DEVELOPMENT OF A POWER MANAGEMENT CIRCUIT FOR MICRO-ENERGY HARVESTERS

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ABSTRACT

This work reports on the development a power management circuit (PMC) for micro energy harvesters. The circuit is design to regulate the power between three different power sources for the operation of a wireless sensor nodes (WSNs). The main components of the circuit are resistors (carbon film), capacitors (electrolytic), inductors (ferric bead, axial leaded), and a DC voltage regulators (TPS62100DRC-BRR). The layout of the circuit is patterned on a printed circuit board (PCB) using PCB fabrication technology. To the circuit three different types of sources (DC power source, rectified AC voltage and a solar energy harvester) are connected and the output regulated voltage provided by the PMC is measured and analyzed. At different input voltage levels (0.5 to 5.5 V) the circuit successfully regulated to almost a uniform output voltage (2.75 to 2.96 V). With the circuit using a DC power source and a solar (solar cell) energy harvester a super capacitor is charged to a voltage of 2.75 and 2.05 V in 180 s and 840 s respectively. Beyond 100 Ω load resistance the PMC regulated a constant output current of 180 mA. Moreover, beyond 100 Ω load resistance the power consumption of the circuit is almost steady for different input voltage levels. The average consumption of the developed PMC is about 70 mW.

KEYWORDS: *Energy harvesters; Micro; Power management circuit, Printed circuit board; Voltage regulation; Wireless sensor nodes*

INTRODUCTION

A Wireless Sensor Node (WSN) is usually used for sensing and monitoring of characteristics (such as, temperature, humidity, pressure, displacement, velocity, acceleration) of environment or equipment. Normally, batteries are used to provide power to function various onboard components of the WSN. However, these batteries need to be replaced constantly because of the limited amount of energy these exist. There are situations where numberous of WSNs are spread over very vast area or these may be located in embedded, remote or harsh environment, where constant human access for replacing batteries is very difficult or even not possible. In resent years, work is carried on converting battery-powered WSNs into autonomus, self-sustaining and self-powered systems. Such autonomus WSNs require no batteries, no maintenance and can be operated in remote and hazardous environments for much longer times. The energy harvesting techniques developed in the last decade is usually utilized to accomplish the power requirements of the WSNs. In WSNs surroundings energy is always present in the form of heat energy, solar energy, seismic energy (mechanical vibrations), wind energy and acoustic energy. Energy Harvesters (EHs) transform the available ambient energy into electrical energy and can be integrated with the WSNs to transform these into self-powered systems, as shown in Figure 1. For this purpose, solar EHs[1], thermal EHs[2], acoustic EHs[3], and vibration-based piezoelectric EHs[4], electromagnetic EHs[5] and electrostatic EHs[6] have been sucessufully developed and reported in literature. However, there exists few problems with the energy harvesting techniques. The voltage levels provided by the harvesters are unsteady because of the varying ambient energy conditions. Sometimes the energy provided by the harvestor is in excess of the required energy and othertimes there is barely any energy generation at all. In order to fill this gap in autonomous WSNs, onboard power management circuit (PMC) is provided. As shown in Figure 2, the PMC provides the functions such as,to regulate the changing voltage levels into a single level for on-board use in WSN, to distribute power among various on-board components, such as, microsensors, microcontroller unit (MCU), signal processing unit (SPU) and RF transmitter, and to supply the excessive harvester energy to supercapacitor (or battery) for storage. Moreover, due to the availibilty of several ambient energies in the vicincity of a WSN, a number of energy harvesters may be integrated with WSN through the PMC. The PMC has to regulate and distribute the power from all the energy harvesters effiecently among all the onboard components.

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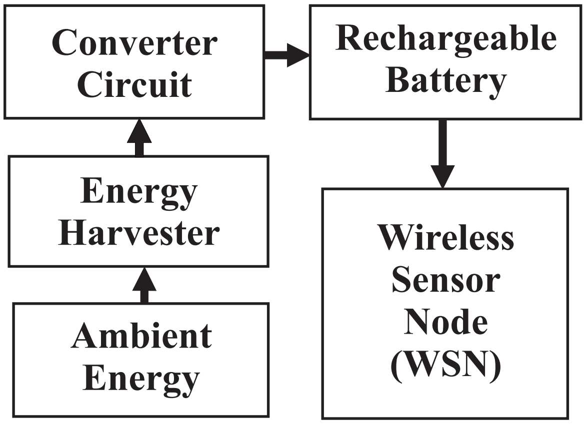

Figure 1: Energy harvesting for wirless sensor nodes applications

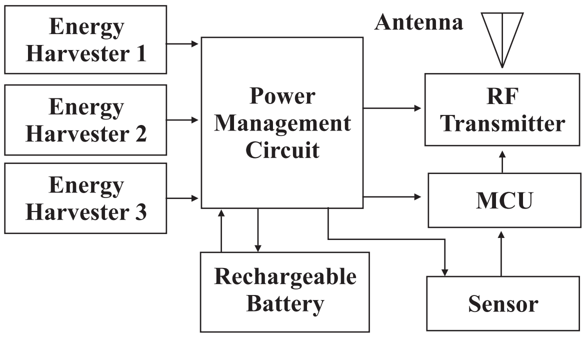

Figure 2: Archetecture of a typical wireless sensor node.

