

Power Harvesting Feasibility Analysis

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ABSTRACT: Power supply design for powering up various DC components in an AC measuring instrument used for industrial power metering needs focused attention. A detailed analysis of the possibility of harvesting AC power from the electromagnetic radiation associated with the industrial loads to power up the electronic components that constitute the DC load for the power supply being designed is carried out. The current transformer output in the AC measurement system is used for power harvesting and is chosen due to its negligible loading effect on its primary side (John Horak et al [1]). The harvested power output is thoroughly analyzed by conducting suitable experiments and the suitable range of AC loads for which power is harvested effectively is also determined.

KEYWORDS: Power harvesting, current measurement, linearity, transient, supercapacitor

I. INTRODUCTION

Reliable and stiff DC output of required level is the quality determining factor for a good power supply for microcontroller based devices. Generally, the power level requirement is dictated by the requirements of the electronic components that are used to build the circuit. Here the device under consideration is a low cost, microcontroller based industrial power metering instrument. Here powering the electronic components is a great subject of concern since the meter is meant for permanent load side installation, and requires to be powered efficiently and reliably all hours of a day. Aim of this paper is to find an optimal solution for this problem. Conventional methods are by using a battery or by directly taking power from mains through AC adapter (Julian Hartline [4]). The usage of battery demands periodic maintenance which requires regular inspection. So demerits of using battery (A.M. Bernardes et al [2]) are its high cost, disposal problems and high maintenance. In case of AC adapters, with the increase in number of loads there will be larger number of wires powering up each instrument and this makes it look complex and difficult to handle. Another problem of going for rechargeable battery or supply from the AC mains is the fact that this application, while providing 24/7 service, may not be always fixed in such convenient places where there is an easy access to the power socket. Energy harvesting for powering wireless networks is a promising approach that addresses these issues as it collects energy from the ambient environment explained by Stefano Basagniet al [13] and J. M. Gilbert et al [15]. Energy can be harvested from rich sources including solar power (Vijay Raghunathan et al [14]), electromagnetic waves, thermal energy, wind energy, salinity gradients, and kinetic energy. Here we are considering the possibility of harvesting power from the output of the current transformer used for measurement purpose. Similar concepts are explained by Bradford Campbell et al [5], Vikram Gupta et al [12] and J. Aholat et al [16]. This paper is different from those in that here we are designing a circuit which integrates both current measurement and power harvesting unlike [5] which uses two current transformers for these purposes. Also, here we are specifying the range of AC loads for which the circuit performs best. The specification of power to be harvested is arrived as minimum voltage of 2.7V and a minimum current of 25 milliamperes based on the requirement of the electronic components under consideration.

II. PROPOSED TOPOLOGY

Figure 1 and figure 2 show the block diagrams for the proposed method of harvesting power. Electronic circuits involved in the power metering instrument need to be powered by a DC voltage which is capable of supplying adequate amount of current determined by the current consumption of the chips involved. Output of the current transformer will be AC and this is to be converted to suitable form for required utilization (figure 1). The current transformer which measures current helps to find out the power through the line. Primary of the current transformer is the loadline itself and a proportional current is produced in the secondary depending on the turn's ratio of the transformer, typically 30/5 or 100/5. AC voltage needs to be rectified and smoothed (figure 2). But the magnitude of the voltage generated this way depends on the output of the current transformer, and in turn on the current in the lines. This should be regulated to a value calculated considering the requirements of the individual chips and so a DC to DC regulator is used which steps down or steps up the DC voltage to the required value. Regulated DC voltage is stored in a capacitor. Capacitor sizing is done and this is decided by the magnitude of voltage it stores and the discharge time (VlastaSedlakova et al [6]). Output of capacitor is connected to the monitoring circuits which will determine the status of voltage output, whether it is good enough or not. Here decision making is done by codes which compare the voltage generated with a predetermined threshold voltage. Also when there is a power outage, capacitor will be still charged for few hundreds of milliseconds so that the context saving operations can be completed before the shutdown, called graceful shutdown.

