An Efficient Solar Energy Harvesting System for Wireless Sensor Nodes

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***Abstract*— The Wireless Sensor Networks (WSN) are the basic building blocks of today's modern internet of Things (IoT) infrastructure in smart buildings, smart parking, and smart cities. The WSN nodes suffer from a major design constraint that their battery energy is limited and can work only for a few days depending upon the duty cycle of operation. In this paper, we propose a new solution to this design problem by using ambient solar photovoltaic energy. Here, we propose a highly efficient and unique solar energy harvesting system for rechargeable battery based WSN nodes. Ideally, the optimized Solar Energy Harvesting Wireless Sensor Network (SEH-WSN) nodes should operate for infinite network lifetime (in years). In this paper, we propose a novel and efficient solar-powered battery-charging system with maximum power point tracking (MPPT) for WSN nodes. The research focus is on to increase the overall harvesting system efficiency, which depends upon Solar Panel Efficiency, MPPT controlled DC-DC converter efficiency and rechargeable battery efficiency. Several models for solar energy harvester system have been developed and iterative simulation was performed in MATLAB/SIMULINK for solar powered DC-DC converters with MPPT to achieve optimum results. From the simulation results, it is proved that our designed solar energy harvesting system has 96% efficiency(η_{sys}).**

Keywords*— *Smart Cities, Solar Energy Harvesting, DC-DC Converters, Maximum Power Point Tracking (MPPT), Battery Charging, Wireless Sensor Nodes

I. INTRODUCTION

In the 21st century, the development of renewable energy harvesting systems is the most important technological design challenge due to the increase in global warming and other environmental issues. Recently, in August 2016, the Zigbee Alliance, USA has announced the new standard for Energy harvesting wireless sensor networks (EHWSNs) known as ZigBee Green Power (GP)[1]. The amendments in IEEE 802.15.4 communication standard protocol for low data rate wireless networks and the ZigBee Green Power (GP) standard for EHWSNs facilitates the use of the Green Power feature for ZigBee applications running on the low power wireless microcontrollers platform [2]. Now a day, the renewable energy harvesting based power management solutions are being proposed for wireless sensor networks by the commercial companies like Texas Instruments, ST Microelectronics and Linear Technology, USA. The design of an efficient solar energy harvesting systems is necessary for the proper planning of solar energy harvesting wireless sensor networks (SEH-WSN). The harvester system extracts the solar

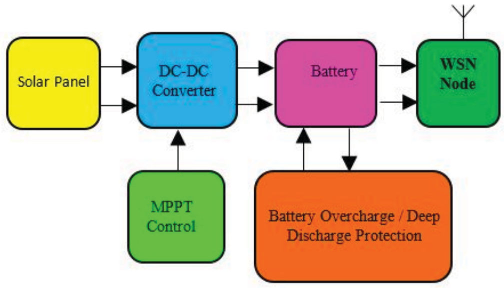

Fig.1. Block diagram of Solar Energy Harvesting System using MPPT Control

energy into the electrical form by using the Photovoltaic (PV) cells. Then, this electrical energy is used to charge the wireless sensor node battery. It reduces the human efforts to replace the battery of hundreds or thousands of sensor nodes by going out in the remote areas. Therefore, the design problem of limited energy availability of wireless sensor nodes is resolved and the human efforts to replace the battery periodically has been reduced. In the year 2008, Ref. [3] proposed Modelling and Optimization of a Solar Energy Harvester System for Self-Powered Wireless Sensor Networks. In 2009, Ref. [4] proposed Design of a Solar-Harvesting Circuit for Battery-less Embedded Systems. In this paper, the simulation results show that by using efficient solar energy harvester circuits the sensor network lifetime can be increased from few days to 20-30 years and higher. Section 1 provides an overview of a basic Solar Energy Harvesting System. Section 2 presents the operation of SEH-WSN Node. Section 3 provides two types of solar energy harvester system most commonly used in practice i.e pulse width modulation (PWM) controlled and MPPT controlled. Section 4 provides simulation parameters and section 5 provides simulation results, section 6 provides efficiency calculations and finally, section 7 provides the conclusion.

