A Reliable Ultracapacitor Based Solar Energy Harvesting system for Wireless Sensor Network Enabled Intelligent Buildings

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Abstract - **Energy consumption is central to design consideration for Wireless Sensor networks (WSN) whether they are powered by batteries or energy harvesters. Lately an alternative to powering WSNs is being actively studied, which is to convert the ambient energy from the environment into electricity to power the sensor nodes.**

In this paper we propose a low-power solar energy harvesting for Wireless Sensor Networks (WSN) in intelligent building. The sensor nodes are powered by solar energy harvester instead of alkaline battery. This design eliminates the need to use alkaline batteries to nodes which require frequent replacement from time to time. The Energy harvesting system consists of two key components viz. an energy harvesting unit and an energy storage module. The energy harvesting module consists of an adequate number of solar cells connected in series and parallel to scavenge energy while the energy storage module consists of combination of a set of Ultracapacitors connected along with alkaline batteries which could be used as a back-up energy source. This setup forms a reliable combination which could be future of the energy crisis.

Keywords— **Wireless sensor networks, energy harvesters, Ultracapacitors.**

I. INTRODUCTION

Wireless sensor networks play a fundamental role in future intelligent building. A building that integrates technology and process to create a facility that is safer, more comfortable and productive for its occupants, and more operationally efficient for its owners. They are distinguished by a tight coupling of HVAC, security, lighting, and fire protection systems. They are sensor rich and can automatically sense, infer and act in order to balance user comfort and energy efficiency a concept also known as ambient intelligence or pervasive computing. The wireless networking of these sensors across the building to a common base for intelligent processing forms a Wireless sensor network, making the building intelligent. These could include hi-tech hospitals, malls, skyscrapers etc.

Safety is the most important requirement of home for people. With the development of MEMS technology, and network technology an intelligent building becomes more and more practicable today. And also the inclusion of solar cell based energy harvesting systems to power WSN makes it a really renewable and efficient system for low-power consumption.

Energy harvesting source are fundamentally different from that in using a battery as the harvested energy from photo voltaic cells typically varies with time in a non deterministic manner. To overcome these, actively controlled “Battery and Ultracapacitors energy bank based hybrid power systems” are used where the power flow from a battery is coupled with an Ultracapacitors for power enhancement and delivery to the load efficiently. This provides the highest power density choice to power an embedded system.

Replacing alkaline batteries with natural Energy harvesting sources within the vicinity of sensor node’s operating space offers a possibility of infinite lifetime to power the system. Out of several possible scavenging schemes available, highest priority is for which has reasonable cost and maximum energy per unit area.

Table 1 compares the power generation potential of some of these energy harvesting modalities. Among this solar energy harvesting through photovoltaic conversion provide relatively higher power densities. The design of an efficient energy harvesting module involves complex tradeoffs due to the interaction of several factors such as the characteristics of the energy sources, chemistry and capacity of the energy storage device(s) used, power supply requirements, and power management features of the embedded system, and application behaviour.

TABLE 1

Power Densities of Harvesting Technologies

Harvesting Technology	**Power Density**
Solar Cells (outdoors at noon)	$15 mw/cm^2$
Piezoelectric (shoe inserts)	$330 \mu W/cm^3$
Vibration (small microwave oven)	$116 \mu W/cm^3$
Thermoelectric (10^0 c gradient)	$40 \mu W/cm^3$
Acoustic noise (100db)	$960 nW/cm^3$

From Table 1, it is clear that solar energy is the most efficient natural energy source available for sensor networks used for outdoor applications. However, for indoor applications, it is important to note that the efficiency of photovoltaic cells is very low as less as 10 W/m2 as compared to 100-1000 W/m2 under outdoor conditions [6]. For example, mono crystalline solar cells have an efficiency of less than 1-3% under typical indoor lighting conditions. In spite of such poor efficiencies, these cells still have a power density of at least 0.5-1 mW/cm2 under indoor 1-5 W/m2 light intensity conditions [6], which is much higher than their nearest energy scavenging competitor. Thus making indoor WSNs operating on solar power appear to be feasible for Home, industrial and hospital environments.

II. RELATED WORK

Energy harvesting is the area that has recently captured the interests of several research groups. The function of such electronics is to provide appropriate power conversion to operate sensor nodes and also to buffer excess energy for future use.

