Design of a CT-Based Energy Harvesting Circuit for Three-Phase AC Motors

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Abstract. This paper presents a current-transformer (CT) based energy harvesting circuit which powers a sensor board used for three-phase AC motors. The design is based on a Texas Instruments reference design with some modifications to suit the customer's requirement. In this design, three-phase current transformers with delta-connected secondary coils are used to harvest energy from the magnetic field surrounding the input line currents. A backup battery is used for cold starting the circuit as well as to provide power backup when there is not enough energy harvested by the current transformers. The practical test results match the simulated test results where the energy harvesting board was able to harvest 5V/1.75W from three phase 10A input line currents or from 0.85A line currents with 12 primary turns on the current transformers.

***Index Terms*— Energy harvesting circuit, EHC , sensor boards power supply, DC/DC converters**

I. INTRODUCTION

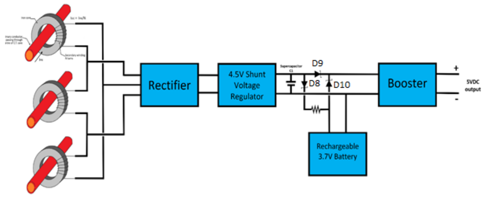
THE demand for energy harvesting power supplies in electric power systems is increasing due to the development of Internet Of Things (IOT) in smart systems and smart electric power grids. Several methods have been implemented to harvest energy from the environment around electric equipment, such as energy harvesting using photocells, thermal energy generators (TEGs), piezo electric vibration sensors, electromagnetic coil sensors and current transformers (CTs). These methods are desirable not only because the harvested energy is free of charge, but because they also help with avoiding direct contact with the HV input line terminals compared to the conventional method of using step-down transformers to generate the required energy at low voltage levels. For this reason, energy harvesting power supplies can be added to the old systems easily with minimum modifications, less risk and faster time. Additionally, they require low maintenance efforts and lower cost. In this research, energy harvesting has been accomplished by using current transformers at the input of three phase lines of an ac motor. As a matter of fact, the energy harvested by current transformers is not free-of-charge since this energy will eventually come from the main input power of the three-phase motor; However, this method, as was mentioned above, does not require a direct contact with the input AC line voltages. This research focuses on the design, build and test of a 5V/1.75 W CT-based energy harvester.

Energy harvesting using current transformers is not a new idea. It has been used in several applications with different approaches. There is an inexhaustible source of concepts and designs that can be found in the literatures. Our design was based on two previous works in this field. The first one is the reference design TIDA-01385 posted by Texas Instruments [1] which was made to harvest 3.6V/100mA from a single CT for a fault indicator system. The second one is the research paper published on IEEE Access [2] for designing a 12V/8W dc power supply for monitoring sensors in power systems. The differences between this design and designs from previous research are, firstly, we used three current transformers, one on each phase, to harvest energy from each line current equally instead of harvesting from just one phase. Secondly, the output of this design is 5V/1.75W which is obviously different than the above-mentioned two designs. This design is also different than the Texas Instruments design [1], as we have moved the rechargeable battery from the output of the booster IC to its input. This modification has made cold start-up faster and battery charging feasible. For the same reason, Q1 has been eliminated. In this sense, this design looks closer to [2];

however, it is still different from that design as we have implemented op-amps, making the adjustments of threshold voltages easier. Also, a boost has been used instead of a Buck converter compared to the design in [2].