II. OPERATION OF AN SEH-WSN NODE

The operation of an SEH-WSN node is explained as follows: The solar energy-harvesting system provides a d.c. power supply (3.6 volts) to the WSN node. This voltage is harvested from the ambient sunlight by using the solar panels

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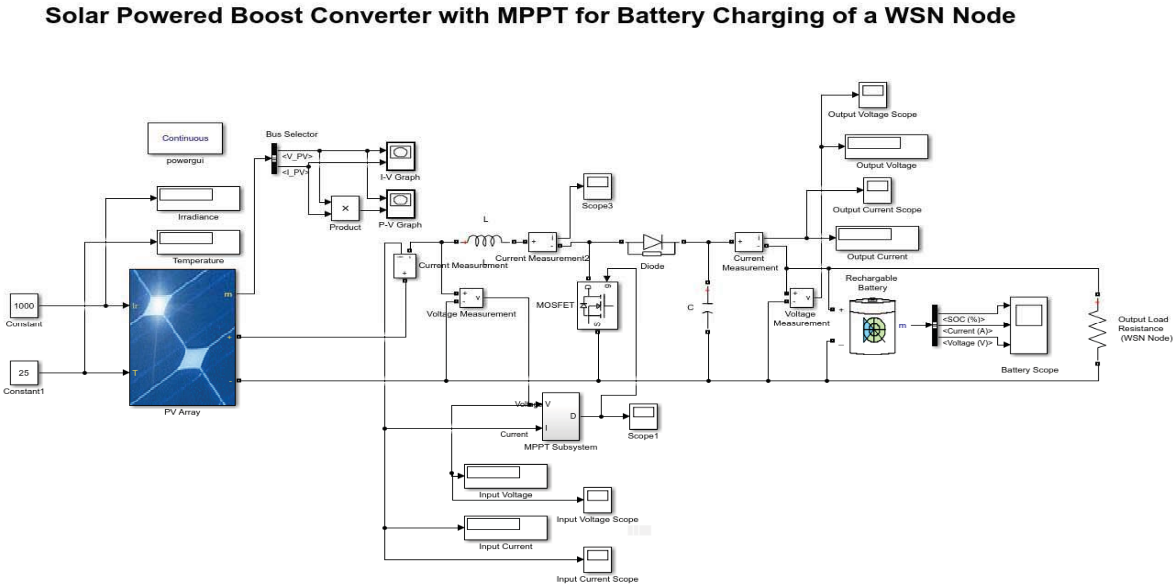

Fig.2. MATLAB/SIMULINK model for MPPT controlled SEH system for WSN Node

[5]. The solar panel converts light energy directly into the d.c. electrical energy. The DC-DC converter regulates this dc voltage to charge the battery. The rechargeable battery powers the WSN node. The WSN node measures the desired physical quantity (e.g. temp., light, humidity, and pressure) by using the sensor measurement unit. A microcontroller in computation unit processes this sensed data. The measured or sensed data is sent to the nearby network node wirelessly, in the form of data packets using transmitter unit. The information is sent to the USB gateway node via cluster head nodes [6]. Finally, the user can remotely monitor & control the application process e.g. temperature monitoring & control of an industrial boiler plant, Air conditioner cooling system control, Traffic light management in a smart city. In this paper, we will focus on modelling and optimization of solar energy harvesting system.

III. SOLAR ENERGY HARVESTING SYSTEM

The figure 1 shows a block diagram of a maximum power point tracking (MPPT) controlled solar energy harvester (SEH) system. The SEH system consists of a solar panel, a DC-DC buck converter, a rechargeable battery, a maximum power point (MPPT) controller, and a WSN sensor node connected as a d.c. load. The ambient solar light energy is harvested using the solar panel and converted into the electrical energy. The DC-DC Buck converter steps down and regulates the magnitude of this harvested voltage, and supplied to the rechargeable battery. The MPPT controller tracks the voltage and current from the solar panel and adjusts the duty cycle accordingly for the MOSFET of DC-DC Buck converter [7]. Finally, the battery voltage is utilized to operate the wireless sensor node. The WSN performs the function of sensing, computation, and communication with other similar characteristics nodes. Thus, autonomous operation of monitoring and control of any physical phenomenon like temperature, humidity, pressure or acceleration can be achieved using SEH-WSN nodes. In this whole scenario, the efficiency of solar energy harvester circuit plays a very important role. If the efficiency of solar energy harvester system is poor, then the battery will not get recharge properly and hence the wireless sensor network lifetime will reduce.

