ENERGY HARVESTING WIRELESS SENSOR NETWORKS: DESIGN AND MODELING

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ABSTRACT

Wireless sensor nodes are usually deployed in not easily accessible places to provide solution to a wide range of application such as environmental, medical and structural monitoring. They are spatially distributed and as a result are usually powered from batteries. Due to the limitation in providing power with batteries, which must be manually replaced when they are depleted, and location constraints in wireless sensor network causes a major setback on performance and lifetime of WSNs. This difficulty in battery replacement and cost led to a growing interest in energy harvesting. The current practice in energy harvesting for sensor networks is based on practical and simulation approach. The evaluation and validation of the WSN systems is mostly done using simulation and practical implementation. Simulation studies, despite their wide use and merits for network systems validation, have some drawbacks such as long simulation times, and practical implementation without knowing the details of the parameters and mathematics involved is cost ineffective and waste lots of resources. In most times, the energy scavenged is directly wired to the sensor nodes. We, therefore, argue that simulation – based and practical implementation of WSN energy harvesting system should be further strengthened through mathematical analysis and design procedures. In this work, we designed and modeled the energy harvesting system for wireless sensor nodes based on the input and output parameters of the energy sources and sensor nodes. We also introduced the use of supercapacitor as buffer and intermittent source for the sensor node. The model was further tested in a Matlab environment, and found to yield a very good approach for system design.

KEYWORDS

Wireless Sensor Networks (WSNs); Mathematical Analysis; Energy Harvesting; Simulation.

1. INTRODUCTION

Wireless sensor networks (WSNs) are large networks composed of small sensor nodes (SNs), with limited computing resources capable for gathering, data processing and communicating. Energy consumption represents a barrier challenge in many sensor network applications that require long lifetimes, usually an order of several years. Sensor nodes, as constituents of wireless sensor networks, are battery driven devices and operate on a meager energy budget. Conventional low- power design techniques and hardware architecture only provide partial solutions which are insufficient for sensor networks with energy-hungry sensors [1]. Wireless sensor nodes normally run on disposable batteries, which have a finite operating life. Based on the application and availability of potential ambient energy sources, using energy harvesting techniques to power a wireless sensor node is a wonderful thing to do.

Wireless Sensor nodes have wide range of applications in our day to day activities. Ranging from a Bluetooth equipped chest band that convey human heart rate to a treadmill, wireless electrocardiograph (ECG) temporarily connected to communicate human cardiac activity to a doctor, Zigbee equipped smart meter that monitors energy usage in a household and provides feedback to the user for decision making [2]. In general, wireless sensor nodes applications include structural monitoring, industrial monitoring, security, location tracking, and radio frequency identification (RFID). These wireless sensor nodes will work efficiently for several years between battery replacements. This can be accomplished by the use of energy harvesting, utilizing ambient sources to prolong the life of the batteries in wireless sensor nodes.

Thin- film batteries are usually paired with a supercapacitor in order to handle the current surge when a wireless node transmits. As a result, supercapacitors are an unsubtle choice as energy buffers in energy harvesting applications. Unlike batteries, supercapacitors show extremely good cycle life and no issues relating to overcharge and over discharge. When the energy harvesting source is sufficient to meet the requirement of the wireless sensor node, then an adequately large supercapacitor may totally get rid of the need for a battery [1]. Low power wireless sensor nodes really requires some form of energy harvesting whether from a single source or multiple sources-in order to minimize maintenance and extend the life of the devices (SNs).

The energy harvesting system is made up of energy collection and energy storage. The collection part consists of the solar array. The energy storage device (supercapacitor), will as well serve as a power supply source to the SN. The sensor node in this project operates at RF 315MHz and is powered by a solar energy harvesting source. In order to properly power the sensor node, a supercapacitor of value 1.2F is needed. Supercapacitor cells typically operate at 2.3 to 2.7V.

The objective of this work is to save cost by independently powering wireless sensor nodes with an energy harvesting source without the use of disposable batteries that require constant replacement. In situation where the batteries are still in use by sensor nodes, a supercapacitor allows the sensor node to transmit its final data to the sink node, in the event of power failure, preventing data loss and its associated problem. Sometimes, the system in question is not properly studied. Also, it will be wise enough to gain more knowledge of how the energy harvested degrades with time through system modeling.

The paper is organised as follows: The introductory part of the paper provided in Section 1, deals with the general perspective and objective of the work. Section 2 reviews relevant work in energy harvesting, energy harvesting power sources and energy storage. Section 3 gives a detailed explanation of the system design and implementation, which includes design specification, methodology, modeling of the supercapacitor discharge and sizing of the supercapacitor. The result of the modeling and its discussion was presented in Section 4. The conclusion and future work that to be done was presented in Section 5.

