Ambient Energy Harvesting and Management on the Sensor Nodes in a Wireless Sensor Network

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Abstract- One of the key problems in wireless sensor networks (WSN) represents the energy. During continuous operation at the sensor nodes, the energy level decreases very quickly and it is pivotal to replace or recharge frequently through power sources. But many times, it is very difficult to perform these functions through conventional methods. To overcome the problems associated with conventional methods, we harvest the energy at the nodes through photovoltaic cells by the help of sunlight (ambient sources).The available energy from the sunlight is random and uncertain. So in this paper, we present various models of photovoltaic cells at different irradiance levels. Our focus is mainly on solar energy harvesting with appropriate energy management schematically and analytically. The proposed analysis and simulation result shows how power increases with the increase in irradiance levels. Finally, we focus at the voltage and power of the storage devices at different times of the day. These models not only manage the connectivity of the network but also scavenge the energy by optimizing the energy consumption.

Keywords- Wireless Sensor Network, Photovoltaic cell, ambient energy, energy harvesting, energy efficient, energy scavenge

1. Introduction

Wireless sensor networks (WSN) mainly consist of small sensor nodes with limited energy and computing resources. The major challenge in this network (WSN) represents longer period of network survival and high consumption of energy. The sensor nodes are driven by supplied battery and due to high consumption; the structure and low power design techniques cannot give an adequate solution [1]. These nodes normally depend upon the finite operating life time batteries. To power a WSN node, the energy at that node can be harvested through availability of potential ambient energy sources. Ambient energy harvesting is the process of accumulating and utilizing the energy from environment such as solar, mechanical, thermal energy and RF energy [2]. In WSN the sensor nodes are equipped with energy harvesting devices, which can scavenge energy from the ambient sources. Although battery is the primary source in all sensor nodes, sometimes the harvested energy can be used as the primary supplement of power sources. The major parts of an energy harvesting model are the sensor nodes (different types), energy sources, primary storage devices, harvesting device and the different processes for consuming the energy [3].The two main approaches for energy harvesting are: (a) the total dependency on an ambient energy as supplementary sources; (b) the energy harvesting devices, called transducer. The transducer generates electric energy from the ambient sources by adapting different techniques [4]. The ambient sources can be thermal, micro wind turbine, piezoelectric, mechanical, solar radiations, radio frequency and special antenna energy sources [5]. Due to stochastic nature of environmental energy sources, it can or cannot be predictable and controllable. Different energy sources, nature of sources and energy harvesting devices are depicted in Table 1. In this approach we focus at how can a sensor node harvest the energy through the sunlight with the help of photovoltaic cells (PV_{cell})?In a harvesting model the most important component is the load which utilizes the initial energy as well as harvested energy. The load regulates the electronic circuit, sensor nodes, processing unit, transceiver and shunt regulators. The characteristics of the load directly affect the energy harvesting architecture [6].

Table 1. Ambient energy sources with corresponding harvesting devices

Energy Source	Nature of source	Transducer
Thermal	Fully controllable	Thermoelectric element
Mechanical	Uncontrollable & unpredictable	Piezoelectric transducer
Solar energy	Uncontrolled but predictable	Photovoltaic cell
RF energy	Partially controllable	Antenna

Generally the most energy consuming component is the transceiver of any device. The required energy and the consumed energy for a sensor node should be lesser or equal to the harvested energy plus the initial energy of the device [7]. It can be represented as in equation (1).

$$\mathrm{E_{Harvested}}(t) + \mathrm{E_{Device}}(t) \geq \mathrm{E_{Consume}}(t) + \mathrm{E_{load}}(t) \qquad (1)$$

where $\mathrm{E_{Harvested}}$ is the harvested energy at any time, $\mathrm{E_{Device}}$ is the energy concerned with the storage device, $\mathrm{E_{Cosumed}}$ is the energy consumed by the device and $\mathrm{E_{load}}$ is the amount of energy required for a load during the operation.

The objective of this paper is to save time as well as the cost by powering the sensor nodes without the use of storage devices like battery. We harvest the energy at the sensor nodes through photovoltaic cells in the networks by the help ambient sources like sunlight [23]. The available energy from the sunlight is random and uncertain. So our various models of photovoltaic cells at different irradiance levels, deliver maximum power at higher irradiance and minimum power at lower irradiance. Lastly we focus at solar energy harvesting with appropriate energy management schematically and analytically. To overcome the conventional methods, our approach is one of the good approach to harvest the energy at the root level.

The rest of the paper is organized as follows. Section 2 reviews some relevant works and covers a general harvesting model with some harvesting module design. In section 3, we proposed our new energy harvesting model with modeling of supercapacitor and maintain the energy management in the network. The analytical model is described in section 4.Simulation and results of the experiments conducted are discussed in the Section 5. Finally Section 6 concludes the paper with some references.

2. Related Work

Lin Longbi et al. [8] described about the energy aware methodology in a sensor network. Static routing is a simple and multi-path routing is optimal in nature. Here the author exploits static routing with traffic patterns and energy replenishment outputs. They also developed a set of pre-computed paths to find an optimal distributed solution. Beheshtiha S.S. et al. [9] further studied about the approach proposed in [8] and focused on energy management capabilities. The authors focus at an opportunistic routing algorithm with adaptive harvesting-aware duty cycle .In this protocol design, exchange of messages can be done by time setting & nodes can be prioritized by applying geographical locations. Yoshida Masya et al. [10] proposed two approaches: data collection protocol probabilistic retransmission (PRT) & PRT with collision consideration to reduce the energy. The main concept behind this protocol is to reduce the retransmission packets with active intervals. The goal is to achieve high reliability & efficiency in data collection in the protocol following energy harvesting. Meng Jian et al. [11] reviewed the ambient energy harvesting technologies and developed a new adaptive energy harvesting aware clustering routing protocol. The basic idea behind this protocol is to find the node state by applying election algorithm. Changing the regular factor ρ , the available alive node gives high throughput as compared to other protocols. M. Shaoba et al. [12] introduced the optimal energy allocation (OEA) techniques for energy harvesting. Applying rechargeable battery in a sensor node aims at maximizing the total throughput in a time varying system. The authors compare OEA with channel-aware energy allocation (CAEA) techniques. Sadegh Hesari et al. [13] design a solar photovoltaic system that can receive maximum power from sun. The system design consists of two solar panels (one served as an online sun tracking one and the other as the power producer), two stepping motors and one Atmega IC that can help the Maximum power point tracking (MPPT)[6]. A. Zaidi et al. [14] introduced a maximum power point tracking method based on fast terminal sliding mode control (FTSMC) for photovoltaic systems. The control scheme can achieve the maximum power point tracking (MPPT)[15] and also fulfill even in transient change of atmospheric conditions.