IV. SIMULATION EXPERIMENT SETUP

The simulation parameters for a solar energy harvesting system are shown in Table 1. Figure 2 shows MATLAB Simulink model of solar energy harvester system using MPPT control. The solar irradiance of 1000 watts/cm^2 is incident on the solar panel with a constant temperature of 25-degree Celsius [8]. The Solar panel can extract only this solar energy into 15 mW/cm^2 with 15% efficiency [9]. For full irradiance on the simulated solar panel, the output voltage of solar panel is 6 volts, 500mA, and 3 watts. Now, this electrical energy from the solar cell is fed to the DC- DC boost converter [10], which increases the output voltage. The Boost converter output voltage is used to charge the rechargeable battery. The rechargeable battery is used to operate the WSN node. Here, the WSN load is modelled as output d.c. load resistance of 100 ohms.

V. SIMULATION RESULTS

The simulation results for the Battery State of Charge (SoC), battery Current (I_B) and battery voltage (V_B) as a function of time (seconds) are shown in figure 3 to figure 5.

TABLE I. SIMULATION PARAMETERS

Parameters	Value	Parameters	Value
Irradiance (W/m^2)	1000 $Watts/m^2$	Capacitor (C)	100uF
Temperature (T)	25 degree Celsius	Inductor (L)	200uH
DC-DC Converter	Boost Converter	MOSFET Switching Frequency (f)	5KHz
Max. Solar Panel output voltage (V_m)	6 volts	Initial duty Cycle	0.5
Max. Solar Panel output current (I_m)	500mA	MOSFET Switching Power Losses (P_{sw})	0.5mW
Max. Power from Solar Cell (P_m)	3 watts	Switching Voltage Loss (V_{sw})	0.2 volts
Rechargeable Battery Type	NiCd	WSN Load Model	10-ohm resistor
Battery Voltage	3.6 volts	Inductor conduction Power Loss (P_L)	50 mW

A. Battery State of Charge (SoC), Voltage and Current during Charging using MPPT

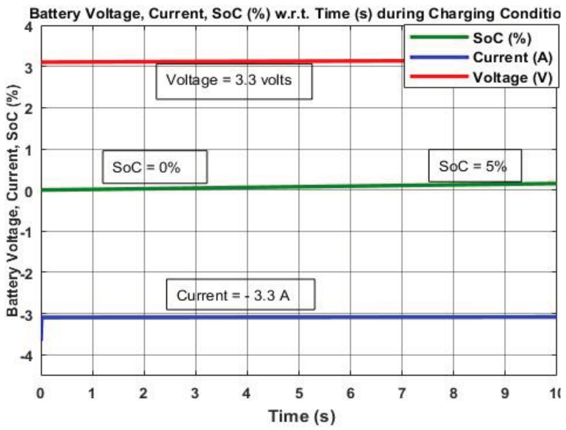

Fig. 3. Simulation results of MPPT controlled SEH system for 10 s.

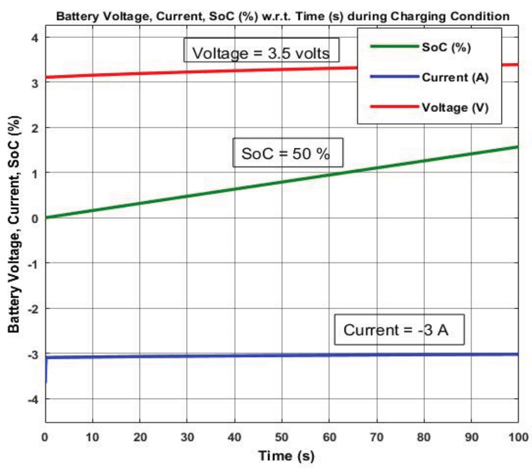

Fig. 4. Simulation results of MPPT controlled SEH system for 100 s.

