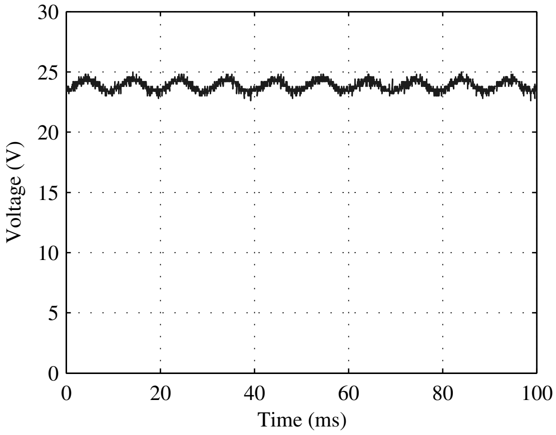

Fig. 6. Output voltage waveform with 80 A (RMS) primary current and 50 Hz supply frequency. The load resistance is adjusted in order to achieve the maximal output power. Voltage regulation by hysteresis comparator is not required, as the output voltage remains between the hysteresis limits (23-24.5 V).

The efficiency of the power converter was also determined by measurements. The primary current was set to 100 A (RMS). The efficiency of the converter was calculated at different loads ranging from 30% to 100% of maximum output power. The converter efficiency as a function of output power is illustrated in Fig. 8.

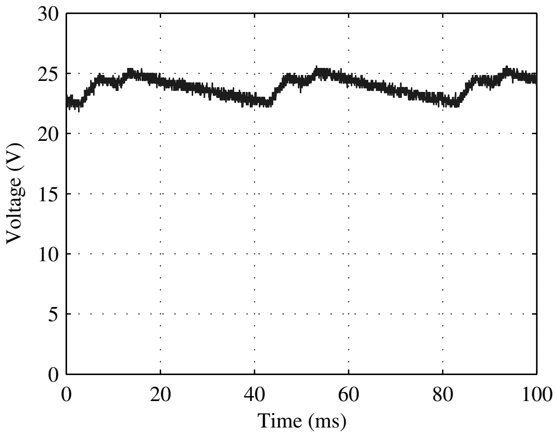

Fig. 7. Output voltage waveform with 80 A primary current and 50 Hz supply frequency. The output voltage is regulated within hysteresis limits by the hysteresis comparator.

According to Fig. 8, the efficiency is about 0.94 at full load and decreases to about 0.83 at 30% load. This is reasonable, since at full load all the rectified current is delivered to the load. The power loss is mainly produced by the rectifier bridge D_1 and the diode D_2. It can be reduced for example by using schottky diodes. At partial loads, the hysteresis comparator regulates the output voltage by the switching transistor Q_1. When Q_1 is off, the power loss is mainly produced by D_1 and D_2. Correspondingly, when Q_1 is on, the power loss is mainly produced by D_1 and Q_1. The total power loss is a combination of these two states. The current transformer and the converter have to be sized according to the maximum required power, the lowest primary current, and the lowest supply frequency. Due to this, the converter probably operates primarily at partial loads. Hence, it is essential to try to minimize the power loss both in rectifier bridge D_1 and transistor Q_1.

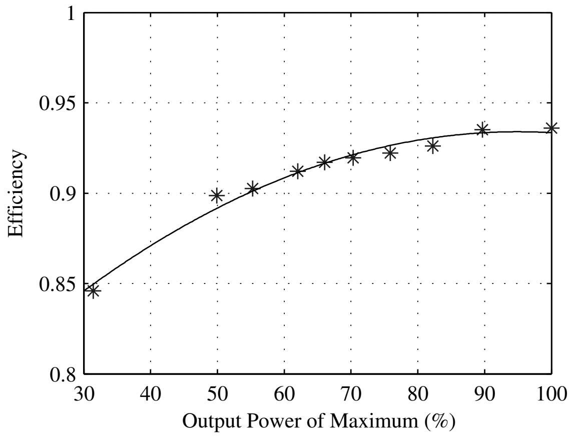

Fig. 8. Efficiency of the power converter as a function of output power. The data points denote measured efficiencies. The curve is produced with a quadratic curve fit for the data points. The primary current was 100 A (RMS) and supply frequency 50 Hz. The output power of 100% corresponds to 12 W.

B. *Measurements with a variable speed drive*

The current transformer based power supply discussed in this paper is designed both for fixed speed and variable speed electrical drives. Hence, measurements were also carried out with a variable speed drive. Drive system consisted of ABB ACS 400 inverter, MCCMK 3x35+15 low voltage power cable (length 90 m), and Invensys 15 kW, 4-pole induction motor. The supply frequency of the inverter was set to 50 Hz. In this case, the number of primary turns in current transformer was set to 15 resulting primary RMS current of 69 A. The load resistance of the power supply was 261 Ω. Measured power supply and current transformer output voltage waveforms are presented in Fig. 9.

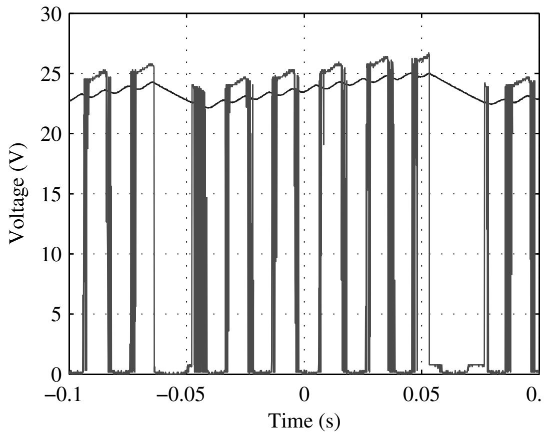

Fig. 9. Regulated output voltage waveform of power converter and current transformer secondary output voltage waveform. The primary RMS current is 69 A and the load impedance is 260 Ω. The voltage regulator circuit switches transistor Q_1 twice on/off.

In Fig. 9, the hysteresis comparator switches Q_1 twice on and off during the measurement. Only positive voltage waveforms of the current transformer output voltage are visible, since the oscilloscope ground was bound to the power supply ground. In order to measure both waveforms correctly (rectified output voltage and current transformer output voltage) two differential measurement channels are required. According to tests carried out, the power supply was also capable to operate with a non-sinusoidal supply current without noticeable transformer core heating. The maximum voltage at the secondary winding remained below 30 V.

V. Conclusions

Maintenance free on-line condition monitoring sensors installed at electric motor require power supply. The power supply should be easy to install and it should operate both with fixed speed and variable speed drives. It should be able to operate with different supply voltage levels. In addition, the power supply should not reduce the reliability of the monitored motor. In this case, energy harvesting from the magnetic field around the phase conductor is a feasible alternative. The energy harvesting can be carried out with a current transformer, which can be manufactured utilizing low-cost materials and simple electronics circuits. In this paper, a current transformer based power supply is considered. A prototype power supply is designed and measured. According to the analysis and results, the method is feasible. However, the available power supply output power depends on the phase current and the supply frequency. Hence, the current transformer has to be carefully sized in order to guarantee the required output power in all operational states of electric motor. The other possibility would be installing additional backup battery.

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