2.1 Harvesting Models

The most important and the basic energy harvesting models for sensor networks are described in the following sections.

2.1.1 Ambient Energy Harvesting Model.

In general approach, the energy harvesting devices accumulate the energy from the ambient sources. The accumulated energy is converted into electrical energy and stored in a battery/capacitor or any storage device [16]. The low power sensor senses it and is used for transmitting and receiving information of the node. The node's transceiver (sending and receiving) operates when energy level reaches a certain threshold value and pauses or stops working when energy level decreases up to a certain level[29].

2.1.2 Two-Storage-Device-Based Model.

The second type energy harvesting model consists of super capacitor and a two-storage-device battery. The super capacitor is used as a primary buffer/storage device and battery is used as a secondary buffer/storage device [17]. A switch controls the operation of the load. When the super capacitor is recharging, no operation works as the consumption is first from super capacitor and then via battery. This model mainly focuses at the life time and the connectivity issues of the network. Due to drastic change in the ambient energy harvesting process, the operation of the node continues and it becomes discrete due to battery operation even if all the sources are not available.

2.2 Harvesting module design with Photovoltaic cells.

A single photovoltaic cell is a semiconductor device that converts solar light into current (direct current). It is made up of two layers of crystalline silicon. The layers have been doped with boron producing surplus of electrons on one side and phosphorous creating deficit of electrons on the other side. When the photons contact with the sunlight the amount of excess electrons can move to the deficit side and makes a voltage difference. For a single PV_{cell}, the value of open circuit voltage Voc is taken as 0.625 Volts and short circuit current I_{SC} of 4.5Amperes. The maximum power achieved is 50watt at standard temperature T = 25^{0}C. A PV module consists of many PV cells wired in series to produce higher voltage in parallel to increase current and series-parallel for specific use [28]. The PV array consists of number of individual PV modules [18][30]. In a PV array[19], the power of each module is greater than the total power. These PV modules basically consist of PN junction devices that are made up of monocrystalline silicon and poly silicon[20]. The output voltage of PV cell is very low. Hence, our PV module is designed by concerning number of PV Cells in series, in parallel and a mix of both. Our last part of this paper describes about how the PV modules are connected in series, parallel or series-parallel arrangements based on the requirements.

3. New Energy Harvesting Model

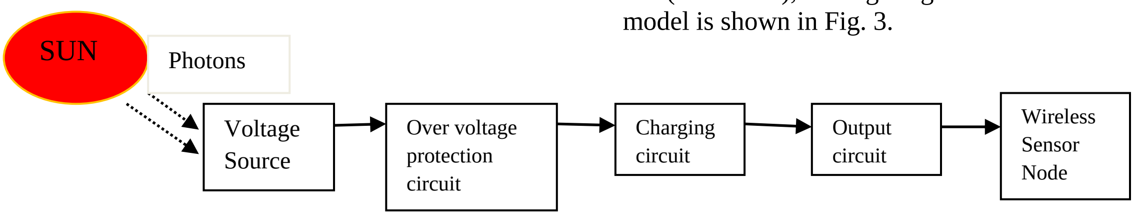


Fig. 1. Ambient energy harvesting model

The energy harvesting functional block diagram is shown in Fig.1. The energy harvesting procedure here is achieved in the following steps:

Step 1: The photographic cell or panel converts the energy to electricity received from the sunlight.

Step 2: The shunt regulator protects the overvoltage in the circuit.

Step 3: The charging circuit stores the energy through capacitor or Lithium-Ion battery .This circuit uses MOSFET and it is a current limiter circuit.

Step 4: The stored energy with the battery supply the current to the sensor nodes.

Step 5: Finally the wireless sensor nodes harvest the energy from the output circuit.

3.1 Detail Design of the Energy Harvesting Model

3.1.1 Voltage Source

Solar cell or panel converts the solar energy to the electric energy in the form of voltage signal. The solar energy is as a result of illuminated junction of the cells. The current source I represent the current produced from electron-hole pair recombination due to solar radiation. The solar cell's P-N junction is considered as diode. Current passes 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 and its reverse saturation current. The parallel resistance of the semiconductor materials and diode current is higher in comparison with the series resistance of the metals used in the solar cell leads.

3.1.2 Overvoltage Protection Circuit:

To get the maximum current, supercapacitor does not charge constantly from the sunlight due to the change of the irradiance value time to time. We consider here the supercapacitor voltage to be less than the open circuit voltage. So we use shunt regulator when excess voltage passes through the supercapacitor. It is simple, of low cost and helps in over voltage protection. Once the supercapacitor is fully charged, the excess amount of energy dissipation does not affect the charging in supercapacitor. Here we use a voltage regulator LM7805 circuit with 5V output voltage and 1A current.

3.1.3 Circuit Characteristics:

Solar panel – 17V, LM7805 voltage regulator, DC battery, Capacitor – 0.33uF, Schottky diode – 3A, 50V, Resistors – 220, Resister-680 ohm, Diode – 1n4007,Potential – 2K and Connecting wires. . Its circuit model is shown in Fig.2 [20].

3.1.4 Charging Circuit Specifications:

Photovoltaic cell – 50W, Output Voltage –Variable (5V – 14V), Maximum output current I – 0.29 Amps, Voltage drop out (2- 2.75V), Voltage regulation: +/- 100mV. . Its circuit model is shown in Fig. 3.