LITRATURE REVIEW

For WSNs, several power management circuits have been developed and reported in research publications. A PMC is developed for a thermoelectric energy harvester (based on the Seebeck effect)[7]. The circuit is produced using printed circuit (PCB) fabrication technology. The energy harvester used the human body temperature to produce an open circuit DC voltage in the range of 0.3 to1.4 V. A 1.8 V, charge pump (Seiko Instruments) is used to store energy for DC Converter (Maxim Dallas Semiconductors) startup. However, during normal operation power is provided directly to the DC Converter. Using this system an input as low as 150 mV is regulated to 2.8 V to charge a Nickel-Metal Hydride (NiMH) rechargeable battery (Sanyo Eneloop).

A PMC is developed as part of an energy harvesting system using piezoelectric and radio frequency (RF) energy harvesters[8]. Piezoelectric energy harvester generated AC voltage in the range of 0.85 to 1.75 V. The AC voltage is rectified using different rectifiers. The DC output from the rectifies varied form 2.15-2.45 V (under no Load Condition). However, the RF energy harvester used a passive floating gate rectifier for a AC to DC conversion and provided a power in DC form with the output voltage up to 9 V (no load condition). The rectifier is controlled by a floating gate programming circuit. The PMC is fabricated on PCB using CMOS technology. For testing of a regulator (DC series regulator with Bungee biasing Circuit) a DC input of 1.25-10 V (under no Load Condition) is applied using a DC power supply. For DC Converter startup, a charge pump (Dickson Charge Pump) is used to store energy. However, during normal operation of the circuit the power is supplied directly to the DC Converter. Using the developed system an input in the range 1.25 to 10 V is regulated to 2.9 V with a variation of about 30 mV only. A battery (NiMH) is used for energy storage during the characterization of the system.

A PMC is developed and integrated with a thermoelectric EH[9]. A voltage of 0.5 V per unit degree Kelvin of human body is reported for the energy harvester, A 1.5 V, charge pump (S-882Z) is used to store energy for the DC converter startup but during normal working power is supplied directly to the DC converter. Moreover, other than a charge pump a coupled inductors are also used to store energy for the converter Startup. Using this system an input as low as 150 mV is regulated successfully.

In a WSN, for a wind (Windlab Junior) and solar (Solarworld module 4-40-100) EHs, a PMC is developed[10]. The circuit is fabricated using PCB Technology. It consisted of three subsystems: energy harvesters (EHs), reservoir capacitor array (RCA), and a control/charger (CC). Each energy harvesting subsystem consists of an energy harvester which harvests energy and charges its own double layer reservoir capacitor (RC) (Panasonic electric),at the source's own maximum power point which is set using a boost regulator. The RCs of different sources comprised the reservoir capacitor array. However, the Control/Charger consisted of two window comparators (LTC1441, Linear Technology) and one current limit switch (ST890, ST Microelectronics) for battery protection. The regulator (LTC3401) can take an input in the range of 0.5 to 5.5 V and the output of the regulator was set to 4.1 V. The entire circuit was fabricated on the same PCB.

For an electromagnetic based energy harvesting system a power management system is designed and fabricated[11]. The developed circuit consisted of an impedance matching circuit, step-up converter, AC-DC converter, DC-DC regulator and a storage capacitor. A PCB technology is utilized to fabricate the reported PMC. Under a 1 A current through the electric cable, the maximum energy harvesting efficiency of 91.67 % is reported for the developed system. Under the same operating conditions the storage capacitor is charged to 3.3 V within 30 minutes. With the system, even the weak stray electromagnetic field around the electric cable is accumulated to drive the WSN with an output power of 54 mW at a distance of 20 m.

For an RF energy harvesting system a power management circuit is designed and developed[12]. The main components of the reported system circuitry are: an impedance matching circuit, a rectifier (Switched Load Rectifier) as AC-DC Converter Circuit and a DC-DC regulator and a storage capacitor. A switching rectifier is used to obtain a voltage of 0-1.3V (DC). The regulator regulated the voltage at 2V thus charging the capacitor ina very small time of 20s only.