II. CHALLENGES AND SOLUTIONS

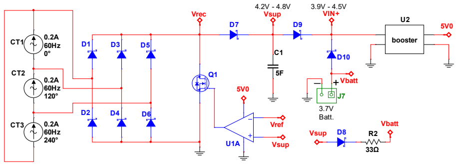
The challenge in using CTs to harvest energy from motors is that the input line current of the motor changes with the mechanical load on the shaft of the motor. The power demand of the load, powered by the energy harvesting circuit, also changes randomly during the operation of the system. Furthermore, when small three-phase motors are used, the input line current becomes proportionally small regardless of the mechanical load which makes energy harvesting even harder. To overcome the aforementioned challenges, the conceptual design shown in Figure 1 was used, in which the fluctuating current source from the motor is addressed with a method of compensation using a rechargeable battery and a supercapacitor storage element to maintain a constant supply of power to the booster stage. The AC currents harvested from the delta-connected CT's are going to be rectified and used to charge a super-capacitor. The shunt voltage regulator is to maintain the capacitor voltage to around 4.6V (+/- 0.23V) where this voltage is used to feed a 5V boost (DC-DC converter) to generate a constant 5VDC voltage. When there is not enough energy to be harvested, the capacitor voltage drops down. Once the capacitor voltage drops below 3.7V, D9 turns off, D10 turns ON and the 3.7V battery supplies the boost converter to prevent the output voltage from being collapsed. D8 allows the battery to be charged by the harvested energy when the super-capacitor voltage is higher than 4.0V. Low voltage-drop Schottky diodes have been implemented to reduce the power losses due to the forward voltage drop.



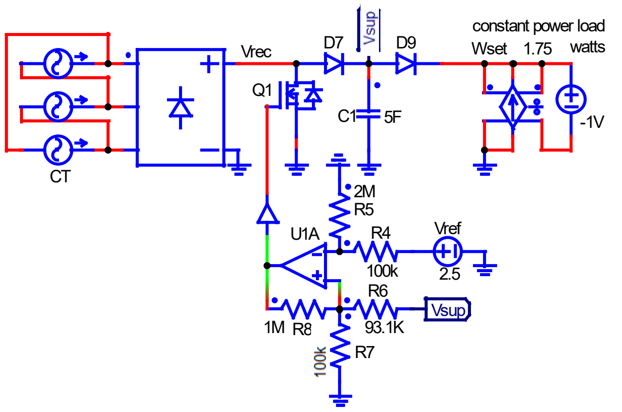
III. THEORETICAL ANALYSIS AND SIMULATION

A. Rectifier and Shunt regulator stage

Figure 2 shows a simplified circuit diagram of the design.



Three constant ac current sources were used to simulate the current transformers in PSIM simulation software as shown in Figure 3. Ideal diodes with forward voltage drop of 0.3V were used to simulate the operation of the Schottky diodes. An ideal IGBT transistor was used for the switching transistor Q1 and an ideal Op-amp with 0-5Vdc supply voltage was used for the U1A comparator simulation. A constant power load circuit was used to simulate the operation of this circuit at different loading level. Due to the high value of the supercapacitor C1, the simulation process was very slow, therefore, the simulation time constant has been reduced to 0.001 seconds to speed up the simulation process.



The rectifier behind the current transformers converts the input ac currents into a constant dc current to charge capacitor C1. When a capacitor is being charged by a constant DC current, its voltage increases linearly and indefinitely. To regulate the capacitor voltage an N-channel MOSFET transistor Q1 switch was used to bypass the DC current when the capacitor is charged at its maximum design voltage. D7 diode prevent the energy stored in the capacitor from being discharged through Q1. Transistor Q1 is controlled by a U1A window comparator circuit which sets the upper and lower limits of the capacitor voltage. The upper and lower limits of the capacitor voltages have been set to 4.82V and 4.35V, respectively.

A 2.5V dc voltage source (V_{ref}) is used to simulate the reference voltage produced by the precision reference voltage regulator used in the design.

The following formulas were used to calculate R4, R6, R7, R9 and R10 to achieve the required V_{max} and V_{min} values of capacitor voltage:

$$V_{max} = V_{ref}\left(\frac{R_5}{R_5+R_4}\right)\left(1+\frac{R_6}{R_8}+\frac{R_8}{R_7}\right) \quad (1)$$

$$V_{min} = V_{max} - V_{ss}\left(\frac{R_6}{R_8}\right) \quad (2)$$

V_{ss}, represents the supply voltage of the comparator, which is 5V in this design. Reasonable values of 100k, 2M and 100k were selected for R_4, R_5 and R_8. The values of R_6 and R_7 were calculated using the above formulas. Figure 4 shows PSIM waveforms of the rectifier output voltage V_{rec} and the super-capacitor voltage V_{sup} when the output power supplied to the load resistor is 1.75W (full load), which represents the maximum amount of power that can be supplied to the load in this circuit. The ON time of Q1 in this case is 5.4 sec. and the OFF time is 71 sec. This represents a duty cycle of around 7%. Therefore; 1.75W is almost the maximum power that can be harvested in this design.