Various key issues and tradeoffs which arise in the design of solar energy harvesting, wireless embedded systems has been studied through the performance evaluation of prototype called Heliomote[1]. Sustainable operation of battery powered wireless embedded systems (such as sensor nodes) with greater effort to energy optimization is studied. Solar harvesting being as a viable technique but it's highly time varying nature pushes for consideration of energy storage elements, such as batteries or Ultracapacitors. But their different voltage-current characteristics along with self-discharge and round trip efficiency, directly affect energy usage and storage decisions. The ability of the system to modulate its power consumption by selectively deactivating its sub-components also impacts the overall power management architecture.

Prabhakar T V et al [2] Explores System Parameters for Viability of Energy Harvesting Technologies. To ensure energy harvesting as a viable option, several system parameters have to be tuned. Some of the parameters include system's operating voltage & frequency, clear channel assessment and finally capacity values of energy storage buffers. Measurements show that there are several possibilities to save energy by trading one system feature for another.

Winston K.G et al [3] has surveyed and studied the challenges various factors for Wireless Sensor Network Powered by Ambient Energy Harvesting especially environmental/habitat monitoring and structural health monitoring of critical infrastructures and buildings, where batteries are hard (or impossible) to replace/recharge. Sensor nodes need to exploit the sporadic availability of energy to quickly sense and transmit the data.

In Enocean [4] research is done on the design approach for embedded systems with limited power resources. Real time operation and power consumption are critical design aspects of these systems. Main focus is energy management, computing resources and price aspect.

Supercapacitor-based Hybrid Storage Systems for Energy Harvesting in Wireless Sensor Networks by saggini et al [5] works only with supercapacitors or together with the lithium battery in order to obtain a good compromise in terms of energy density and lifetime. It also investigates dedicated power management architecture.

III. PROPOSED SYSTEM

In order to conserve energy, most WSN Remote devices spend 99% of their lives in a very low current timer sleep mode, waking regularly to interface with a sensor/controller and then transmit a telemetry signal back to the head end. The current consumption profile for a typical WSN device with a 5 minute wake cycle might look like the following diagram[9].

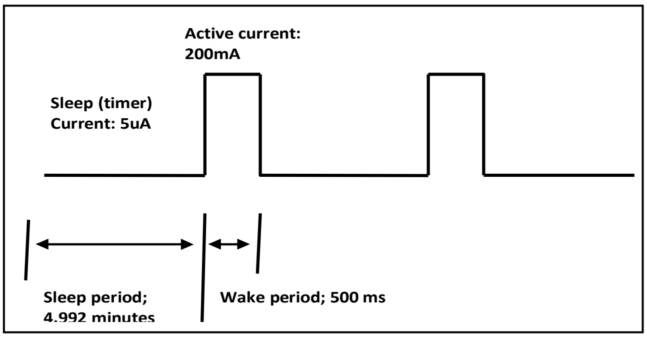

Fig.1 WSN current consumption profile.

To power the WSN node which could require approximately 200mAh power when the voltage is higher than 2.8v[9] we propose solar Energy harvesting and storage system which when coupled together could act as better replacement to conventional battery.

A. Wireless Sensor Network Node Module

A simplified block diagram of a wireless node operating on solar energy is shown in Fig 2.

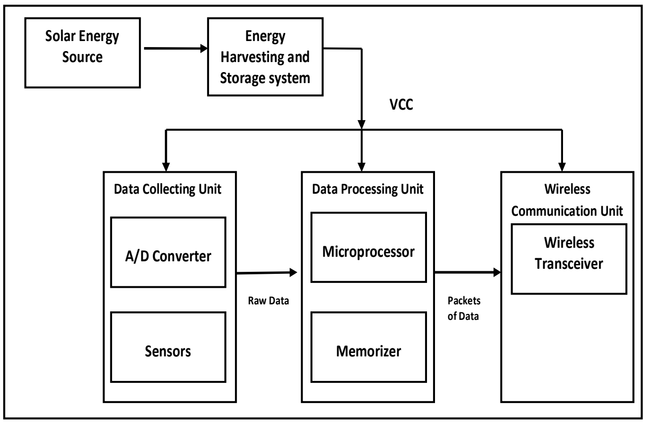

Fig.2 Block diagram of solar energy harvesting wireless node.