2. REVIEW OF RELEVANT WORK IN ENERGY HARVESTING SYSTEM

Aaron et al. [3] worked on a wireless sensing platform utilizing ambient RF energy. In their work an ambient RF energy harvesting sensor node with onboard sensing and communication functionality was developed and tested. The minimal RF input power required for sensor node operation was -18 dBm (15.8 μW). Using a 6 dBi receive antenna, the most sensitive RF harvester was shown to operate at a distance of 10.4 km from a 1 MW UHF television broadcast transmitter, and over 200m from a cellular base transceiver station. A complete ambient RF-powered prototype was constructed which measured temperature and light level and wirelessly transmitted these measurements. They explained that, “In practical wireless sensor usage, the need for a battery limits the application space and increases initial and recurring costs, making traditional wired sensors more appealing in some cases. Ambient RF (Radio Frequency) energy harvesting offers a unique solution to this practical problem and facilitates the implementation of a battery and supercapacitor-free wireless sensing node with 24-hour operation”. The ambient RF sources are Wi-Fi transceivers, cellular base stations, AM/FM radio transmitters, and TV broadcast transmitters. In their work, they targeted TV broadcast and cellular base transceiver station (BTS) signals as ambient power sources, as these signals represent two of the most promising ambient RF sources due to their high transmit power (TV) and ubiquity in urban environments (cellular BTS). Action Nechibvute, Albert Chawanda both of Department of Physics, Midland State University, Gweru Zimbabwe, and Pearson Luhanga of Department of Physics, University of Botswana, Gaborone, Botswana, presented a paper on a concise review of piezoelectric microgenerators and nanogenerators as a renewable energy resource to power wireless sensor nodes. In their presentation, they observed that, while solar energy harvesting is a fairly established technology, it is not the best choice for mobile, implantable, and embedded electronics where solar energy is not accessible. Mechanical energy in the form of ambient vibrations, fluid flow, machine rotations, and biomotion presents a source of energy that is available widely and at all times. Piezoelectric materials can be used to harvest this energy since they have the unique ability of converting mechanical strain energy into useful electrical energy. Piezoelectric energy harvesting devices—in the form of MEMS generators or nanogenerators—are a novel technology that is a reliable alternative energy source for powering wireless sensor devices. Unlike conventional MEMS generators, nanogenerators have an added advantage of being flexible and foldable power sources which is ideal for applications such as implantable biomedical sensors [4].

2.1. Energy Harvesting Power Sources

Energy harvesting (also known as power harvesting or energy scavenging) is the process by which energy is derived from external sources (e.g. solar power, thermal energy, wind energy, salinity gradients, and kinetic energy), captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks. Energy harvesters provide a very small amount of power for low- energy electronics. While the input fuel to some large- scale generation cost money (oil, coal, etc.), the energy source for energy harvesters is present as ambient background and is free [5].

The following are some of the potential sources available for energy harvesting depending on the application and location: vibration, heat, light, wind, and RF.

Light: In almost all applications, energy scavenging from ambient light will be an unsubtle choice. Photovoltaic cells are used in generating electrical power by converting solar radiation (both indoors and outdoors) into direct current electricity using semiconductors that display the photovoltaic effect. Outdoors during the day, solar energy flux averages 0.1 W/cm^2, which is sufficiently large that even a very small photovoltaic (PV) cell is usually sufficient to power a wireless sensor node. Indoor solar sensors are frequently employed to manage lighting levels. However they are much less useful for powering wireless devices, since the power available from indoor lighting is usually 10 to 100 $\mu W/cm^2$, and its usefulness depends to some extent on the spectral composition of the light [2].

Photovoltaic (PV) energy harvesting wireless technology gives remarkable advantages over wired or only battery – powered sensor solutions: nearly inexhaustible sources of power with little or no adverse environmental effects [5].

Vibration: The following are the approached employed for converting vibration into electricity: piezoelectric, electromagnetic, and electrostatic. In piezoelectric transducers, vibrations deform the crystalline structure of the sensor, thereby generating electricity. In electromagnetic transducers, electricity is generated by the relative motion of a coil and a magnet. Electrostatic transducers respond to changes caused by vibration in distance between two electrodes of a polarized capacitor [2].

The strain in piezoelectric transducers can come from many different sources such as human motion, low-frequency seismic vibrations, and acoustic noise. Except in rare instances the piezoelectric effect operates in AC requiring time-varying inputs at mechanical resonance to be efficient. Most piezoelectric electricity sources produce power on the order of a few microwatts to several milliwatts, too small for system application, but enough for hand-held devices such as some commercially available self-winding wristwatches [5].

Heat: Thermal energy harvesting is based on the seebeck effect. In this case, two dissimilar metals kept at different temperatures will display an open circuit voltage between them, with the voltage varying directly with the temperature differential. If the seebeck coefficients of the two metals remain relatively constant over temperature, the available voltage is approximately

$$\mathrm{V} = \Delta\mathrm{S} * \Delta\mathrm{T} \tag{1}$$

where ΔS is the difference in the seebeck coefficients of each metal and ΔT is the temperature difference between them. The simplest thermoelectric generator is the thermocouple, a junction of two dissimilar metals. Most thermoelectric generators (TEGs) are thermophiles, consisting of a large number of thermocouples connected in series and sandwiched between two metal or ceramic plates. The amount of voltage and, therefore, power available from a thermocouple varies directly with the difference in temperature between two metals [2]. Large voltage outputs are possible by connecting many junctions electrically in series and thermally in parallel. These can be used to capture mWs of energy per time from industrial equipment, structures, and even the human body. They are usually coupled with heat sinks to improve temperature gradient [5].

Radio Frequency (RF): Radio transmitters existing everywhere are possible source of energy. In order to get useful power levels from radio transmitters either a large collection area or close proximity to the radiating wireless energy source is required. Simply put, there is need to have a powerful transmitter or a good antenna- preferably both – to be able to capture a useful amount of RF energy. In urban centers, ambient RF might occasionally prove to be a useful supplemental energy source, but its usefulness will be highly location dependent [2]. One idea is to deliberately broadcast RF energy to power remote devices: This is now commonplace in passive radio frequency identification (RFID) systems, but the safety and US federal communication commission (and equivalent bodies worldwide) limit the maximum power that can be transmitted this way to civilian use. This method has been used to power individual nodes in a wireless sensor network [6].

Table 2.0 shows a summary of the amount of power available from each of the sources discussed above, which will help in in decision making and power budget.