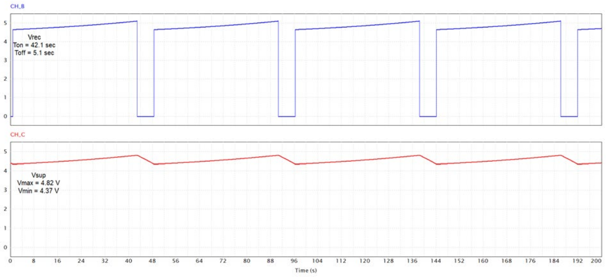


Fig. 4: Simulation waveforms of V_{rec} and V_{sup} at 1.75W load.

Figure 5 shows V_{rec} and V_{sup} when the output power supplied to the load is around 0.1 W (light load). The duty cycle in this case is around 95%.

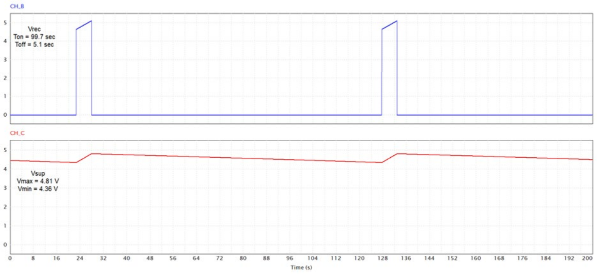


Fig. 5: Simulation waveforms of V_{rec} and V_{sup} at 0.1 W load.

B. Battery charging discharging control Stage

Based on the research and simulations, using the specified CT architecture, the team developed a circuit design based on a Texas Instruments reference design TIDA-01385 with some modifications. In the design, shown in Figure 6, three delta-connected CTs, not shown in the diagram, were used to harvest the required energy. The outputs of the delta-configured CTs are connected to J1, J2 and J3 connecters. Six diodes were used to convert the three phase input AC currents into a DC current to charge the super capacitor (C1) via D7 Schottky diode. NMOSFET transistor Q1 (Vishay SI2300DS-T1-GE3), which is controlled by U1A (TLV3492AID) op-amp, is used as a shunt regulator to limit the voltage of the supercapacitor to V_{max} of 4.82V. If the supercapacitor voltage reaches V_{max}, Q1 is switched ON, short circuiting the rectifier output to return the current back to the CTs. Q1 turns OFF once the capacitor voltage drops below V_{min} which is 4.35V.

C1 is coupled to a 3.7V backup battery (and a solar panel or other backup source if available) via coupling diodes D9, D10 and D11 to form and uninterruptable unregulated DC supply (VIN+), which feeds the input of the 5V boost switching regulator U2 (TPS61023). With insufficient energy to harvest by the CTs, the supercapacitor voltage drops down and the 3.7VDC battery intervenes to prevent (VIN+) voltage from going below the battery voltage, maintaining the input supply of the booster IC.

The regulated 5.0V generated by the DC-to-DC converter is used to power the op-amps and the 2.5VDC reference voltage regulator U3 (ALT431). Diode D8 and the 33 Ohm resistor are used to charge the 3.7V backup battery from the supercapacitor.

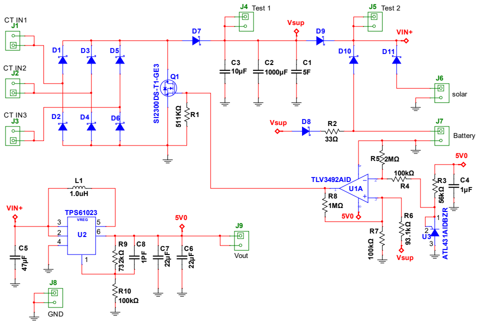


Fig. 6: Complete schematic diagram of EHC

IV. IMPLEMENTATION AND EXPERIMENTS RESULT

Current transformers were designed and manufactured by Hammond manufacturing as a support to the College and its research. Each transformer is a toroidal type transformer and can generate 5V, 0.2A from a single turn primary current of 10A with turn ration of 1:50. Figure 7. shows one of these transformers. The dimensions of each CT are: Outer diameter = 63mm, Inner diameter = 25mm, Width = 32mm. The material of the core is of 2.79mm M4 annealed grain silicon strip steel.