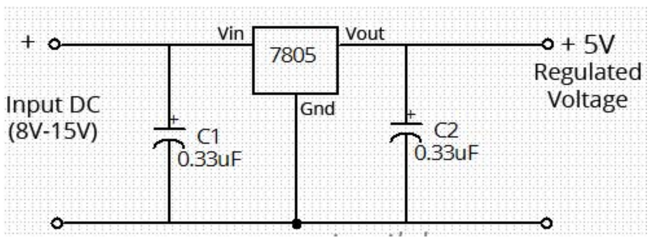


Fig. 2. Shows the overvoltage protection circuit

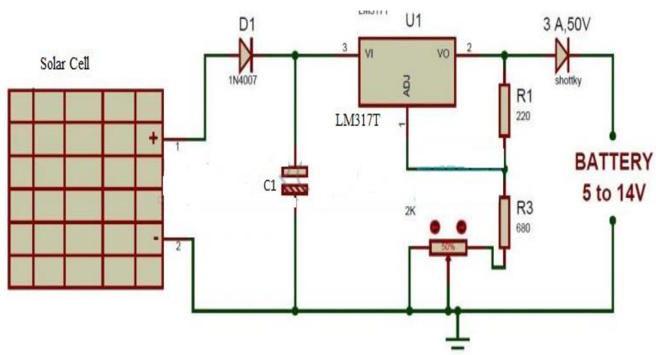


Fig. 3. Charging circuit with solar panel

We considered the IC LM358 circuit for charging. For switching the current we use a MOSFET(Q1 IRFZ44N) and a supercapacitor with high capacitance and low ESR(equivalent series resistance). MOSFET helps in charging the supercapacitor in a current limiting mode. Another low power dual operational amplifier called as comparator is used around the MOSFET. One zener diode is connected to the non-inverting input (pin 3) of the IC leading to a constant 4.3V input pin. In this zener diode voltage in input pin V_{in} = 5V, voltage in output pin V_{out} = 4.3V and series resistance R= 200Ω. Now we can calculate the available current at this pin as in equation (2).

$$I = \frac{V_{in}-V_{out}}{R} = \frac{5-4.3}{200} = 3.5\text{mA} \quad (2)$$

Therefore, I= 3.5mA The typical input offset current required by the IC (i.e.2nA) which is less than the inverting input of the IC. If the charging voltage is less than 4.3V, the output of the comparator (pin 1) remains at a voltage of V_{cc} = - 1.5V.

$$V_{out\_final} = V_{out} - V_{cc} = 5 - 1.5 = 3.5\text{V} \quad (3)$$

In MOSFET the Gate Source Voltage V_{source} = 10V at 25^{0}C. Continuous Drain Current represented as I_d = 50mAand the Gate Threshold Voltage (minimum)V_{th} = 2V.

From the trans inductance curve of the MOSFET,

$$I_d = K(V_{source} - V_{th})^2 \quad (4)$$

$$K = \frac{I_d}{(V_{source}-V_{th})^2} = \frac{50mA}{10-2^2} = 780\text{mA/V}^2 \quad (5)$$

where K is used as a constant value throughout the operation. Thus Drain current I_d operated at the low voltage V_{source} = 3.5V .Now I_d can be calculated as $0.78 \times (3.5-2)^2 = 1.755A$. So MOSFET can conduct up to 1.755A across the drain current with the input voltage of 3.5V.

3.1.5 Output Circuit:

The wireless sensor nodes are dependent on the output circuit consisting of the supercapacitor. The supercapacitor cells typically operate at 2.3V to 2.7 V and the nodes operate between -20^{0}C to +80^{0}C. To power a sensor node more supercapacitor must operate at (3 – 5) V. The detail energy harvesting circuit design is depicted in the Fig.4.

3.1.6 Energy harvesting circuit:

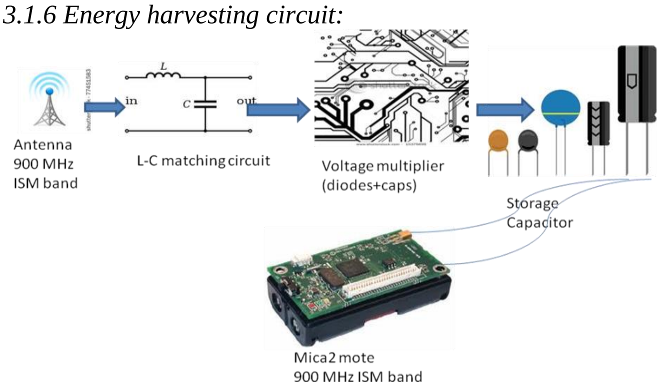


Fig. 4. General method of energy harvesting circuit

3.2 Modeling the Supercapacitor Discharge

Supercapacitor cells [24] typically operate at 2.3 to 2.7V. Limiting its charge in voltage to less than the cell-rated voltage and storing enough energy for a particular application is most efficient and cost effective method. An easier approach method to sizing it is to calculate the energy necessary to support the peak power of the application and this value can be calculated as

$$V_{Load} = V_{Scap} - I_{Load} \times ESR \quad (6)$$

$$P_{Load} = V_{Load} \times I_{Load} = (V_{Scap} - I_{Load} \times ESR) \times I_{Load} = V_{Scap} \times I_{Load} - I_{Load}^2 \times ESR \quad (7)$$

where V_{Scap} is the super capacitor's voltage, V_{Load} is the maximum voltage load, I_{Load} is the maximum current load and P_{Load} is the peak power of load.

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

$$I_{Load}^2 \times ESR - V_{Scap} \times I_{Load} + P_{Load} = 0 \quad (8)$$

Supercapacitor discharge can be simplified in equation (9),(10) and (11).

$$I_{Load}(t) = \left[\frac{V_{Scap}(t) \pm \sqrt{(V_{Scap}(t))^2 - 4 \times ESR \times P_{Load}}}{2 \times ESR}\right] \quad (9)$$

$$V_{Load} = V_{Scap}(t) - I_{Load} \times ESR \quad (10)$$

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

3.2.1 Sizing the Supercapacitor

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

Maximum charged voltage (Vmax), if different from the working voltage (Vw), Minimum Voltage (Vmin), Power (W) or Current (I) required, Discharge duration (t), Duty cycle, Required life, Average operating temperature.