Table 1. Comparison of energy harvesting sources for WSNs

Energy Source	Classification	Performance (power density)	Weakness	Strength
Solar Power	Radiant Energy	$100mW/cm^3$	Require exposure to light, and low efficiency if device is in building	Can use without limit
RF Waves	Radiant Energy	0.02µW/cm2 at 5Km from AM Radio	Low efficiency inside a building	Can use without limit
RF Energy	Radiant Energy	40µW/cm2 at 10m	Low efficiency if out of line of sight	Can use without limit
Body Heat	Thermal Energy	60µW/cm2 at 5^oC	Available only when temperature different is High	Easy to build using Thermocouple
External Heat	Thermal Energy	135µW/cm2 at 10^oC	Available only when temperature different is High	Easy to build using Thermocouple
Body Motion	Mechanical Energy	$800\mu W/cm^3$	Dependent on Motion	High power density, not limited on interior and exterior
Blood Flow	Mechanical Energy	0.93W at 100mmHg	Energy conversion efficiency is low	High power density, not limited on interior and exterior
Air Flow	Mechanical Energy	$177\mu W/cm^3$	Efficiency is low inside a building	High power density, not limited on interior and exterior
Vibrations	Mechanical Energy	4µW/cm3	Has to exist at surrounding	High power density, not limited on interior and exterior
Piezoelectric	Mechanical Energy	50µJ/N	Has to exist at Surrounding	High power density, not limited on interior and exterior

2.2. Energy Storage

The major challenge with energy harvesting sources is that their energy is often only intermittently available, so some method of storing excess power to match supply and demand is very necessary. Generally, energy can be stored in a capacitor or battery. Capacitors are used when the application needs to provide huge energy spikes. Batteries leak less energy and are therefore used when devices needs to provide a steady flow of energy [5]. Thin film batteries are usually paired with either a large capacitor or a supercapacitor in order to be able to handle the current surge when a wireless node transmits. Ultra- high density supercapacitors are preferable as energy buffers in energy harvesting [2].

Supercapacitors are used in this work as storage device to provide for long term back-up power to the wireless sensor nodes and help to get rid of battery back-up units, along with its maintenance and monitoring problems. It also helps to eliminate the environmental compliance issues that comes with battery disposal, and offers superior shelf life compared to batteries. A well sized supercapacitor will last for a long period of time.

2.2.1. Supercapacitor

Supercapacitors are also referred to as electric double- layer capacitor (EDLC). Ultracapacitor is the generic name used for a family of electrochemical capacitors. In general, capacitors are constructed with dielectric placed between opposed electrodes, functioning as capacitors by accumulating charges in the dielectric material. Conventional capacitors store energy by the removal of charge carriers, typically electrons from one metal plate and depositing them on another. The potential between the two plates is created due to the charge separation, which can be utilized in an external circuit. Supercapacitors have a rare high energy density of several orders of magnitude greater than a high capacity electrolytic capacitor compared to common capacitors. Supercapacitors do not have a conventional solid dielectric, but instead utilize the phenomena typically referred to as the electric double layer. The effective thickness of the "dielectric" is extremely thin in the double layer, and because of the porous nature of the carbon the surface area is exceedingly high, which means a very high capacitance.

Supercapacitors bridge the gap between conventional capacitors and rechargeable batteries. They are able to store the most energy per unit volume or mass (energy density) among capacitors. They support up to 10,000 F per 1.2V [8], up to 10,000 times that of electrolytic capacitors, but deliver or accept less than half as much power per unit time (power density) [9]. However, the ultra-capacitor can only withstand low voltages (usually less than 2.7V per cell), as a result of which supercapacitors rated for higher voltages must be made of matched series – connected individual capacitors [7].

The following are some of the advantages of supercapacitor as a storage device.

- They have high energy storage capacity compared to conventional capacitors;
- Their equivalent series resistance (ESR) is low compared to batteries, hence providing high power density;
- The can operate in low temperature up to – 40°C with minimal effect on efficiency;
- They have a simple charging method;
- They have high power density;
- Very fast charge and discharge;
- They are rugged and can be operated in harsh environmental condition due to their epoxy resin sealed case which is non-corrosive;
- Improve environmental safety;
- They can last for a very long period of time. They have virtually unlimited cycle life.

The following are some of the disadvantages associated with supercapacitor as a storage device.

- They have a low voltage per cell, typically about 2.7V. In high voltage application, cells have to be connected in series;
- They cannot be used in AC and high frequency circuits, because of their time constant.

Supercapacitors are typically used in applications where batteries have a shortfall when it comes to high power and life, and conventional capacitors cannot be used because of their inability to store enough energy. They offer a high power density along with adequate energy density for most short-term high power applications.

Figure 1. A real view of a supercapacitor

Table 2.0 compares supercapacitors with other energy storage devices, including batteries and conventional capacitor. Each of them has its own advantages and disadvantages compared to other technologies.

Table 2. Supercapacitor vs. Battery and Conventional capacitors

Available Performance	**Lead Acid Battery**	**Supercapacitor**	**Conventional Capacitor**
Charge Time	(1 to 5) hrs	(0.3 to 30) s	(10^{-3} to 10^{-6}) s
Discharge Time	(0.3 to 3) hrs	(0.3 to 30) s	(10^{-3} to 10^{-6}) s
Energy (Wh/kg)	10 to 100	1 to 10	< 0.1
Cycle life (Years)	1,000	> 500,000	> 500,000
Specific Power (W/kg)	< 1000	< 10,000	< 100,000
Charge/discharge efficiency (%)	0.7 to 0.85	0.85 to 0.98	> 0.95
Operating temperature (℃)	-20 to 100	-40 to 65	-20 to 65

3. System Design and Implementation

3.1 System Design Specifications

- CAP XX Supercapacitor: 1.2F, ESR of 50mΩ, rated voltage 5.5V, operating voltage (2.3 – 2.7) V cell.
- Sensor Node Voltage rating: (3 – 5) V.

- Power and current consumption of sensor node: 32mW and 8mA.
- Operating ambient temperature of Sensor node: (-20 to +85)^{0}C.
- Solar panel rating: Maximum Power Voltage = 5.82V, Maximum Power Current = 0.52A, Short circuit current = 0.55A, Open circuit voltage =7.38V, Output Power tolerance = 3%.