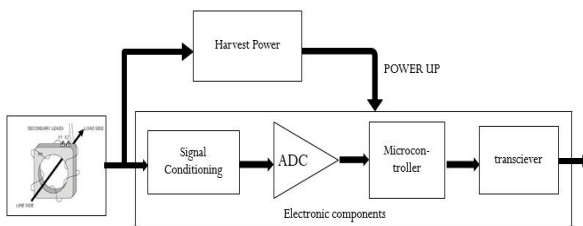


Figure 1: Overall block diagram of the power measurement set-up

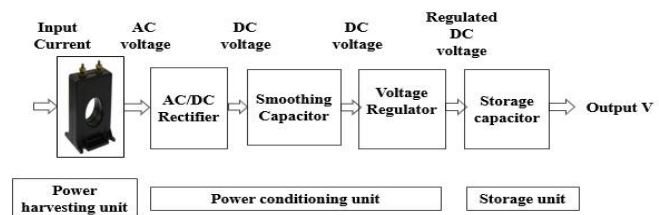


Figure 2: Block diagram of the DC power harvesting set-up

III. METHODOLOGY

Current transformer is the source of AC power for the harvesting circuit and characteristics of the same was analyzed by performing CT test. The circuit up to the smoothing capacitor was simulated first in order to arrive at a suitable selection of voltage regulator. The range of input available for the same is analyzed. Simulation and experiment conducted for half wave rectification revealed the undesired properties like high power dissipation due to shunt burden resistance and low value of output which also supports the concept presented by Vacuumschmelze GmbH & Co. KG in [3] and Sachin Tiwari et al in [7]. Thus the choice of full wave rectification was made and experiment was conducted without shunt burden resistance. Output was satisfying and is shown in figure 4 and figure 5. Experiment to analyze the transient response was also done. DC-DC regulator to be used in the circuit was decided based on the outcome of the experiment. The last step was to test the performance of the whole circuit, including the regulator chip and the storage element, and to find the range of AC load current for which the circuit is able to provide the required power specifications.

IV. SIMULATION STUDIES

Simulation is carried out to observe the output after rectification and smoothing. A load resistance is connected at the DC side of full wave rectifier. For full wave rectification, burden resistor was removed because of the power dissipation problem and insufficient output voltage mentioned before. Also, since full wave is used, the secondary is not left open circuited at any instant in a cycle, which eliminates the need for burden resistor from the safety point of view. Zener diode is connected across the output to restrict the voltage from changing in large values. Readings are shown table 1. Zener conducts as a normal diode when the voltage across it has not reached the knee voltage. Once it enters the zener mode of operation, output voltage is maintained around 3V, which also defines the range of currents in

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the primary for which the voltage is in desired range. When the primary current is increased such that the current through zener exceeds its maximum reverse current, it no longer regulates and load voltage increases.

Table 1: Readings for power harvesting circuit up to full wave rectification

Ip (A)	Is(A)	IL (mA)	VL (V)	Zener operation
3.9	0.065	64	2.1	VL < V _{knee}
4.3	0.07	68	2.3	VL < V _{knee}
4.9	0.08	72	2.45	VL < V _{knee}
5.3	0.088	76	2.5	VL < V _{knee}
5.6	0.09	86	2.9	Regulation
6.7	0.112	90	3	Regulation
7.7	0.13	95	3.1	Regulation
8.5	0.14	98	3.2	Regulation
10.6	0.18	170	5.5	No regulation
14	0.23	250	9	No regulation
21	0.35	400	13	No regulation
42	0.7	650	20	No regulation