To determine the number of cells and appropriate size required we proceed as follows: In supercapacitor, during discharge cycle we have to take care of two variables: (1) The voltage drop and (2) the capacitance. The voltage drop occurs due to equivalent series resistance (ESR).

The equivalent series resistance is represented by V_{ESR} in equation (12).

$$V_{ESR} = I_{Load}(t) \times ESR \quad (12)$$

where I_{Load} is the current used to discharge the supercapacitor expressed in amperes. For equation (12) we assume I_{Load} be a constant current discharge.Voltage drop due to the capacitance of the supercapacitor can be represented as V_{Scap} in equation (13).

$$V_{Scap}(t) = \frac{I_{Load}(t) \times \Delta t}{C} \quad (13)$$

Where Δt is the time taken to discharge the capacitor between working voltage (V_{work}) and minimum voltage (V_{min}) can be represented in equation (14). C is the total capacitance of the supercapacitor expressed in farad (F).

$$\Delta t = \frac{V_{tvd} - I_{Load}(t) \times ESR \times c}{I_{Load}(t)} \quad (14)$$

Now the total voltage drop V_{tvd} in equation (15) can be calculated as: $V_{tvd} = V_{ESR} + V_{Scap}$ where V_{tvd} is the total voltage drop when the capacitor is discharged.

$$V_{tvd} = I_{Load} \times ESR + \frac{I_{Load}(t) \times \Delta t}{C} \quad (15)$$

Allowing a larger V_{tvd} will need to reduce the capacitance size used. In supercapacitor if one cell is used then it is referred as cell capacitance where as in case if many cells are used then we have to calculate the equivalent capacitance. Usually by allowing the capacitor to drop to 0.5 V, 75% of the capacitor energy is discharged. The equivalent capacitance can be derived in equation (16) from the number of capacitors in series or parallel when more than one cell is used. Now

$$C = C_c \times \frac{Number\ of\ capacitors\ in\ parallel}{Number\ of\ capacitors\ in\ series} \quad (16)$$

where C_C is the cell capacitance and ESR is the total equivalent series resistance represented in ohms (Ω). If a single cell is used, then it is called the cell resistance. The equation (17) also calculates the equivalent resistance based on the same condition as in equation (16).

$$ESR = ESR_{cell} \times \frac{Number\ of\ resistors\ in\ series}{Number\ of\ resistors\ in\ parallel} \quad (17)$$

From the system design specification; we have Vmax = 10V,Vmin = 8V, I = 0.008 A and P =VI= 3.7 × 0.008= 0.0296W.Using the values above lets us determine the size of the supercapacitor. To determine the value of our stack supercapacitor, Energy can be given as

$$P \times \Delta t = 0.5 \times C \times (V_{initial}^2 - V_{final}^2) \quad (18)$$

Therefore $C = \frac{2 \times P \times \Delta t}{V_{initial}^2 - V_{final}^2} = \frac{2 \times 0.0296 \times 281}{100-64} = 0.462F$ (19)

$$ESR = ESR_{Cell} \times \frac{Number\ of\ resistors\ in\ series}{Number\ of\ resistors\ in\ parallel}$$

$$= 0.05 \times \frac{3}{2} = 0.075 \text{ ohms} \quad (20)$$

From equation (15), neglecting the effect of the ESR,

$V_{tvd} = \frac{I_{Load}(t) \times \Delta t}{c}$,Where V_{tvd}= 10-8 = 2 (21)

and $\Delta t = \frac{V_{tvd} \times c}{I_{Load}(t)}$ =150seconds =2.5minutes (22)

Given Vmax = 5V, since each supercapacitor cell is usually rated at 2.7V, and from equation (22), the cell needed will be in the range of 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

3.3 Energy Management in a sensor node

Photovoltaic cells are used to convert the sunlight into direct current (electrical) by virtue of photovoltaic effect. Solar energy harvesting is the common way of employing ambient energy sources, replacing battery power supplies and supporting. The output current of a photovoltaic cell is mainly dependent on its terminal voltage and the light intensity, irradiating the cell [16]. The current-voltage (IV) and power-voltage (PV) characteristic equation as in equation (23) of the photovoltaic cell can be represented from the equivalent circuit shown in Fig. 5.

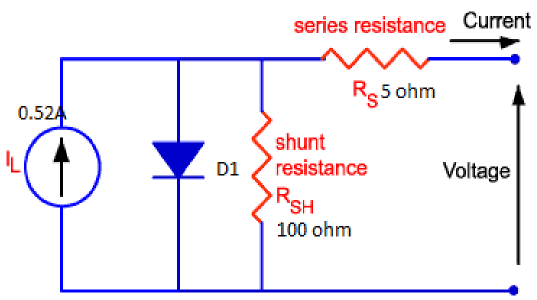


Fig. 5. Equivalent electrical circuit of a photovoltaic cell

$$I = I_{PV} - I_0 \left[\exp\left(\frac{q(V+IR_S)}{KT}\right) - 1\right] - \frac{V+IR_S}{R_{SH}} \quad (23)$$

where PV is the cell, I_{PV} is the output current = I_{SC} = Short circuit current, I_0 is the reverse leakage current, R_S is the series resistance , R_{SH} is the parallel resistance = R_P , where K is the Boltzman's constant, T is the standard temperature, q is the charge of an electron. The equation can be modified as in (24).

$$I = I_{SC} - I_0 \left[\exp\left(\frac{q(V+IR_S)}{KT}\right) - 1\right] - \frac{V+IR_S}{R_P} \quad (24)$$

By taking some assumptions, the complex equation (2) can be solved .For better performance in a solar cell, it is assumed that, $R_p \to \infty$ and $R_s \to 0$,$\exp\left(\frac{q(V+IR_S)}{KT}\right)$ » 1. So the equation (24) can written as

$$I = I_{SC} - I_0 \left[\exp\left(\frac{qV}{KT}\right)\right] \quad (25)$$

for an open circuit V= V_{OC}, we have I =0

$$I_0 = I_{SC} \left[\exp\left(\frac{-qV_{OC}}{KT}\right)\right]$$

putting the value of I_0 in equation (25), current and power can be calculated in equation (26) and (27).