3.2. Design Methodology

This section gives an overview of the modules and operation of the entire system. The modules are as shown in Figure 2.

3.2.1. Operating Principle of the Energy harvesting wireless sensor nodes

The functional block diagram for the intended system is shown in Figure 3.1. The voltage source (Transducer) helps in converting the solar energy into an electrical signal (voltage). The voltage source is protected by an overvoltage circuit (shunt regulator). The third stage, the charging circuit, is a current-limiter circuit, and uses MOSFET to charge the supercapacitor in the final circuit (output circuit), which in turn store the energy used to charge the sensor battery or directly supply the sensor node. The overall system is subdivided into 4 basic modules.

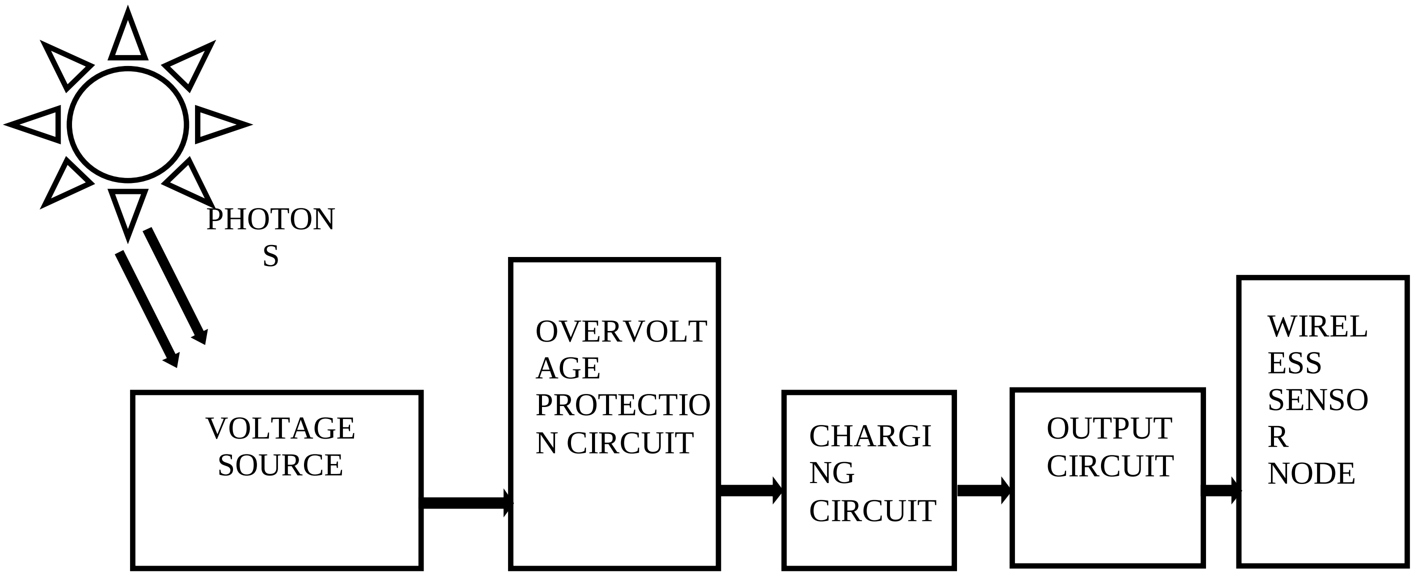

Figure 2. Block diagram of energy harvesting wireless sensor nodes

3.2.1.1. Voltage source

Solar cells (solar panel) are used to convert solar energy to electrical energy in the form of the voltage signal. The solar energy is as a result of illuminated junction of the cells. The typical solar cell can be represented by the circuit model shown in Figure 3.2. The current source, I_1, represents the current produced from electron-hole pair recombination due to solar radiation. The diode represents the solar cell's P-N junction characteristics. Current will pass through the solar cell just like it would pass through a diode when voltage is applied or produced across the terminals. The diode is characterized by its *ideality factor*, n, and its *reverse saturation current*. R_2 is the parallel resistance of the semiconductor materials, and diode current. R_1 is the series resistance of the metals used in the solar cell leads and contacts. Typically, $R_2 >> R_1$. The solar panel operating current and voltage is 0.52A and 5.82V respectively. It also has an open circuit voltage of 7.38V.

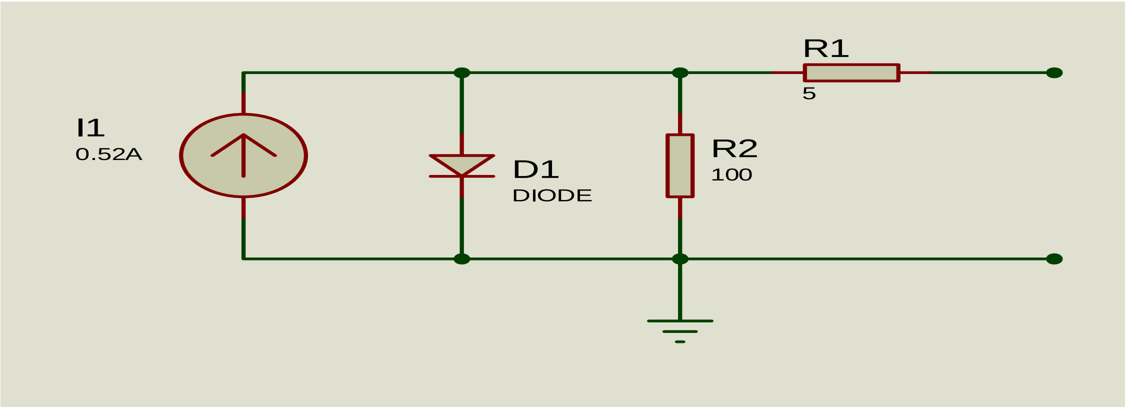

Figure 3. Solar cell circuit model

3.2.1.2. Overvoltage Protection Circuit

In contrast to a battery, a supercapacitor need not charge at a constant voltage, but charges most efficiently by drawing the maximum current the source can supply. In our design specifications, the energy source's open-circuit voltage is greater than the supercapacitor's voltage, as such, we then requires overvoltage protection for our supercapacitor using a shunt regulator. A shunt regulator is an inexpensive and simple approach to overvoltage protection, and, once the supercapacitor fully charges, it does not matter whether the excess energy dissipates. Figure 3.3 shows the overvoltage protection circuit.