V. EXPERIMENTAL SETUP

CURRENT MEASUREMENT

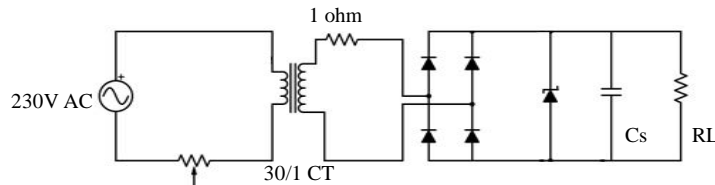


Figure 3: Circuit incorporating current measurement

A series resistance of small value connected in series to the secondary winding as shown in figure 3 can be used for current measurement if the voltage across it varies linearly with the primary current. Zener diode used was IN4728A (1W, 3.3V). Smoothing capacitor Cs was taken as 100microF. Primary current was varied to analyze voltage across the series resistance connected in the secondary circuit. Experiment was repeated for different load resistance values of RL such as 16.5, 33, 66, 122,244 ohms. This is to observe the impact of varying load resistance on the current measured in the secondary. Series burden value of 1 ohm is used for experiment.

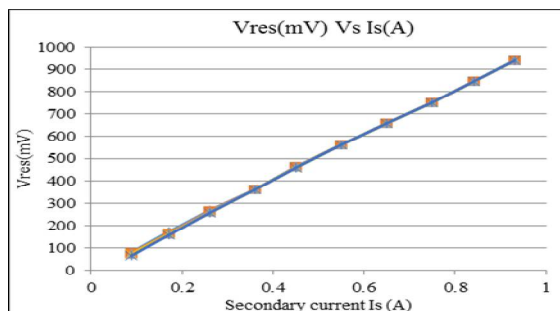


Figure 4: Voltage across current measurement resistor for different RL values

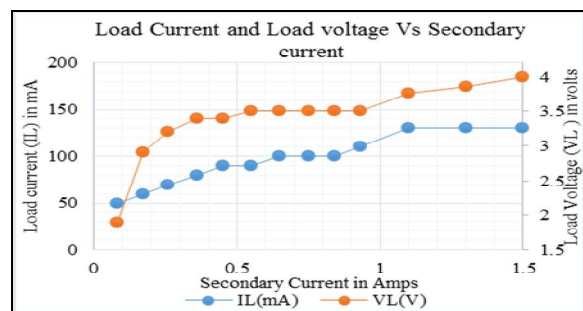


Figure 5: Output voltage and current characteristics when RL=33ohms

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Linearity of V_{res} and I_s is clearly visible from fig.4 and irrespective of DC load resistances the outputs almost overlapped. This signifies the advantage of low measurement error which is relevant only when the secondary current of the transformer is less than 0.3A. This ensures that the current measurement is not affected by the incorporation of power harvesting into the current measurement circuit for secondary current range of 0.3A-1.0A. So by measuring V_{res} it is possible to calibrate it to show the current through primary winding of the current transformer, with negligible error content. Calibration can be done by finding primary current from V_{res} and burden resistance value and then dividing it by current transformer turn's ratio.

Experiment was also conducted to increase primary current such that at some point zener stops regulating, output of which is shown in fig.5. When secondary current goes beyond 1A, zener regulation stops and output voltage increases linearly beyond the desired value. It means that the secondary current of the transformer should not go beyond this value. Another thing to be noted is that the load current is almost constant even after the increase in current. This is because more current flows through the zener diode once the voltage across it exceeds the limit specified. If the load current is increased further, at some point the zener completely stops conducting and burns out.

TRANSIENT ANALYSIS

DC resistance load represents the electronic circuitry for which the power is harvested. Practically the board acts as a variable load which consumes different values of current during different modes of operation. An effective measure of current consumption of a wireless sensor network node during operation is presented by Antonio Moschitta et al [10] and it shows change in current consumption in a wireless system happens in steps since current jumps from one value to another instantaneously to a value dependent on the conversions happening in the microcontroller like sleeping, booting, receiving, transmitting etc. These variations occur in milliseconds range and the equivalent resistance of the DC load also varies accordingly. The concern here is to check the transient response of voltage across series burden resistor due to the incorporation of power harvesting units in the same circuit during these transitions. Fig. 6 shows the circuit experimented. Step change in equivalent DC load resistance was got by using electronic switches rather than mechanical so that the changes were fast and prolonged only for few milliseconds. Three transistors were used to change load resistance. The base triggers to these switches were given through the digital pins of Arduino Mega 2560 microcontroller board. Arduino was programmed such that the switches were turned on in sequential manner. When Q1Q2Q3=000 equivalent R_L was 150ohms, Q1Q2Q3=100, R_L was 75ohms, Q1Q2Q3=110, R_L was 33.3 ohms and Q1Q2Q3=111, R_L was 16.5 ohms.