The energy harvesting circuit of a solar EH is connected with a PMC to provide power to a sensor unit[13]. The power management circuit is fabricated using PCB technology and is designed to connect with a mica2 or MK-II sensors. The PMC contained an energy monitor (Max-DS2438), DC-DC converter, a NiMH (Energizer no. NH15 AA size) battery for storage. Moreover on the circuit an undervoltage protection and overvoltage protection units are also provided for the battery. Solar EH (solar cell) directly charged the battery with the protection circuit preventing it from charging or discharging beyond its normal operating range. The converter regulated the unsteady voltage to a constant value of 3 V for the sensor usage.

For a solar cell (Module 4-4.0-100, Solar World) based energy harvesting system, a PMC is fabricated[14] by PCB technology. The reported circuit is developed to be connect with a MTS300/310 sensor from Crossbow. A NiMH Battery AA size was used to store excess power while undervoltage protection and overvoltage protection were used to protect the battery from damage. An energy monitor constantly supplied the data about the input current to the sensor and DC-DC converter regulated the voltage level of the sensor input. Solar cell directly charged the battery (NiMH, AA size) through the protection circuit preventing it from charging or discharging beyond its allowable operating range. The batteries were selected keeping in mind the maximal power point of the solar panel, which is 3V at peak of day and variates slightly depending on other time of day. The batteries keep the solar panel operating at maximal power point. The converter regulated the constantly shifting voltage to a constant 3V. The circuit is reported to be operated with an efficiency of 80 to 84%.

POWER MANAGEMENT CIRCUIT

In this research work energy is supposed to be harvested from three different energy harvesters, namely, vibration based, solar and thermal. The harvested power is supposed to be supplied power to three different devices, a sensor, transmitter and a microcontroller, and at the same time the excessive energy has to be stored in a rechargeable battery for later use. In completing all of these tasks the energy lossed must be kept as low as possible. There is also the issue of different sources providing different voltage levels at a particular time and the fact that most of the time the voltage level produced by these sources may be lower than the voltage level of the rechargeable storage, this may cause back-flow of power and might result in damage to the sources. In order to rectify all of these problems a PMC is to be implemented. The aim of the PMC is to regulate the flow of electrical power between the sources, storage and devices, including the times during which the devices are in power conservation mode or sleep mode.

OPERATION OF PMC

The topology of PMC reported in this work is shown in Figure 3. Based on the values of the resistors R_1 and R_2 in the voltage divider circuit that provides input voltage V_{FB} to the feedback pin in the regulator, the output voltage V_{out} can be set anywhere between 1.8 to 5 V using the Equation 1.

$$R_1 = R_2\left(\frac{V_{out}}{V_{FB}} - 1\right) \quad (1)$$

Where R_1 is kept at 200 kΩ and V_{FB} is 0.5 V. Using these values and the required output voltage the value of R_2 can be obtained. The regulator[15] accepts input voltage in the range of 0.3 to 5.5 V. Moreover, other than this the PMC is also constrianed by the law of conservation of energy, which is (Equation 2)

$$P_{in} = P_{out} + P_{consumed} \quad (2)$$

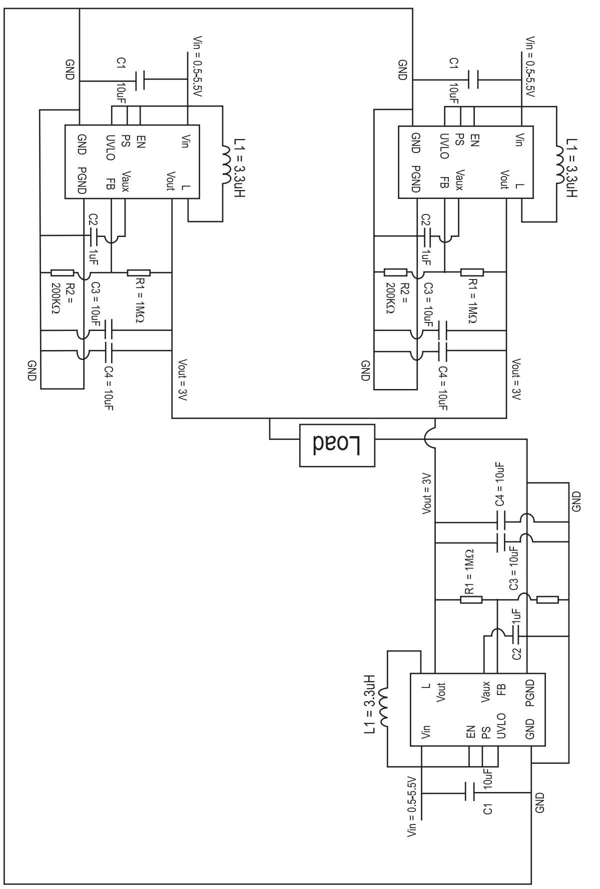

Figure 3: Circuit topology of power management circuit.