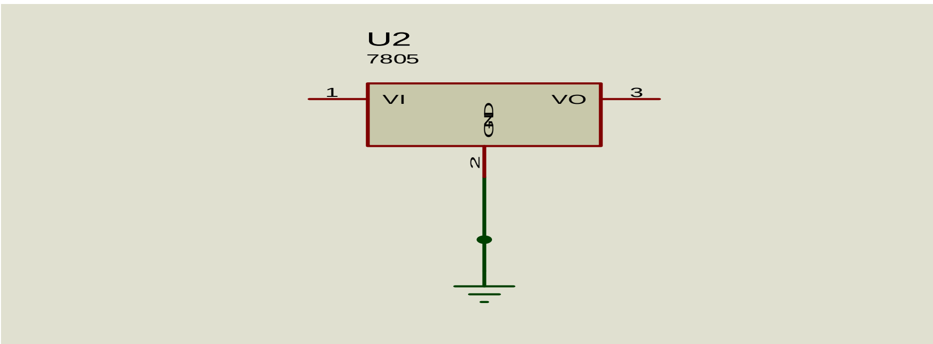

Figure 4. Fixed output voltage regulator

The voltage regulator used is LM7805, a 5V, 1A regulator. Since its minimum input voltage is 7V, it is suitable to function properly with the 7.38V delivered by the solar panel and it will maintain an output voltage of 5V.

3.2.1.3. Charging Circuit

This is basically switching/current limiting stage. We will be using a MOSFET for this purpose. In this case, we shall be using MOSFET in load switching application. In this module, we employed CAP-XX supercapacitor with high capacitance and low ESR on the power rail, which will now serves as the load that the MOSFET will be seeing. The low ESR enables the supercapacitor to deliver high power (with only a small voltage drop at the beginning of the peaks), while the high capacitance stores sufficient energy to power the load during the load pulses without a significant voltage drop. The supercapacitor is re-charged between load pulses. However, the large capacitance may introduce a new problem, which is the high charging current it requires on power-up. A solution to the start-up current problem is to limit it to a safe, known value until the supercapacitor is charged. This section is expected to handle that effect, i.e. to limit the current delivered to the supercapacitor when the power is first applied to the circuit, so that the supercapacitor charges without imposing a high current load on the supply. We will be using MOSFET to charge the supercapacitor in a current- limiting mode.

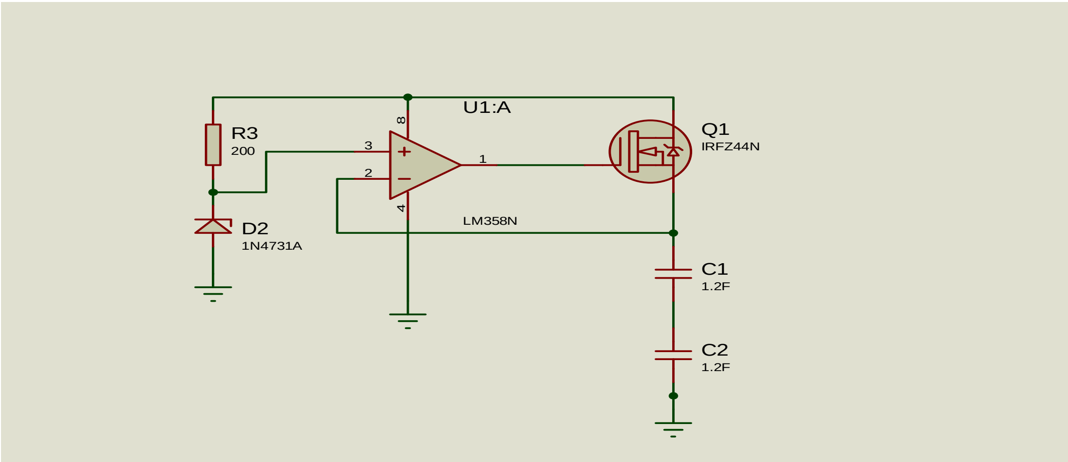

Figure 5. Simple solar cell charging circuit

The charge controller is built around the IC LM358 low power dual operational amplifier configured as a comparator. A 4.3V zener diode is connected to the non-inverting input (pin 3) of the IC leading to a constant 4.3V at this input pin. The zener diode current available at this pin is obtained as

$$I = \frac{V_{in} - V_{out}}{R} \qquad (2)$$

Where, I = current, V_{in}= input Voltage = 5V,

V_{out} = output voltage = 4.3V and

R = Series resistance = 200Ω

Therefore, I= 3.5mA which is greater than the typical input offset current required by the IC (i.e. 2nA).