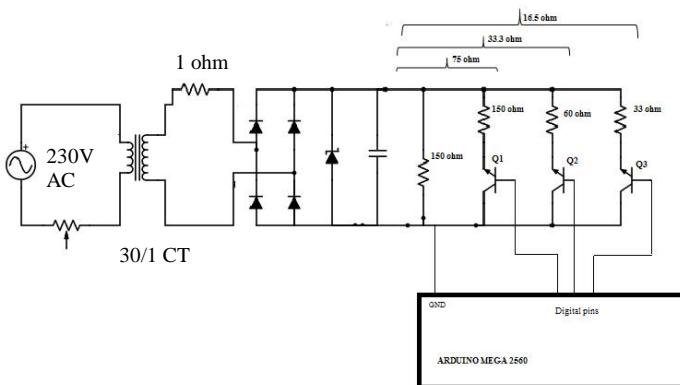


Figure 6: Experimental setup to analyze transient response

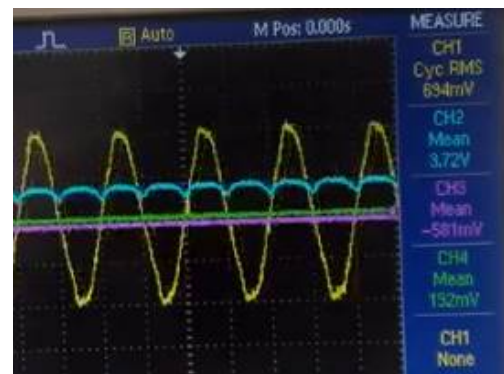


Figure 7: Waveform viewed on DSO for 0.75A secondary current and $R_L = 33.3\text{ohms}$

The voltage across series resistor was observed on a digital storage oscilloscope for these changes. Fig.7 shows the waveform of voltage across series 1 ohm resistance and voltage across the transistor switches. It was seen that there were no significant transient behaviour while current drawn by the DC load was changed. However there was a change in the same in few millivolts for various DC loads, as explained in the previous section.

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CHOICE OF VOLTAGE REGULATOR AND STORING ELEMENT

Suitable voltage regulator chip was chosen based on the range of inputs available to the regulator, seen from previous experiments. A dc-dc boost converter is selected over a linear regulator due to the better range of operation and efficiency. Output of the regulator is to be connected to a storage element, considering the possibility for power failure in which case the storage element is expected to provide power until the metering instrument gets time to sample and save the data before going to sleep mode, known as graceful shutdown. Supercapacitors are used here since they have better power density than batteries and better energy density than any other capacitor family (Vincenzo Musolino et al [9]). Also their charge-discharge cycles are 100-200 times that of batteries. So with regards to rechargeable batteries supercapacitors feature low cost per cycle. Maintenance cost for batteries is also high (Marin S. Halper et al [8] and Maria Teresa Penella et al [11]). Capacitor value was calculated considering the least possible voltage of operation at the time of power failure and discharge time which ensures graceful shutdown while discharging to the lowest possible voltage set by the voltage regulator chip (Vlasta Sedlakova et al [6]). Circuit (figure 8) and the graphical representation of the readings (figure 9 and figure 10) are shown below. Readings were taken by considering one whole capacitor charge-discharge cycle for dc load resistance values 30, 50, 75 and 100 ohms. Primary current was varied from zero to maximum (capacitor charging) and again down to zero (capacitor discharging).