Depending on the increase of input or output current a decrease in the input or output voltage is seen which is in accordance with the above rule. With the regulator regulating the voltage of all sources to the same level, all the sources can be connected in parallel combination.

FABRICATION OF PMC

The PMC developed in the work is composed of resistors (carbon film), capacitors (electrolytic), inductors (ferric bead, axial leaded), and a DC voltage regulators (TPS62100DRC-BRR). In the circuit the output of all regulators are connected in parallel. The development of the circuit involved the drawing of the layout of the circuit which has to be printed on the PCB. The transfer of the layout pattern on the PCB, etching of the board and finally the mounting of the various components of the PMC on the fabricated PCB.

(a) Layout of PMC

The Electronic-Computer Aided Design (ECAD) software a 'PCB Artist' is used for designing the PMC. PCB Artist is an open source software, and provides an easy environment for designing a PCB. Furthermore, it gives added options of providing output in .xps file format and .dxf file format (used for 3D designing using AutoCAD). The layout of the PMC developed in the PCB artist is shown in Figure 4. First of all track pads for the regulator (TPS61200DRC-BRR) was created in the software. The width of the regulator pins is 0.08 mm, however, to provide a greater surface area for the regulator to mount upon the track, the connection pads to the regulator pins was kept 0.2 mm a side. As the distance between the mid points of two pins was 0.5 mm, we kept the distance between two tracks at 0.5 mm. Moreover, widthwise the distance between two tracks was kept at 1.5 mm. Track pads for the capacitors were designed to have the dimensions 1 x 1 mm^2 with the distance between them being 3 mm. For the resistors the track pads for GND and Vout terminals was kept the same as the pads for the capacitors with the distance between them being 2.0 mm and for the common pin connecttion to V_{FB} the track pad was kept at 1 x 5 mm^2. The distance between

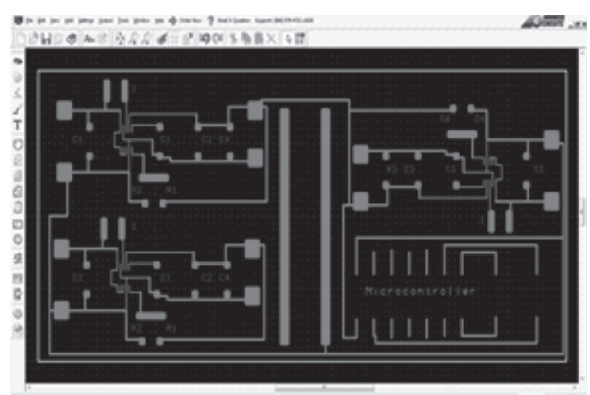

Figure 4: PCB Design of Power Management Circuit.

the common pin and the V_{out} and GND pins was kept at 3.0 mm. The track pads for the inductors were kept at 3 x $1mm^2$ with the distance between them being 2 mm. We created two pads of 32 x 2 mm, with the distance between them at 5 mm for any power storage unit that may be connected to the circuit. The components were connected with the help of 0.4 mm tracks. Connections were also made for a microcontroller based on the datasheet of ATtiny24A with the distance between two tracks being 60 mm widthwise and 2.5 mm lengthwise.

(b) Printing and etching of PMC

After layout designing of PMC the printing is performed on a PCB board. Initially, the fabrication is performed manually at the local PCB fabrication facility, however, due to small connection pads of the regulators and the line widths involved, the final product was not developed upto the standard of the requirements. Therefore, the PCB based PMC is developed at the National Institute of Electronics (NIE) in Islamabad. The circuit manufacturer only accept circuits design layouts in Gerber file format. Therefore in order to meet manufacturer requirements the layout is first save as XPS file which is then converted to PDF format. The file is afterward opened using Adobe Reader IX Pro and the

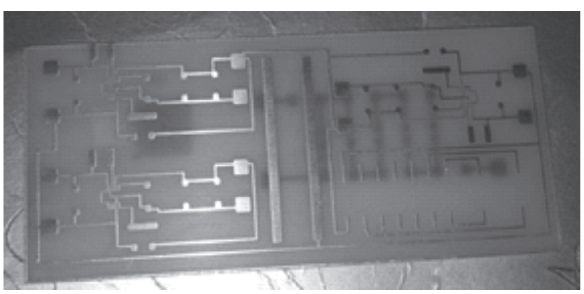

Figure 5: Developed PCB for power management circuit.

layout is saved as postscript file format. Finally, using LinkCAD software the layout postscript file is converted to Gerber format, which is then sent to the manufacture lab for fabrication. The gerber file format actually contains CNC Codes which are used in CNC machines at the lab for both fabrication and testing of the circuit. Multiple layout of the circuit are patterned on a 12 x 6 $inch^2$ PCB sheet using CNC machine after which the sheet is dipped in a etchant solution for etching. The etched sheet are diced into the individual PMC. Finally,