Fig. 7: Current transformer made by Hammond Manufacturing.

Figure 8 shows the final PCB that was built at Humber College Prototyping LAB. Due to the unavailability of the TPS61023 boost regulator (U2) in the market, a decision has been taken to use the evaluation board TPS61023EVM instead of TPS61023 and all other required components around it. The boost converter integrated chip TPS61023 was only available from Texas Instruments and at the time of fulfilling the BOM, the chip was not available for purchase. Additionally, due to soldering difficulties, the IC could not be removed from the Texas Instruments evaluation board and resoldered on the main design board. As such, the board was used as an extension to our PCB as shown.

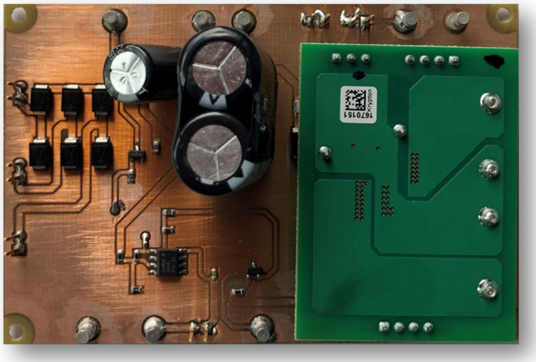


Fig. 8: Energy harvesting PCB

The circuit was tested using an existing test setup at BCIT (Barret Center of Innovation Technology) at Humber College. The setup is consisting of a 10kW, 3PH 600V induction motor coupled to a 10kW single-phase synchronous generator, and a resistive load bank. Figure 9 and Figure 10(a) depict the setup. A junction box, shown in Figure 10(c) has been designed and built to serve as a housing to keep the harvesting transformers protected from external elements or hazards. The junction box was planned and sized in order to properly fit the CTs and PCBs with terminal blocks for electrical continuity between the main source and the motor (or any machine from which energy can be harvested).

The CTs were connected in a delta configuration and the primary turns of the CTs was just one turn to harvest the required energy from the, approximately, 10A per phase input line current of the motor when fully loaded.

After successfully testing the circuit on the existing 10kW motor-generator setup, the circuit has been tested using an SEW VFD/Motor setup shown in Figure 10(b). A LabVolt Prony brake with adjustable torque was used as a mechanical load on the motor during the test. As the motor had a rating of 3ph 480 V, 1kW with a maximum current of 900mA per phase, the CTs were given a primary of 12 turns to harvest the goal amount of energy. Another junction box was designed and built for this setup to match the new wire sizes. The experimental platform is shown in Figure 10(d).

The resulting output was 4.8V at 1.75W with the battery charging successfully via D8 and R2 when there is enough amount of input line current. The addition of the 3.7V battery solved the issue of current fluctuation of the input line current. The battery also functioned as a cold start to the circuit before running the motor. Figure 11 shows the output DC voltage (yellow) and the supercapacitor voltage (blue) at 1.75W output load. The "noise" on the output voltage is due to the VFD harmonics. The supercapacitor voltage V_{sup} is fluctuating between 4.82V maximum and 4.36V minimum.