IV. SOLAR HARVESTING MODULE DESIGN

The core of the harvesting module is the harvesting circuit, which draws power from the solar panels, manages energy storage, and routes power to the target system. The most important consideration in the design of this circuit is to maximize efficiency [6].

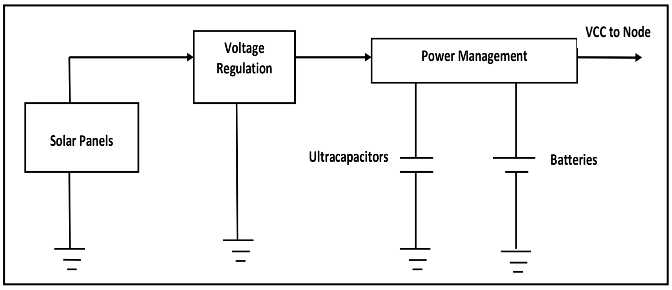

Fig .3 Block diagram of a solar energy harvesting system

A. Solar Cell Characteristics

Solar or other light energy can be converted to electric power using solar cells. The magnitude of energy generated varies from approximately 15mW/sq.cm in noon-time sunlight to 10µW/sq.cm in indoor incandescent lighting.[6]

Solar panels are characterized by two parameters, the open circuit voltage (*Voc*) and the short circuit current (*Isc*). Plotting these parameters in the V-I curve format respectively, following observations are made. First, the solar panel behaves as a voltage limited current source (as opposed to a battery which is a voltage source). Second, there exists an optimal operating point at which the power extracted from the panel is maximized. Finally, as the amount of incident solar radiation decreases (increases), the value of *Isc* also decreases (increases). However, *Voc* remains almost constant.

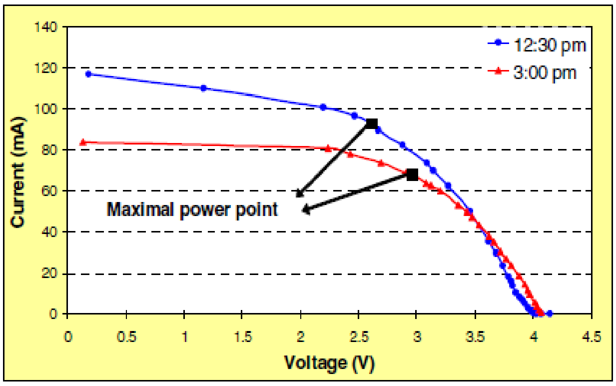

Fig. 4 Measured V-I characteristics of the Solar World 4-4.0-100 solar panel

B. Energy Storage Mechanism

One of the crucial design decisions involves the energy storage mechanism. Traditionally battery is used to store the energy harvested by the panel and provide a stable voltage to the system. But their some of the limitations makes for consideration for alternative form of storage.

The two choices available for energy storage are batteries and electrochemical double layer capacitors, also known as Ultracapacitors. Batteries are a relatively mature technology and have a higher energy density (more capacity for a given volume/weight) than Ultracapacitors, but Ultracapacitors have a higher power density than batteries and have traditionally been used to handle short duration power surges. Also they offer higher lifetime in terms of charge-discharge cycles.

Higher power density and low energy density along with longer life cycle than makes Ultracapacitors more viable. Also its faster energy release, much faster (with more power) than a battery has led to new concepts of hybrid charge storage devices. Here electrochemical capacitor is interfaced in parallel with a fuel cell or battery. Ultracapacitors acting as main energy source where as batteries only acting as reserve of backup energy.

C. Regulator

The solar power charge regulator assures that the battery is working in appropriate conditions. To ensure proper charging and discharging of the battery, the regulator maintains knowledge of the ***state of charge*** (***SoC***) of the battery. The SoC is estimated based on the actual voltage of the battery. By measuring the battery voltage and being programmed with the type of storage technology used by the battery, the regulator can know the precise points where the battery would be overcharged or excessively discharged.

D. Working Principle of UltraCapacitor.

Ultracapacitors also called as electric double layer capacitor, where the electrical charge stored at a metal/electrolyte interface is exploited to construct a storage device.. The high content of energy stored by Ultracapacitors came from activated carbon electrode material having the extremely high surface area and the short distance of charge separation created by the opposite charges in the interface between electrode and electrolyte. Randomly distributed ions in electrolyte move toward the electrode surface of opposite polarity under electric field when charged. It is purely physical phenomena rather than a chemical reaction and hence highly reversible process, which result in high power, high cycle life long shelf life, and maintenance-free product[11].