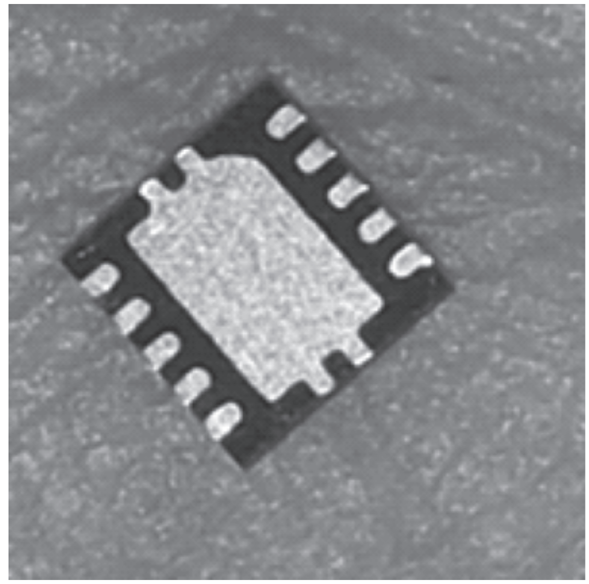

Figure 6: Regulators used in the developed power management circuit.

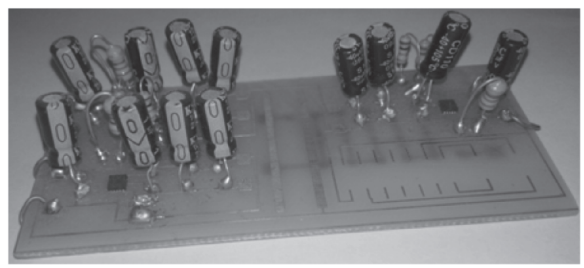

Figure 7: Developed power management circuit after soldering variuos components.

the fabricated circuits are placed in an inspection CNC machine where the CNC Code in the Gerber file are utilized to test the circuit for any problems (such as, short-circuits and open-circuits). The photographic image of the developed PCB for the PMC is shown in Figure 5.

(c) Mounting components

In order to mount and connect the various components on the fabricated PCB, first of all the PCB is cleaned with a cleanroom dustless paper and acetone. Initially, the regulators (shown in Figure 6) are mounted first due to their small size and the tiny connection pads. These regulators are attached to the PCB using a heat-Gun and epoxy silver, because the normal high temperature soldering could damage the regulator. After connecting the regulators, capacitors, resistors and inductors are soldered to the circuit. Figure 7 shows the developed PMC when all the components are mounted on the PCB. The details of the electrical components used for the reported PMC is listed in Table 1. Power management circuit is fabricated in area of 4×9 cm^2.

EXPERIMENTATION, ANALYSIS AND DISCUSSIONS

To analize the power management circuit's behavior for different parameters, characterization of circuit is performed using a rectified AC and DC power sources. The experimental setup used for the characterization of the PMC is shown in Figure 8 and Figure 9. In Figure 8, DC power supply is used to provide various DC voltage inputs to the developed circuit. The DC Power supply is able to provide voltage levels in the range of 1.3-2.4 V, for a maximum current level of 1 A. However, as shown in Figure 9, a function generator is used to generate a variable AC voltage signals, which are rectified using Cockcraft-Walton rectifier. An oscilloscope is used to observe the AC input signal's frequency, amplitude. Sinusoidal waveforms of different frequencies and amplituted are subjected to the rectifier and afterward the rectified DC voltage is provided to the PMC. During experimentation the response of the developed PMC is analised for different output voltage levels from severa values of rectified AC voltage inputs as well as for different values of DC voltage input levels provided directly from a DC voltage source.

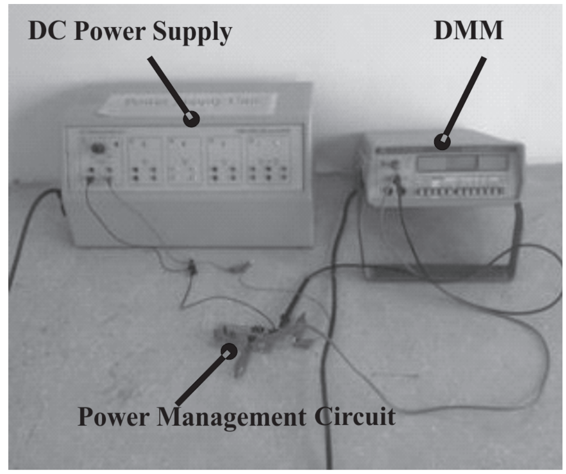

Figure 8: Power management circuit connected for characterization using a DC voltage Source.