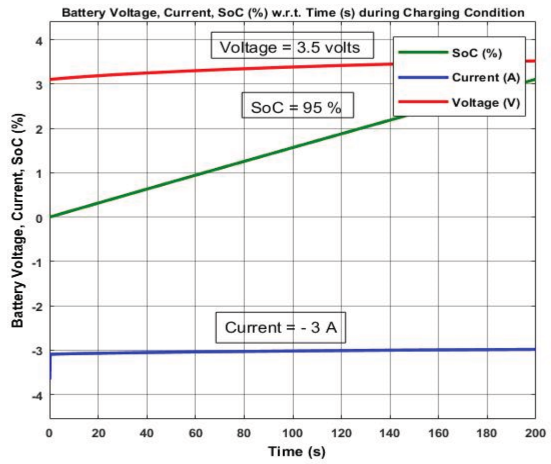

Fig. 5. Simulation results of MPPT controlled SEH system for 200 s.

In figure 3, MPPT controlled solar energy harvesting battery charger (i.e. Battery State of Charge (SoC), battery Current and Voltage) are shown for a simulation time of 10 seconds. Here, the battery SoC reaches from 0 to 5 % Similarly, in figure 4 the MPPT results for 100 s simulation time have battery SoC till 50 %. Finally, in figure 5 the battery SoC reaches till 95 % in just 200 s simulation time. Thus, the battery charging time is dynamically increased by using MPPT controlled solar energy harvesting systems for WSN nodes.

VI. ENERGY HARVESTER SYSTEM EFFICIENCY ($\boldsymbol{\eta_{sys}}$)

The energy harvester system efficiency is calculated for MPPT control methods. By using P&O MPPT the max. Power available from the solar panel is 2.8 watts. Now the MPPT efficiency is calculated as [11]:

$$MPPT\ Efficiency\ (\eta_{MPP}) = \frac{P_{MPP}}{P_m} \tag{1}$$

From the simulation parameter table 1, the (P_{MPP}) is 2.8 watts and maximum theoretical power (P_m) is 3 watts. Thus MPPT efficiency is calculated as 2.8w / 3w = 93.33 %. Here, the P_{loss} also changes due to MPPT in DC-DC Buck Converter. The P_{loss} is the sum of MOSFET switching loss (P_{sw}) and Inductor conduction loss (P_L). From the simulation results table, the output power (P_o) is 1.8 W and MOSFET switching losses are 2 mW and inductor power loss is 20 mW. Thus buck converter efficiency is calculated as 1.8W /1.8 W+ 22 mW = 98.79%. Finally, the overall energy harvester circuit efficiency (η_{sys}) is the average of Buck converter efficiency and MPPT efficiency.

$$Harvester\ Systems\ Efficiecny\ (\eta_{sys}) = \frac{(\eta_{buck}) + (\eta_{MPP})}{2} \tag{2}$$

TABLE 2. SIMULATION RESULTS FOR MPPT CONTROL SEH SYSTEM

Energy Harvester Parameters	Value
Max. Solar Panel output Power (P_m)	2.8 watts
Average Buck Converter Output Voltage(V_m)	3.6 volts
Average Buck Converter Output Current(I_m)	500mA
Buck Converter Output Power	1.8 watts
Inductor Loss	20mW
MOSFET Switching Loss	2mW
Harvester System Efficiency (η_{sys})	96 %

From the formula of eq.2, the calculated overall energy harvester system efficiency (η_{sys}) is (98.79%+93.33%) / 2 = 96.28%.

VII. CONCLUSION

In this paper, we have modeled and simulated an efficient solar energy harvester system for WSN nodes with MPPT in MATLAB/SIMULINK. The MPPT based harvesting system charges the battery using at a very fast rate. The battery SoC and Terminal voltage start increasing while charging. The overall energy harvester circuit efficiency (η_{sys}) is the sum of Boost converter efficiency and MPPT efficiency. From the simulation results, it is proved that the MPPT based Solar Energy Harvester system efficiency is 96.28%.

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