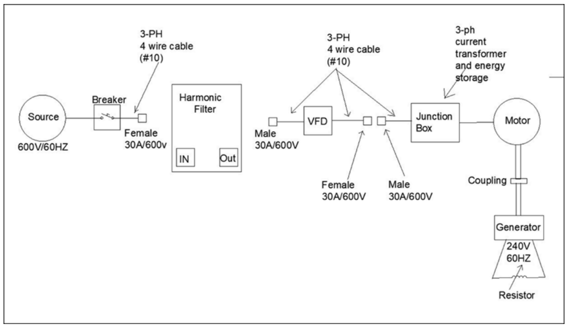
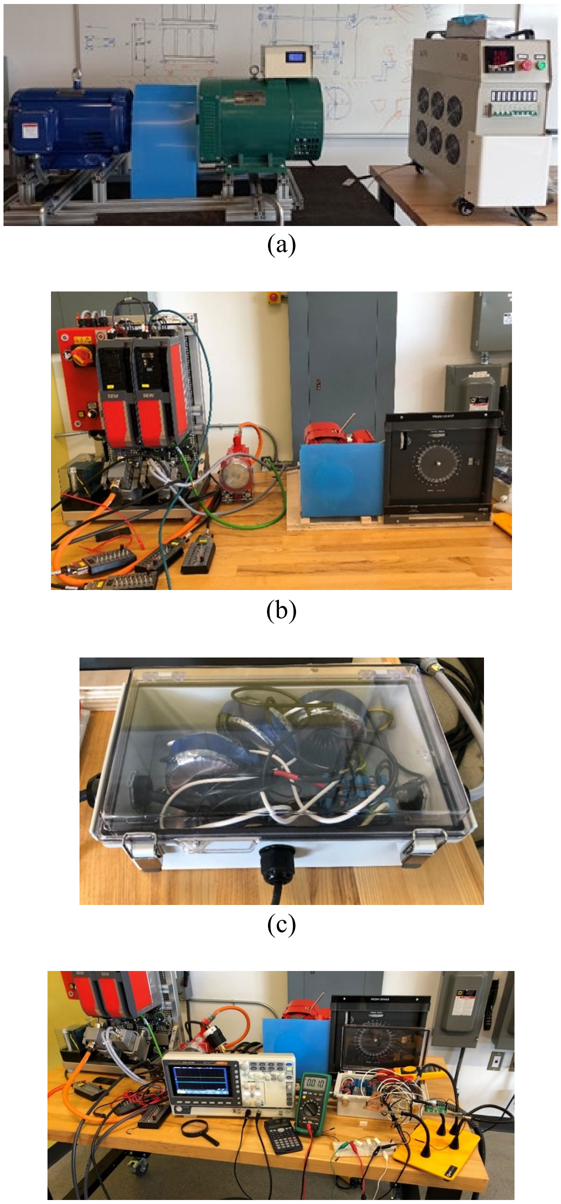


Fig. 9: Block diagram of testing setup.



(a)

(b)

(c)

(d)

Fig. 10: Photos of test equipment and environment.
(a) 10 kw motor-generator setup with load bank. (b) 1kw SEW motor with Prony break. (c) mounting box for current transformers. (d) experimental platform.

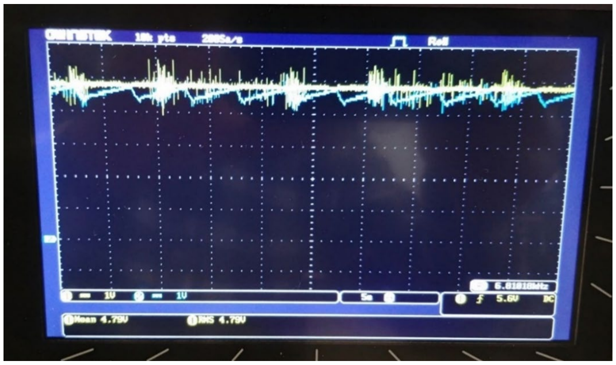


Fig. 11: Oscilloscope waveform of output and supercapacitor voltages at 1.75 watts.

V. CONCLUSION

Test results proved that the circuit was able to harvest 1.75 watts from three phase line currents. The size of the PCB is acceptable; however, the dc output voltage has dropped to 1.8V at full load. This problem is not severe, and it can be fixed by redesigning the PCB layout or adjusting the values of the feedback resistors. The size of the current transformers is a little big and more work is required to reduce its size. Moreover, the number of the primary turns on the current transformers have been increased to 12 to harvest the same amount of energy from 3-ph1kW motor. If one turn primary CT is to be used, the CT design should be upgraded.

The circuit was designed to harvest energy from current transformers only; however, other ways of energy harvesting should be considered in the future such as harvesting energy from solar rays, sources of heat, or vibrations.

Texas Instruments' boost regulator was used in this design; However, there are other high-quality boost regulators available in the market manufactured by other manufacturers, like Analog Devices, Monolithic Power Systems, and Cypress which can be considered in future designs.

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