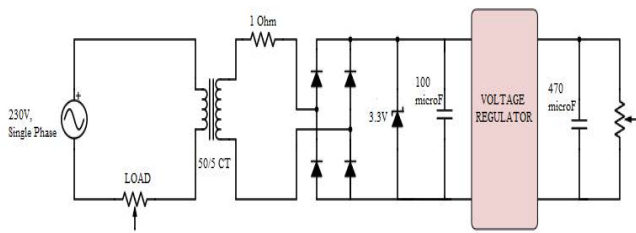


Figure 8: Overall power harvesting circuit

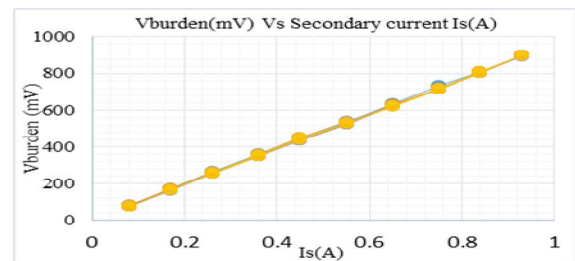


Figure 9: Voltage across current measurement resistor for one cycle of charging and discharging

It can be seen from the fig.9 that the burden resistor voltage drop values for the same load during charging and discharging of the capacitor differ in below 15mV and the error in any case was less than 4%. Also this error is less when the output dc load voltage is close to 3.3V. This means that the current measurement is not much affected due to the change in DC load when the operating voltage is high. Another important point to note is from fig.10 and fig.10 that when the secondary current is below 0.2, output is not sufficient to meet the required power level. Thus AC loads for a CT is decided such that the secondary current is always above 0.2A. If load is varying, an alternate solution should be found to power up the electronics whenever the corresponding secondary current is less than 0.2A, excluding the power failure cases which will be taken care by the storage capacitor.

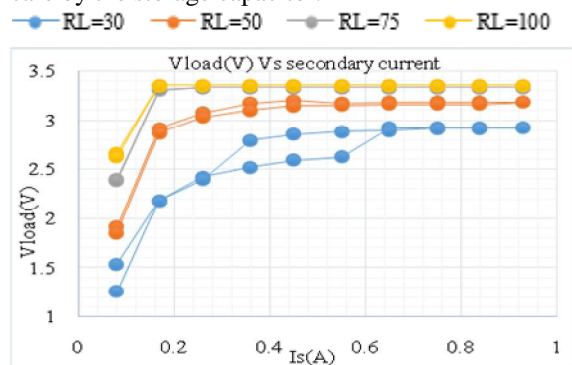


Figure 10: DC load voltage characteristics one cycle of charging and discharging

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VI. CONCLUSION

In this paper we have analysed and proved the feasibility of power harvesting from the secondary of current transformer with linearity analysis for incorporating current measurement and power harvesting in same circuit and transient analysis to ensure the stable current measurement. Output is got based on the equivalent resistance of the DC load and for an equivalent resistance of 50ohms, the power harvesting circuit is able to provide constant voltage of 3.2V at 64mA of current when operated with AC loads varying from 12A to 30A when a 30/1 CT is used. By the use of supercapacitor instead of rechargeable battery, cost efficient solution for storage of data on occurrence of power failure is ensured. Turns ratio of current transformer suggested is X/1, X decided by the AC load to which the arrangement is connected and secondary current restricted to 1A considering the ratings of the components used in the power harvesting circuit and the dc load. Efficient power harvesting is feasible when the current transformer secondary current is 20%-100% of the rating. Current transformer when operated below 0.2A (in the lower 20% current rating), the DC output voltage does not meet the minimum requirement. Also errors like current transformer ratio error and error in current measurement due to change in DC load are more. Thus the limitation of this concept is that the AC loads should be selected such that the operating range of an X/1 CT used in this circuit should not fall short of 20% of its rating. As an alternate solution, CT of turns ratio X/5 can be used, thereby increasing the range of operation of the CT for the same loads. Then the limited range can be reduced to 4% from 20% of the current transformer rating. But proper measures should be taken to limit the current that will be supplied to the electronic circuits, since chances for damage due to power dissipation and overheating is more. Hussaini Habibu et al [17] explain the use of MOSFET to charge the supercapacitor in a current limiting mode.

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