Table 1: Main components of the developed PMC

Name	Type	Model	Value
Resistor	**Carbon film**	**-**	**200 KΩ**
Resistor	Carbon film	-	1 MΩ
Capacitor	Electrolytic	SK0920	10 uF
Capacitor	Electrolytic	CD110	0.1 uF
Inductor	Ferric bead (Axial Leaded)	-	3.3 uH
Regulator	Step down/boost	TPS61200DRC-BRR	0.5-5.5 V (input)

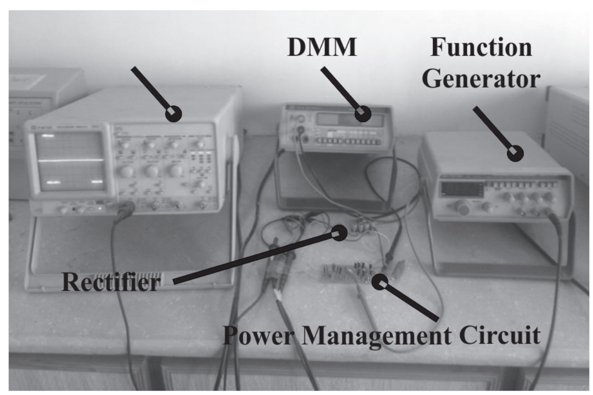

Figure 9: Power management circuit connected for characterization using a rectified AC voltage levels.

The output voltage taken out of the PMC when a rectified AC (DC voltage) is supplied to the circuit is shown in Figure 10. The circuit is designed to regulate the input voltage levels to a constant output voltage level of 3 V, however, the PMC output voltage do not reach the desired value of 3 V but approach very close to it and this is likely due to an error in the resistance of the feedback resistors during the experimention. From Figure 12, it is evident that at higher input voltage levels the power transfer is very efficient and due to which the

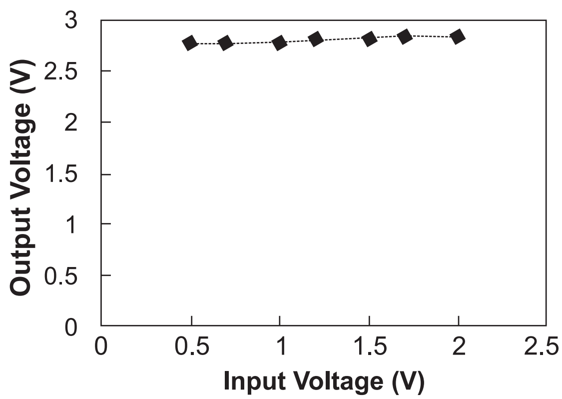

Figure 10: Output voltage versus input voltage using rectified AC voltage source.

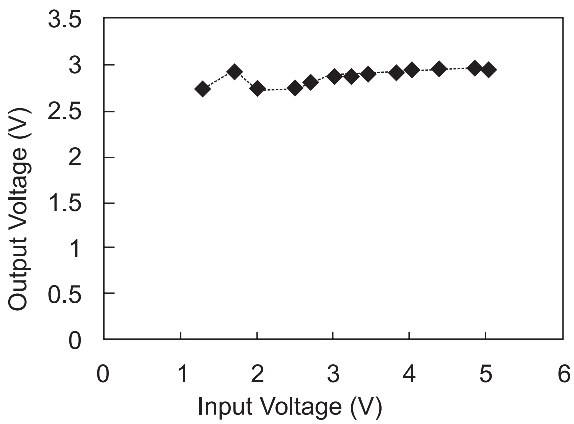

Figure 11: Output voltage versus input voltage using DC voltage source.

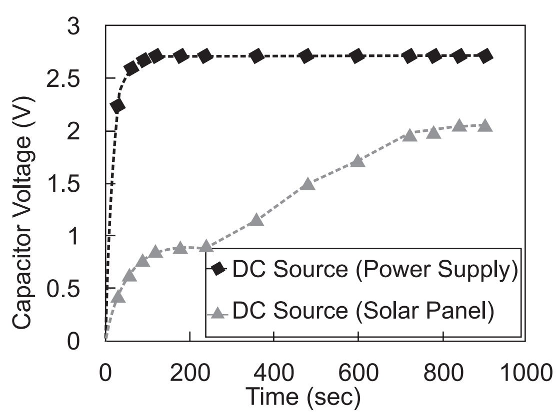

Figure 12: Super capacitor voltage as a function of time.