The inverting input of the IC is connected to the capacitor charging input. Thus, when the capacitor is charging, the IC compares the capacitor charge voltage with the 4.3V in pin 3. If the charge voltage is less than 4.3V, the output of the comparator (pin 1) remains at a voltage of Vcc - 1.5V (LM358 datasheet)

which is obtained as

$V_{out} = V_{cc} - 1.5V = 5 - 1.5 = 3.5V$

This voltage serves as the gate voltage of the N-channel MOSFET IRFZ44N with ratings:

Gate to Source Voltage V_{gs} = 10V at 25°C

Continuous Drain Current $I_D = 50mA$ at 25°C

Minimum Gate Threshold Voltage $V_{gs\,(th)} = 2V$

From the trans inductance curve of the MOSFET,

$$I_D = K\,(V_{gs} - V_{gs\,(th)})^2 \tag{3}$$

$$K = \frac{I_D}{(V_{gs} - V_{gs\,(th)})^2}$$

$$K = 780\ (mA/V^2)$$

K is a constant, thus Drain current I_D, for Vgs = 3.5V is obtained as

$$I_D = 0.78\,X\,(3.5 - 2)^2 \ = \ 1.755A$$

This means that the MOSFET can conduct up to 1.755A with the input voltage of 3.5V and this value is ok since only 0.52A flows across the drain current.

3.2.1.4. Output Circuit

The output circuit basically consists of the supercapacitor that feeds the wireless sensor node. The supercapacitor is to power a sensor node operating at (3 – 5) V. The sensor node is designed in such a manner that, it requires a solar panel charging voltage between 6V-12V. The temperature at which the nodes operate is also between -20 ^{0}C to +85 ^{0}C. An ideal supercapacitor circuit model is shown in Figure 3.5. The supercapacitor should be sized, because, supercapacitor cells typically operate at 2.3 to 2.7V. The most efficient and cost-effective strategy is to limit the supercapacitors' charge voltage to less than the cell-rated voltage and store enough energy for the intended application.

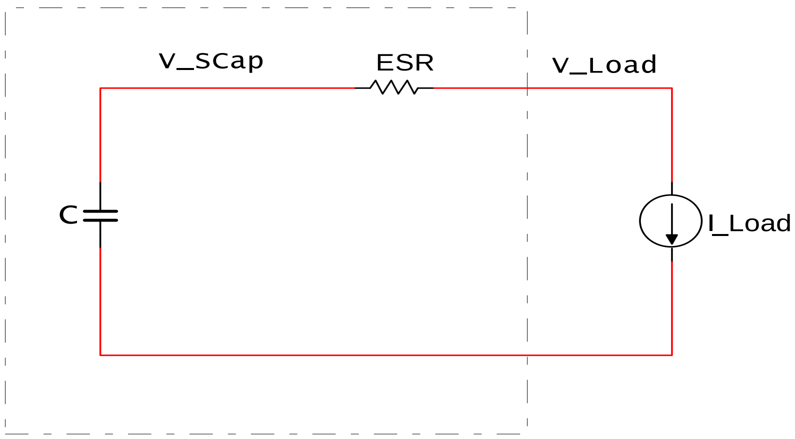

Figure 6.   An ideal supercapacitor circuit model

3.3. Modeling the Supercapacitor Discharge

Supercapacitor cells typically operate at 2.3 to 2.7V. The most efficient and cost-effective strategy is to limit the supercapacitor's charge voltage to less than the cell- rated voltage and store enough energy for a particular application. A simple approach to sizing the supercapacitor is to calculate the energy necessary to support the peak power of the application, P.t, and set this value equal to $0.5 \times C \times (V_{initial}^2 - V_{final}^2)$, where C is the capacitance, $V_{initial}^2$ is the square of the supercapacitor's voltage just before the peak power burst, and V_{final}^2 is the square of the final voltage. However, this equation does not allow for any losses in the supercapacitor's ESR (equivalent series resistance). The load sees a voltage of $V_{initial} - ESR \times I_{Load}$, where I_{Load} is the load current. Because the load voltage decreases, the load current increases to achieve the load power. Referring to Figure 3.1, our supercapacitor discharge can be modelled as:

$$V_{Load} = V_{Scap} - I_{Load} \times ESR; \tag{4}$$

$$P_{Load} = V_{Load} \times I_{Load} = \left(V_{Scap} - I_{Load} \times ESR\right) \times I_{Load}$$

$$= V_{Scap} \times I_{Load} - I^2{}_{Load} \times ESR \tag{5}$$

where V_{scap} is the supercapacitor's voltage

The equation further leads to load current, i.e.

$$I^2{}_{Load} \times ESR - V_{Scap} \times I_{Load} + P_{Load} = 0 \tag{6}$$

Supercapacitor discharge can then be simply modelled using Matlab as:

$$I_{Load}(t) = \left[\frac{V_{Scap}(t) \pm \sqrt{(V_{Scap}(t))^2 - 4 \times ESR \times P_{Load}}}{2 \times ESR}\right] \tag{7}$$

$$V_{Load} = V_{Scap}(t) - I_{Load} \times ESR \tag{8}$$

$$V_{Scap}(t + \Delta t) = V_{Scap}(t) - \frac{I_{Load}(t) \times \Delta t}{C} \tag{9}$$

3.4. Sizing the Supercapacitor

In order to size the supercapacitor the following variables need to be defined.

I. Maximum charged voltage (Vmax), if different from the working voltage (Vw).

II. Minimum Voltage (Vmin)

III. Power (W) or current (I) required.

IV. Discharge duration (t)

V. Duty cycle.

VI. Required life

VII. Average Operating temperature.

The last three (3) variables are used to calculate the life degradation factor to use for the supercapacitor. This is not part of the research scope. In the determination of the appropriate size and also number of cells required for our application, we proceed as follows:

During the discharge cycle of a supercapacitor there are two variables to look at. The voltage drop due to equivalent series resistance (ESR) and the voltage drop due to the capacitance [17].

From [17]; Voltage drop due to the equivalent series resistance is obtained as

$$V_{ESR} = I_{Load} \times ES \tag{10}$$

Voltage drop due to the capacitance of the supercapacitor

$$V_{Scap}(t) = \frac{I_{Load}(t) \times \Delta t}{C} \tag{11}$$

The total voltage drop is therefore obtained as:

$$V_{dt} = I_{Load} \times ESR + \frac{I_{Load}(t) \times \Delta t}{C} \tag{12}$$

V_{dt} is the total voltage drop when the capacitor is discharged. This is equal to the difference of V_w (working voltage) and V_{min} (minimum voltage) as shown in Figure 3.6. Allowing a larger V_{dt} will reduce the capacitance size used. Usually by allowing the capacitor to drop to 0.5 Vw, 75% of the capacitor energy is discharged.