$$I = I_{SC} - I_{SC} \left[\exp\left(\frac{-qV_{OC}}{KT}\right)\right] \left[\exp\left(\frac{qV}{KT}\right)\right]$$

$$= I_{SC} \left[1 - \exp\left(\frac{q(V-V_{OC})}{KT}\right)\right] \quad (26)$$

now P=VI and the power can be represented as

$$P = V\left[I_{SC} - I_{SC}\left[\exp\left(\frac{q(V-V_{OC})}{KT}\right)\right]\ \right] \quad (27)$$

Where p is the output power and I is the achieved current and Putting the value V=0 to 0.7, T=25^0 , I_{SC} = 4.5 Amperes, V_{OC} = 0.625 V, I= -2 to 6, q= 1.6 ×10^{-19}col and k= 1.380 ×10^{-23}j/k.

By using MPPT (Maximum Power Point Tracking) techniques, we can considered as energy harvesting model is highly efficient. Here MPPT tracker delivers the load, extracts the maximum power and stores it in a battery. DC-DC Converter is used to obtain a regulated and maximum DC voltage for the load [21]. DC-DC converter used in our model is in switch mode base. it's choice depends upon the battery or storage devices. Load : A processor of a devices operates in sleep mode through the transceiver[22]. The operation of a transceiver operates with a certain condition, i.e. $V_{L(min)} < V \leq V_{L(max)}$, where V≅ $V_{L(min)}$ where electric relay switch is on and V = $V_{L(max)}$ where relay shifts the load to the storage devices.

4. Analytical Model

Generally each and every sensor node can operate with the help of battery [23-26]. In our model the harvesting energy is the main aim to make the process stochastic. Due to the random change in sunlight, each node operates with the harvesting energy. If the ambient energy is not sufficiently available or too low due to random change in climate, we must continue our system through battery. The accumulated ambient energy from sunlight helps in transmission and reception processes and surplus energy transferred to the battery. This process continues until the ambient energy harvesting process continues [27].

The analytical model is described as follows. Let the output power of the harvesting device with any sensor node of the model can be represented as $P_{Harvested}$ in equation (28). Let $E_{Initial}$ be the initial energy of a storage device and $P_{Consume}$ be the power consumed by a harvesting device. For transceiver operation, the amount of power required can be expressed as $P_{Transive} = P_{Transmit} + P_{Recive}$, where $P_{Transmit}$ is the transmitting power of a node and P_{Recive} is the receiving power of that node. The output power P_{Output} can be represented as

$$P_{Output} = P_{Intial} + P_{Harvested} - P_{Transciver} \quad (28)$$

$$\Rightarrow P_{Harvested} = P_{Output} - P_{Intial} + P_{Transciver}$$

By the transceiver the available harvesting energy is represented by equation (29).

$$E_{Harvested}(t_1, t_2) = \int_{t_1}^{t_2} P_{Harvested}(t)dt \quad (29)$$

where energy harvesting time period can be considered as t_1 (starting time) to t_2 (ending time). This ambient energy is supplied directly to the transceiver for operation and if $E_{Harvest}(t_1, t_2) > E_{transciver,U}(t_1, t_2)$ and the surplus energy presented can charges the battery and it can be calculated as in equation (30).

$$E_{Surplus}(t_1, t_2) = [E_{Harvest}(t_1, t_2) - (E_{Transcive}(t_1, t_2) + E_{Likage}(t_1, t_2))] \quad (30)$$

where E_{Likage} is the leakage energy between the operation.

Now in the storage device the total energy can be stored as in equation (31).

$$E_{Storage}(t_1, t_2) = E_{Intial} + E_{charge}(t_1, t_2) \quad :0 < E_{Storage} \leq C \quad (31)$$

where E_{in} and C are the initial energy stored and maximum capacity of the storage device, respectively. The total energy of the node can be calculated as in equation (32).

$$E_{Total}(t_1, t_2) = E_{transciver}(t_1, t_2) + E_{Storage}(t_1, t_2) \quad (32)$$

we considered as $E_{Harvest} = E_{Threshold}$ and the energy charging of the storage device is suspended, i.e. $E_{charge} = 0$ and $E_{Harvest} = E_{transciver}$. Thus, the total actual harvested energy is used for the transceiver's operation in a sensor node.

5. Simulation and Result Discussion

The current voltage (IV) characteristics curve of a solar cell is plotted in Fig. 6. For simulation, the value of open circuit voltage Voc is taken as 21.5 Volts and short circuit current I_{SC} as 3.1Amperes. The solar panel specification is given in the Table 2.

The IV and PV characteristics of the 50W solar panel at different irradiance is shown as in Fig 6.Form the Fig. 6 it is clear that the output power of solar panel highly depends upon the irradiance, i.e. more the irradiance, more will be the power generation and vice versa. The I_{sc} is dependent on G as $I_{SC}(G) = I_{SC(standard)} \frac{G}{G_{standard}}$, where $G_{standard}$ is the standard (maximum) value in the peak hour of a solar day. The parameters of solar panel at STC are given in Table 2.

Table 2. Specification of solar panel at STC

Parameters	Range
P_m	50W
V_{oc}	21.6V
I_{sc}	3.1A
V_m	17.47V
I_m	2.865A

The irradiance during different time of the day is shown in Fig. 6. It implies that the irradiance value is higher during noon time (12-1pm), when the panel is perpendicular to the sunlight. After simulation, the plotted graph in Fig.7. depicts the IV and PV characteristics under different irradiance values. Here PV modules deliver maximum power at higher irradiance and minimum power at lower irradiance that makes PV system irradiance dependent.