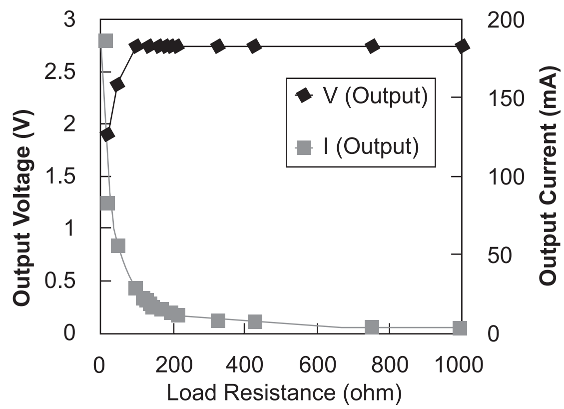

Figure 13: PMC, output voltage and output current against the load resistance.

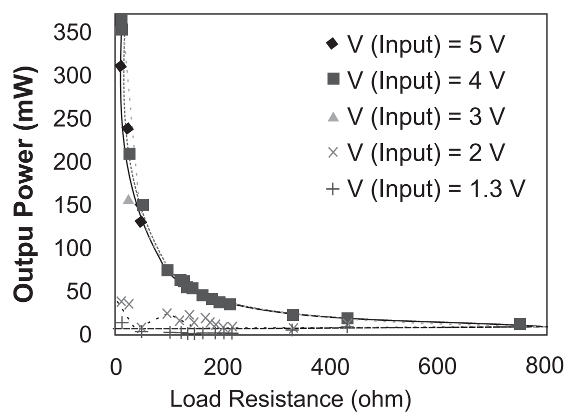

Figure 14: Input power as a function load resistance.

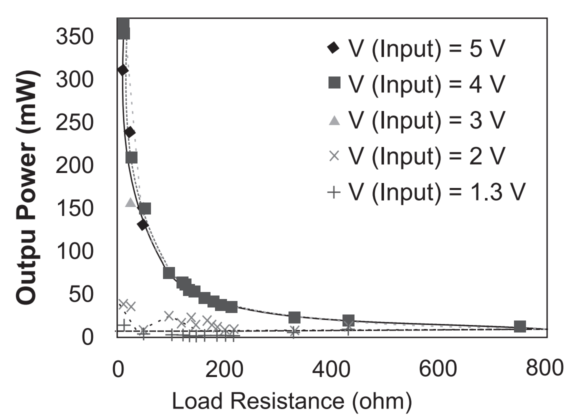

Figure 15: Power consumption of the load resistor as a function of load resistance.

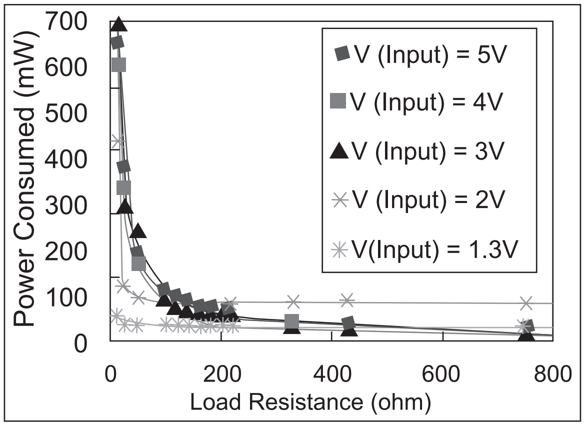

Figure 16: Power consumed by the PMC as a function of load resistance.

soldered to the circuit. Figure 7 shows the developed PMC when all the components are mounted on the PCB. The details of the electrical components used for the reported PMC is listed in Table 1. Power management circuit is fabricated in area of 4×9 cm^2.

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Figure 11 shows the output of the PMC when voltage levels are supplied from the DC voltage source. It can be seen in the plot that the power transfer is more efficient than the DC Source, however, the rectified AC voltage (DC) is unable to compensate at higher voltage levels hence the maximum output voltage the circuit can produced is 2.84 V for an input voltage level of 2 V. At lower input voltage levels the plot is relatively smoother showing no spikes, however, in this case there is a slight shoot up response round about at 1.5 V input voltage. In both experimentations the output voltage remained within the required range of 2.6 to 3.6 V which is the usual range of input voltage requirements for most low power sensors.

The charging time of a super capacitor (), when it is connected to the PMC is shown in Figue 12. During this measurement an input voltage from DC power supply and a solar energy harvester is regulated by the PMC. The DC power supply has a greater amount of current delivery as a result of which the super capacitor is charged in as little time as 180 s to the maximum voltage level of 2.75 V. However, when the setup is connected the solar energy harvester, the solar cells provided small current levels in comparison and thus it took relatively a larger time (840 s or 14min) to charge the same super capacitor. Moreover, because of the low current of the solar cells due to power equalization across input and output the capacitor is only charged upto 2.05 V.