I_{Load} = current used to discharge the supercapacitor in amperes. For equation (12) we assume I_{Load} to be a constant current discharge.

Δt = time taken to discharge the capacitor between Vw and Vmin in seconds.

C = Total capacitance of the supercapacitor in farad. If a single cell is used, then it is referred to as the cell capacitance. If more than one cells are used the equivalent capacitance is obtained based on the number of capacitors in series or parallel as shown below.

$$C = Cc \times \frac{Number\ of\ capacitors\ in\ parallel}{Number\ of\ capacitors\ in\ series} \tag{13}$$

$C_{C\,=}$ cell capacitance.

ESR = total resistance of the supercapacitor in ohms. If a single cell is used, then it is called the cell resistance. If more than one cells is used the equivalent resistance is obtained based on the number of capacitors in series or parallel as shown below.

$$ESR = \text{ESRcell} \times \frac{Number\ of\ resistors\ in\ series}{Number\ of\ resistors\ in\ parallel} \tag{14}$$

From the system design specification;

V_{max} = 5V

V_{min} = 3V

I = 0.008 A

P = 0.032W

Using the values above let us determine the size of the supercapacitor.

To determine the value of our stack supercapacitor, recall that, Energy is given as

$$P \times \Delta t = 0.5 \times C \times (V_{initial}^2 - V_{final}^2)$$

Therefore, $C = \frac{2 \times P \times \Delta t}{V_{initial}^2 - V_{final}^2} = \frac{2 \times 0.032 \times 150}{16} = 0.6F$

But, $ESR = \text{ESRcell} \times \frac{Number\ of\ resistors\ in\ series}{Number\ of\ resistors\ in\ parallel}$

Therefore, $ESR = 0.05 \times 2 = 0.1\ ohms$

From equation (12), neglecting the effect of the ESR,

$V_{dt} = \frac{I_{Load}(t) \times \Delta t}{C}$, therefore $\Delta t = \frac{V_{dt} \times C}{I_{Load}(t)}$

where $V_{dt} = 5 - 3 = 2V$

$$\Delta t = \frac{2 \times 0.6}{0.008)} = 150\ seconds = 2.5\ minutes.$$

Given V_{max} = 5V, since each supercapacitor cell is usually rated at 2.7V, then we divide V_{max} by 2.7 and round up.

$\frac{5}{2.7} = 1.85 = 2\ approximated$, 2 cells in series are required.

From equation (13), the cell needed will be in the range of

$$C = Cc \times \frac{Number\ of\ capacitors\ in\ parallel}{Number\ of\ capacitors\ in\ series}$$

$$C = Cc \times \frac{Number\ of\ capacitors\ in\ parallel}{Number\ of\ capacitors\ in\ series} = \frac{1.2 \times 1}{2} = 0.6F$$

Each of the 1.2F cells will have a rated voltage of 2.7V, since they will be connected in series, hence the total voltage will be 5.4V which will be enough to drive our wireless sensor node.

Considering the effect of ESR, from equation (12), i.e

$$V_{dt} = I_{Load} \times ESR + \frac{I_{Load}(t) \times \Delta t}{C},$$

$$\Delta t = \frac{(V_{dt} - I_{Load}(t) \times ESR) \times C}{I_{Load}(t)} = \frac{(2 - 0.008 \times 0.1) \times 0.6}{0.008} = 150\ seconds = 2.5\ minutes.$$