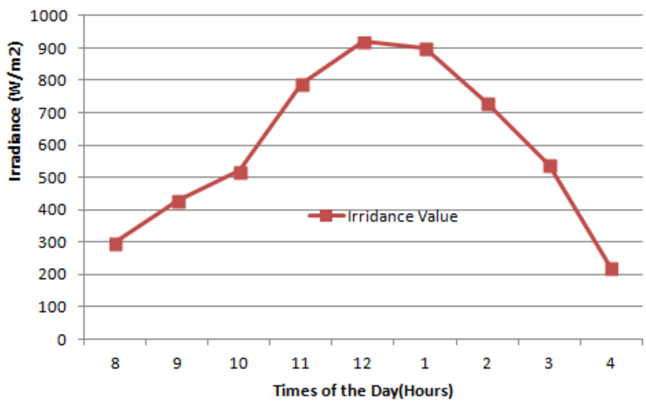


Fig.6. Irradiance value at different times of a day(Data collected from IMT, BBSR in the period of March-2017)

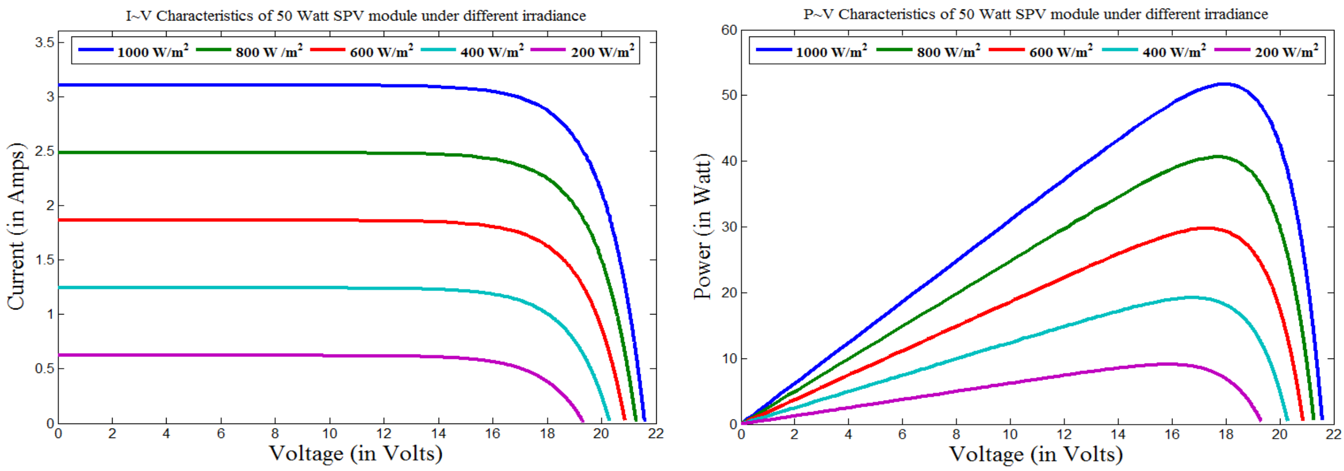
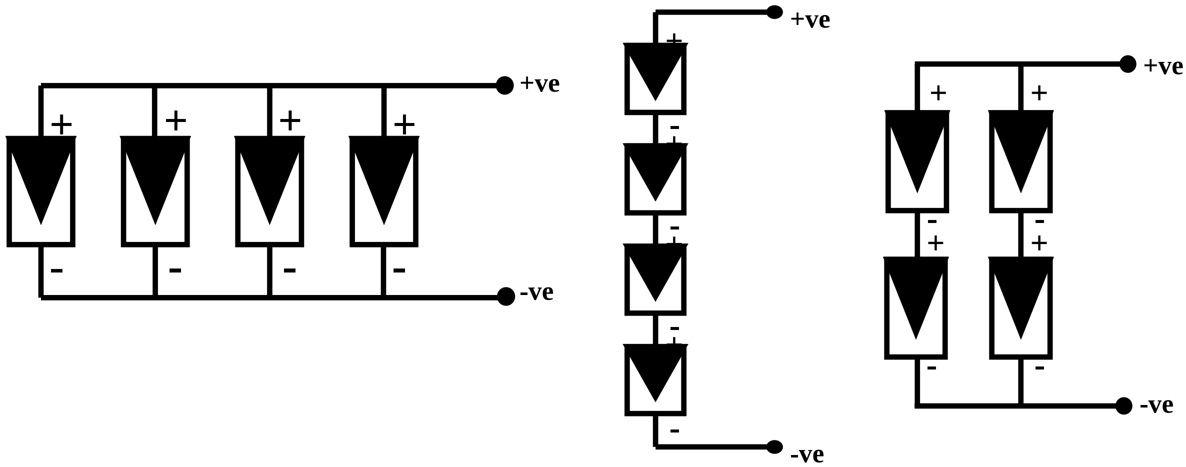


Fig. 7. Simulation model of PV array with different irradiance



(a) (b) (c)

Fig. 8. (a) Series Connection modules (b) Parallel Connection modules & (c) Series-Parallel Connection modules of Solar Panels

5.1 Series connection:

The series connection of photovoltaic modules is shown in Fig. 8. (a) where all solar panels are connected to each other in series. The connected PV panels contribute a voltage of (21.4× 4)V and output current of 3.1A, and maintain the system voltage by keeping the system current constant. The series connected PV channels are tested under different irradiances during different times of day ranging from 8.00am to 4.00pm. From Fig. 9.(a) and (b) we may concluded that during 920W/m^2 PV panels deliver 189.04W, during 730W/m^2- 147.30W, during 520W/m^2-102.11W, during 300W/m^2-56.28W and during 220W/m2-40.19W.

5.2 Parallel connection:

The parallel connections of photovoltaic modules are shown in Fig. 8 . (b) where four 50W PV panels are connected in parallel with each other. The connected PV panels generate a voltage of (21.4) V and current of (3.1I×4) A, which rise up the system current by keeping the system voltage constant. The parallel connected PV channels are tested under different irradiances at different times of day ranging from 8.00am to 4.00pm.From Fig.10 it can conclude that during 920W/m^2 PV panels deliver 188.56W, during 730W/m^2- 147.24W, during 520W/m^2-102.10W, during 300W/m^2-56.28W and during 220W/m2-40.19W. Fig.10.(a) and (b) shows the VI & PV characteristics of Parallel connected Solar panels under different irradiances. For each irradiance value we get minimum power when G =220W/m^2 and maximum power when G =920 W/m^2.