Table 2: Comparison of PMC reported in literature

Main Components	Energy Harvester	Min Input Voltage (V)	Max Input Voltage (V)	No. of Sources	Efficienc (%)	Ref.
Charge pump, DC-DC converter, NiMH battery	**Thermoelectric**	**0.13**	**0.3**	**1**	**55**	**7**
Charge pump, DC-DC converter, NiMH battery	Piezoelectric, RF	1.25	20	2	-	8
Charge pump, coupled inductors, DC-DC converter, NiMH battery	Thermoelectric	0.13, 0.5	0.3,2.1	1	55	9
Boost regulator, capacitor, window comparator, current limiter switch	Wind, Solar	0.5	5.5	2	-	10
Impedance matching circuit, up converter, AC-DC converter, DC-DC regulator, storage capacitor	Electromagnetic	-	-	1	98	11
Impedance matching circuit, Rectifier, DC-DC regulator	RF	0	1.3	1	-	12
NiMH battery, undervoltage & overvoltage protection, energy monitor, DC-DC converter	Solar	2	3	1	82	13
NiMH Battery, undervoltage & overvoltage protection, energy Monitor, DC-DC converter	Solar	2	3	1	82	14
DC-DC converter, super capacitor, regulator	Solar, Rectified AC, DC Power Supply	0.5	5.5	3	-	This Work

Figure 13 shows the output voltage and output current of the PMC with respect to the load resistance. From the plot it can be infered that the circuit performance is better at higher load resistances, however, its voltage regulation efficiency drastically decreases when the PMC is connected to lower load resistances.

Figure 14 shows the power input to the developed PMC at various input DC voltage as a fuction of load resistance. Both the subjected voltage and the current drawn by the circuit when it is connected to variable load are measured and the input power is computed using the measurements.

The power dissipated in the load resistance with respect to the variable load resistance in shown in Figure 15. The voltage across the load and the current flowing through it is measured and is used to compute the power consumed by the respective load resistor. A similar trend is observed at all input voltage levels and the load power decreases with the increase in the load resistance.

As the input power to the PMC should be the sum of both load power (power dissipation in the load resistance and the power consumed by the PMC. Therefore knowing the load power and the input power, the power consumption of the circuit can be easily calculated. Figure 16 shows the power consumed by the PMC with respect to the load resistance at various input voltage levels. The power consumption of the developed PMC is relatively high at lowload resistance, however, beyond 170 Ω load the power consumptions almost becomes steady. Relatively more power consumption is recorded for an input voltage of 2 V when the load resistance is varied from 200 to 800 Ω.

COMPARISION AND DISCUSSION

The summary of the power management circuits developed and reported in literature is provided in

Table 2. The comparision for the reported PMCs can be performed by a number of characteristics of the circuit, such as, minimum input voltage regulation, maximum voltage regulation, number or multipule power sources it can regulate, power consumption of the circuit and efficiency of the circuit. The reported PMCs[7,9,10] can regulated lowest input voltages in the range from 0.13 to 0.5 V. Only PMC[8] can regulated an input voltage as high as 20 V and the PMCs[10] and developed in this work are capable of regulating a high input of 5.5 V. Most of the reported PMCs are developed only to regulate the power from a single source, except PMC[8] and PMC[10]. However the PMC produced in this work can simultaneously regulate the voltage from three separate sources, which is its main advantage over the other circuits. By comparing with respect to efficiency, PMC[11] has the highest reported efficiency, followed by the developed PMCs[13,14]. For these circuits, the overall minimum regulation voltage range is 0.13 to 2, however, the maximum regulation voltage reported for all PMCs range from 0.3 to 20 V.

CONCLUSIONS

The power management circuit (PMC) developed in this work is an efficient and low cost circuit for providing the regulated power to low voltage devices (wireless sensor nodes) from energy harvesting Sources (solar energy harvester, vibration energy harvester and acoustic energy harvester). Work has been performed in the past on PMC using various regulators connected with different sources, however, the basic circuit design has remained the same. In this research three different types of sources (DC power source, rectified AC voltage and a solar energy harvester) and the output voltage provided by the regulator is measured and analyzed. At different input voltage levels (0.5 to 5.5 V) the circuit successfully regulated to almost a uniform output voltage (2.75 to 2.96 V). With the circuit using a DC power source and a solar (solar cell) energy harvester a super capacitor is charged to a voltage of 2.75 and 2.05 V in 180 s and 840 s respectively. Beyond 100 Ω load resistance the PMC regulated a constant output current of 180 mA. Moreover, beyond 100 Ω load resistance the power consumption of the circuit is almost steady for different input voltage levels. The average consumption of the developed PMC is about 70 mW. As most the wireless sensor nodes resistance is on higher side (in kΩ range) the circuit is expected for better operation. The performance of the developed PMC is comparable to the reported PMCs reported in literature, however due to the provision of connecting to three different energy harvesting systems provide an edge over the other circuits.

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