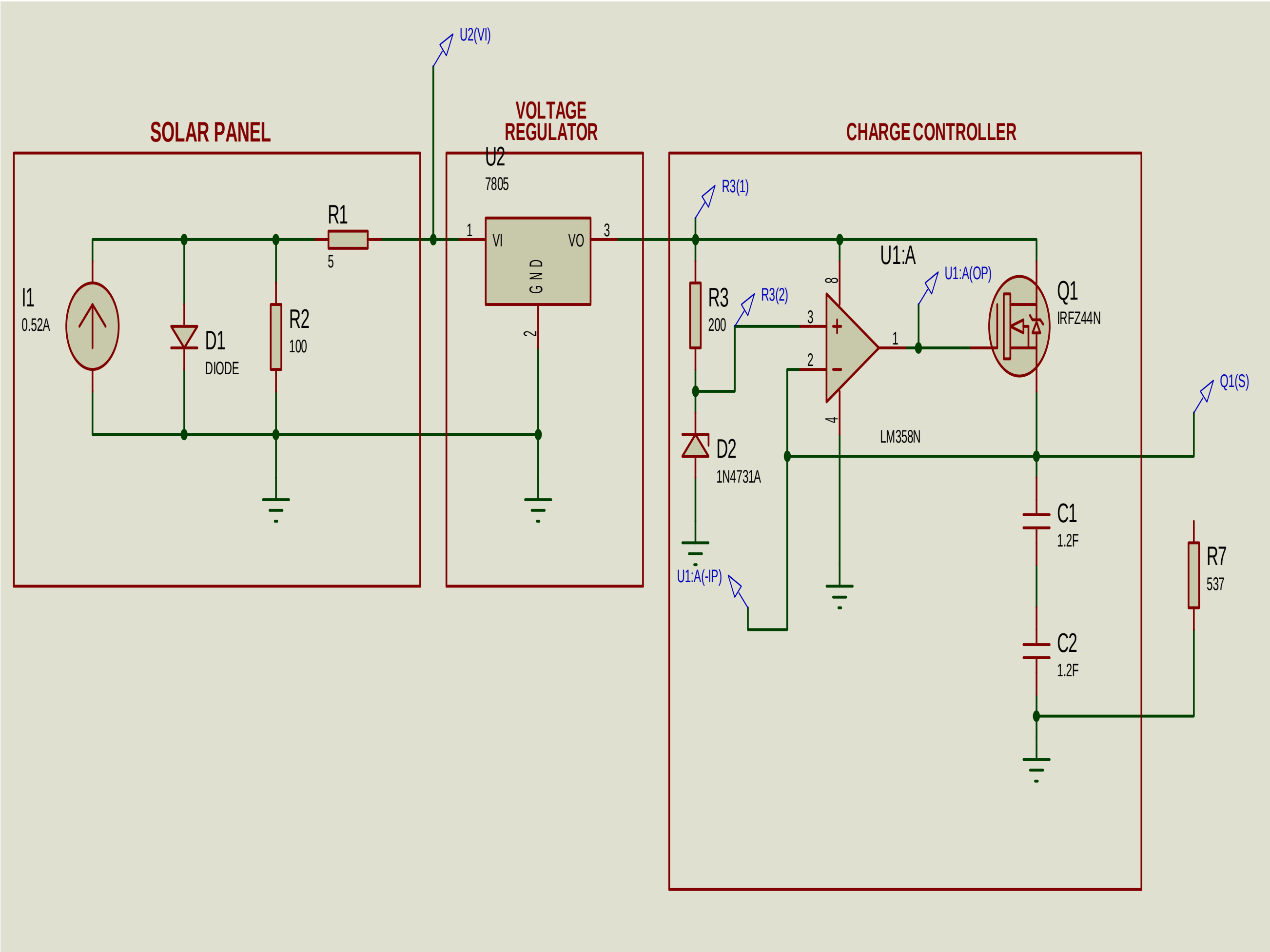

Figure 7. Overall circuit diagram of energy harvesting wireless sensor nodes

4. Results from Modeling

Table 3. Result of the Modeling of Supercapacitor discharge voltage

Discharge Voltage (V)	**Discharge duration of the capacitor (minutes)**
5.4000	0
4.8073	1
4.2147	2
3.6220	3
3.0294	4

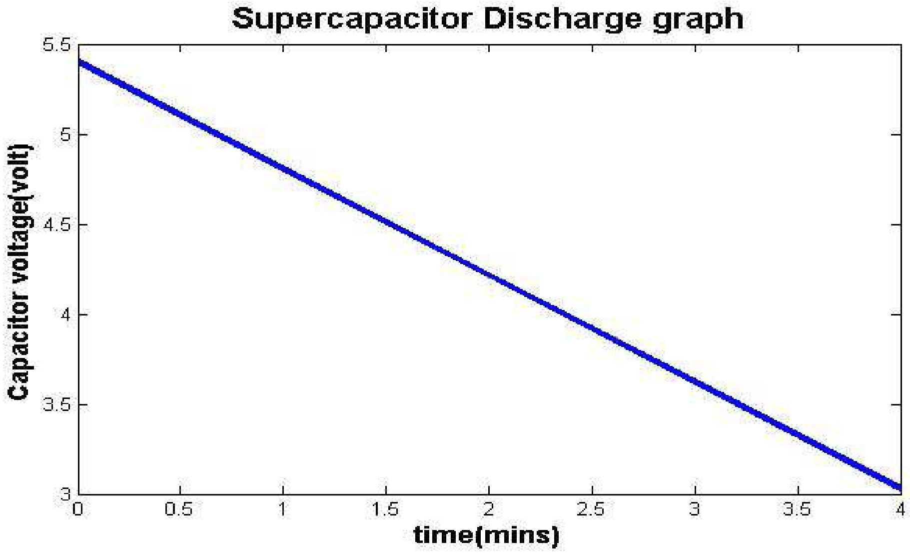

Figure 8. Supercapacitor discharge graph

4.1. Discussion of Results

The result obtained from the modelling of the supercapacitor discharge is as shown in Table 4.0. In the table, the maximum value the capacitor is charged to is 5.4V and the minimum operating voltage which the wireless sensor node that was backed up by the capacitor can tolerate before it stops working is 3.0294V. The specification for the wireless sensor node requires a maximum voltage of 5V and a minimum voltage of 3V. The implication of this is that, only a part of the stored energy is available for applications, because the voltage drop and the time constant over the internal resistance mean that some of the stored charge is inaccessible. The voltage drop is used in determining the size of the supercapacitor capacitance to choose for a given application. A larger drop in voltage when the capacitor is discharged will reduce the capacitance size used. When the voltage drop is more than the allowable voltage drop, the chosen capacitance is sized up and vice versa. Typically by allowing the capacitor to drop to half of the working voltage of the supercapacitor, 75% of the capacitor energy is discharged.

5. CONCLUSION AND FUTURE WORK

Low power wireless sensor nodes indeed need some form of energy harvesting either from a single or multiple sources- in order to minimize maintenance and extend the life of the devices. Energy harvesting using solar cell is an interesting alternative source of energy that has the potential to provide energy independence to wireless sensor devices without the use of expensive wires, or batteries that will need replacement every now and then. From our results, it is can be said that, only a part of the stored energy is available for applications, we can now conclude that a larger drop in voltage when the capacitor is discharged will reduce the capacitance size used and this knowledge can be used to further strengthened simulation approach and practical implementation of energy harvesting wireless sensor network.

In general, there is need for optimal design considerations and energy budget for a successful implementation in any energy harvesting system. Reduction in the operation of the energy of wireless sensor nodes will allow for a smaller storage capacitor value to be used, thereby reducing system cost and improving sensitivity and efficiency due to the lower parasitic leakage of smaller capacitors. There is a need for more than one energy harvester for a successful energy harvesting application.

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