From the Fig.10 it is clear that the irradiance value is low (200W/m^2) in the morning hours and keeps on increasing as the sun rises up to 12pm (Maximum temperature in the environment). The irradiance level increases as the Sun continues its journey to peak point. At 12pm we can consider the maximum irradiance value (920 W/m^2). After 12pm the irradiance value decreases as the day passes on and reaches at low level where the voltage varies from 19V to 22V and the power also varies to 40W to 190W.

5.3 Series-Parallel connection:

The mixed series-parallel connection of photovoltaic modules are shown in Fig. 8.(c) in which two 50W PV panels are connected in series and other two 50W PV panels are connected in parallel with each other.

The connected PV panels achieve a voltage of (21.4×2) V and current of (3.1I×2) A which rise up the system current and the system voltage simultaneously. The series-parallel connected PV channels are tested under different irradiances at different times of day ranging from 8.00am to 4.00pm.From Fig.11 it can be concluded that during 920W/m^2 PV panels deliver 189.04W, during 730W/m^2-147.30W, during 520W/m^2-102.11W, during 300W/m^2-56.28W and during 220W/m2-40.19W. Although all the power calculations are nearly equal in different modules, however the photovoltaic cells are series-connected in some parts and in parallel in others parts.

We can't be able to apply a single set of rules to every part of it and identify which parts of the photovoltaic cells are in series and which parts are in parallel and also selectively apply series rules, parallel rules and mixed series-parallel rules as necessary to determine the efficiency of the photovoltaic cells. Here the short circuit current I_{SC} increase from 0.6A to 3.5A as irradiance varies from 200W/m2 to 1000 W/m2. The value of open circuit voltage varies due to change in irradiance as temperature depends on irradiance. We can get the power 30W to 200W.

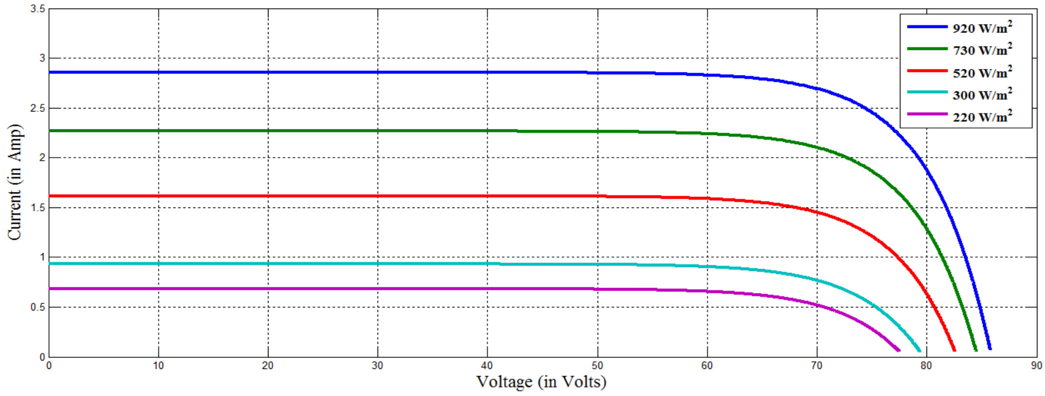


Fig. 9. (a) IV characteristics of series connection under different irradiance

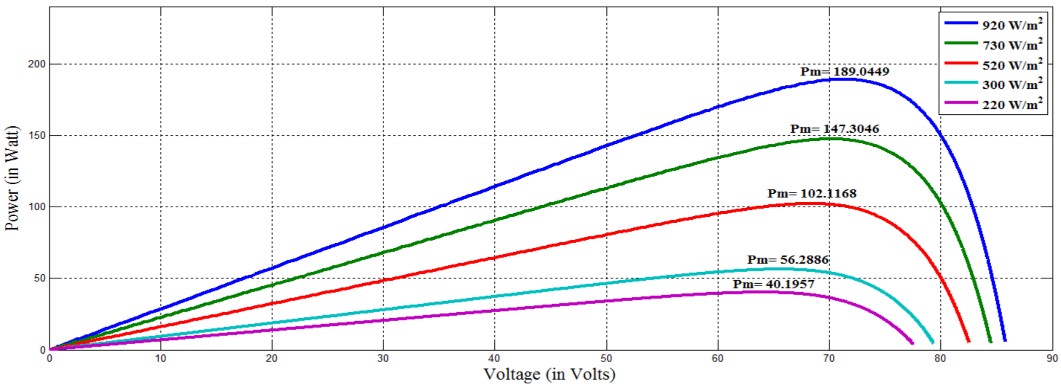


Fig. 9. (b) PV characteristics of series connection under different irradiance

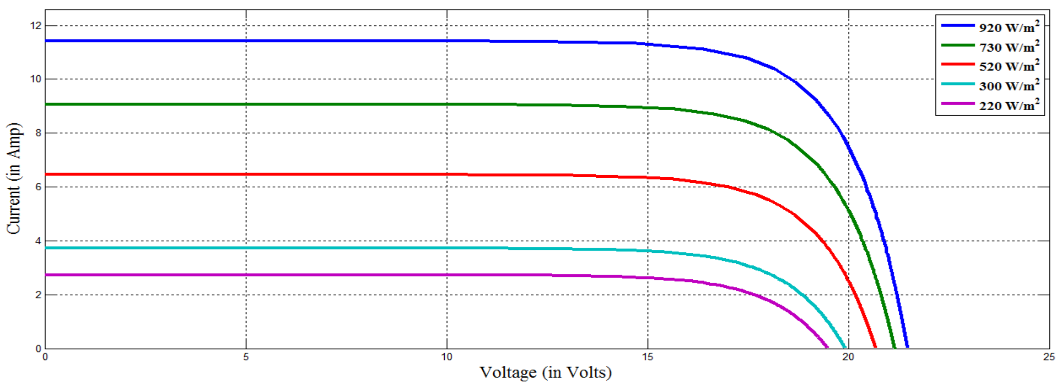


Fig. 10. (a) IV characteristics of parallel connection under different irradiance