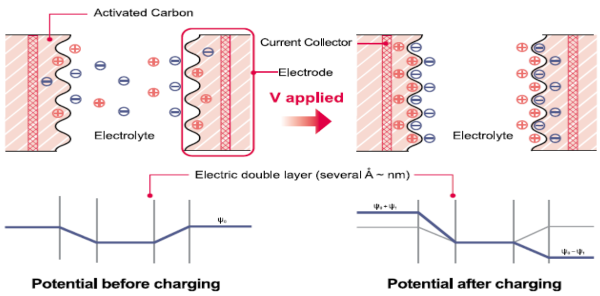

Fig.5 Working principle of Ultracapacitor.

E. The Converter

The electricity provided by the panel array and battery is DC at a fixed voltage but might not match load requirements. A direct/alternating (DC/AC) converter, also known as ***inverter***, converts the DC current from your batteries into AC. Also converters can be used to obtain DC at voltage level other than what is supplied by the batteries, to match the supply voltage required by the target system.

F. Harvesting Aware Power management

In wireless sensor network, where each node may have different environmental harvesting opportunity appropriate power management strategies should be used. Instead of just minimizing the total energy consumption, it becomes necessary to adapt the power management scheme to account for these spatio-temporal variations.

When the load current is small, the converter in power management circuit is controlled such that the battery discharges at a constant rate regardless of the battery voltage variation, and it charges the ultracapacitor. The discharge rate of the battery is determined by the average load demand, and is controlled via an appropriate feedback mechanism. To protect the battery, the current is controlled so as to not exceed the safety limit. At this time, the ultracapacitor is charged at a constant current.

Secondly, when the load current is high, both the battery and the ultracapacitor supply current to the load. By controlling the battery current at a constant value throughout the operating cycle, the battery can be kept in extremely steady state; it is therefore electrically and thermally preferred for the sake of a safe and long lifetime. Most importantly, the hybrid provides much higher power without drawing excessive current from the battery.

G. Summarizing

The complete photovoltaic system incorporates all of these components. The solar panels generate power when solar energy is available. The regulator ensures the most efficient operation of the panels and prevents damage to the batteries. The battery bank stores collected energy for later use. Converters and inverters adapt the stored energy to match the requirements of your load. Finally, the load consumes the stored energy to do work. When all of the components are in balance and are properly maintained, the system will support itself for years. The function of such energy harvesting circuit is to provide appropriate power conversion to operate sensor nodes and also to buffer excess energy for future use.

H. Energy Equation for Ultra capacitor

Different units between Ultracapacitor (Farad) and battery (Ampere hour) can bring compatibility issues when adopting Ultracapacitor in their system. The amount of energy stored in Ultracapacitor can be easily calculated by using following equation [11].

Energy (Joule) = 1/2 x Capacitance (Farad) x Voltage^2 (Volt)

It can be converted from Farad for Ultra capacitor to Watt hour unit which is normally used for conventional rechargeable battery.

Energy (Watt hour) = Energy (Joule) / 3600 (sec)

The high content of energy stored by Ultracapacitor in comparison to conventional electrolytic capacitor is came from activated carbon electrode material having the extremely high surface area and the short distance of charge separation created by the opposite charges in the interface between electrode and electrolyte[11].

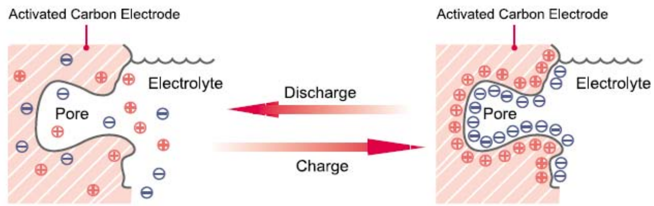

Fig 6. Charging and discharging mechanism of Ultracapacitor

Ultracapacitors have different charge & discharge characteristics compared with rechargeable battery. Battery has voltage plateau region but Ultracapacitors shows only linear relationship with voltage during charge and discharge. The linear relationship with voltage can change to constant voltage by simply connecting DC-DC converter. The amount of energy stored in Ultra capacitor can be easily calculated by measuring voltage.