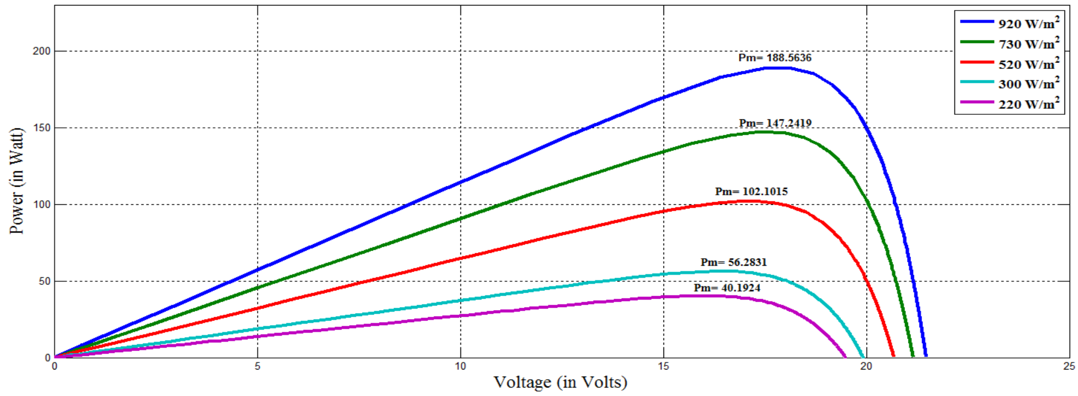


Fig. 10. (b) PV characteristics of Parallel connection under different irradiance

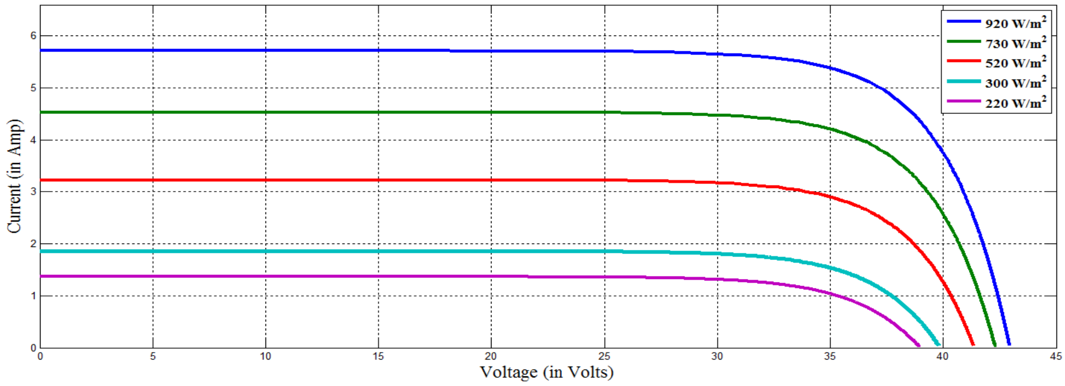


Fig. 11. (a) IV characteristics of Series-Parallel connection under different irradiance

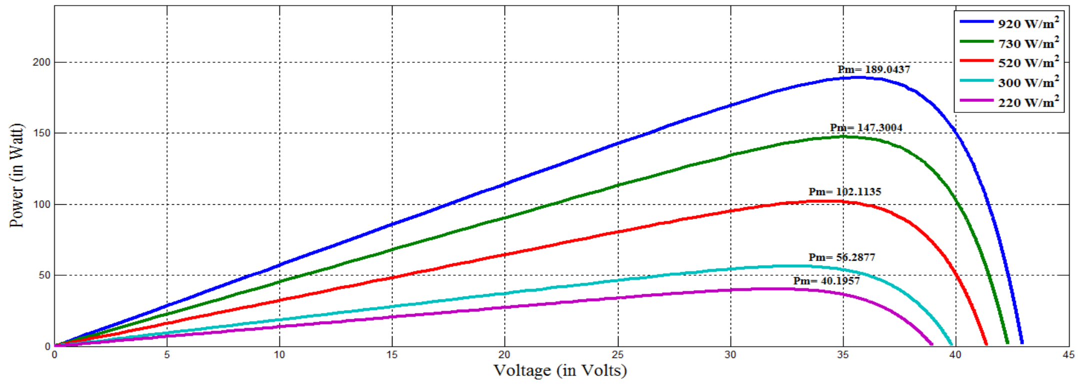


Fig. 11. (b) PV characteristics of Series-Parallel connection under different irradiance

Fig.11. (a) and (b) shows the IV & PV characteristics of series-Parallel connection under different irradiances respectively. Here I_{SC} increase from 1.2A to 6.2A as G varies from 200W/m^2 to 920 W/m^2. The power level also increases up to 200 W with respect to G value (P=30W starting when V = 39V) and the voltage varies from 39V to 44V. The maximum power extracted by MPPT from energy harvested devices is less than the required load power.

At the transceivers, the harvested energy is used from the storage device. Initially the battery power decreases with increase in G value till the maximum power is achieved by the devices. The power starts consuming continuously when the sun sets and the load is shifted onto the storage devices. For each irradiance level, we achieve maximum power, but the maximum power for G = 920 W/m^2 is greater than all others.

6. Conclusion

Ambient energy harvesting is one of the important approach through which a sensor network can work efficiently for a longer period. Therefore various energy harvesting models with different modules along with energy management system are described here. In this perspective some numerical solutions state the results of various characteristics of IV & PV in different scenarios. Our main empaphasis is how to harvest the energy from sunlight and the analytical behavior of the harvesting model is also explained clearly. The proposed harvesting models maximize the energy in a sensor node and when different modles are connected with the sensor node, the system performance is better. Finally we conclud that in order to operate a sensor network in different situations, the above discussed models can be useful for harvesting energy in a sensor node.

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