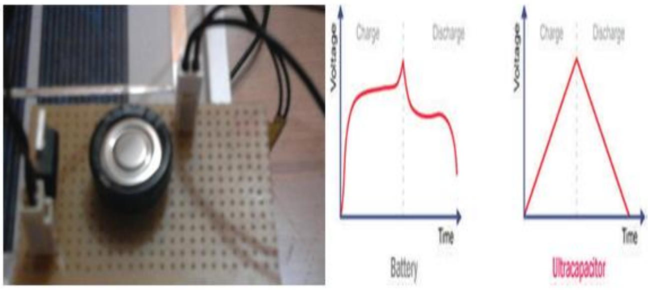

Fig 7 a) 5.5V /1F Coin cell Ultracapacitor b) Charging and discharging of Battery and Ultracapacitor

I. Advantages of Ultracapacitors

Ultracapacitors have Capacitance values of up to 50 Farads which are not unheard of. Working voltages are usually limited to 2.5 volts so Ultracapacitors can be many times stacked in series to handle the voltages needed to power the WSN device circuitry (3.3 volts to 5.0 volts)[2].

But some of the basic advantages that's could be seriously considered are:

- Can be charged and discharged almost an unlimited number of times.

- Can discharge in matters of milliseconds or as long as tens of seconds or several minutes.
- Can be charged in seconds to minutes.
- High power density.
- Do not release any thermal heat during discharge.
- There is no danger of overcharging; when fully charged the ultra capacitor simply quits accepting a charge.
- Are not affected by deep discharges as are chemical batteries.
- Have a long lifetime, which reduces maintenance costs; anecdotal evidence suggests that they lose about 80% of their storage capacity after 10 years, with a lifetime estimated to be 20 years.
- The DC-DC round-trip efficiency is 80%-95% in most applications.
- Operating temperature range as great as between -50C and 85C, capacity increases as temperature decreases below the rating temperature.
- They do not release any hazardous substances that damage the environment.

V. PROTOTYPE SYSTEM

We set up a sample prototype system in our lab room. A 10w/12v solar panel is connected to combination of two 5.5v /1F ultracapacitor and 12v/ 7.5AH rechargeable battery which are shunted together. Also a dc load in the form of 5v Node is connected to the output of the whole setup.

The ultracapacitor is first charged and tested independently.

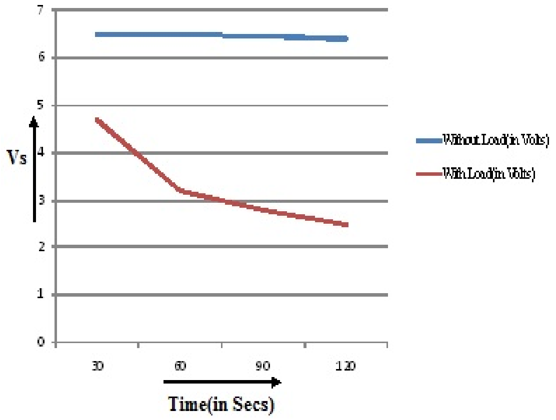

Fig 8a Discharging of Ultracapacitor without and with load

The charging and discharging graph of Ultracapacitors with and without load Discharging is almost negligible without load whereas its linear and quick with load. Charging is very linear and slow with load and quick in case of without load.

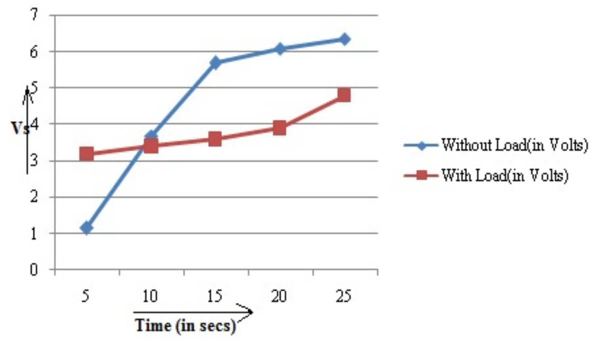

Fig.8b Charging of Ultracapacitor without and with load

This hybrid combination is connected to solar panel through PV voltage regulator. Then, we can start the test with this prototype system by exposing the solar panel to different intensity of light. This setup produces varied voltage of 5v to 6.4v across the Node. This harvesting circuit is tested for varied intensity of lights.

Fig 9 Proposed solar energy harvesting system prototype

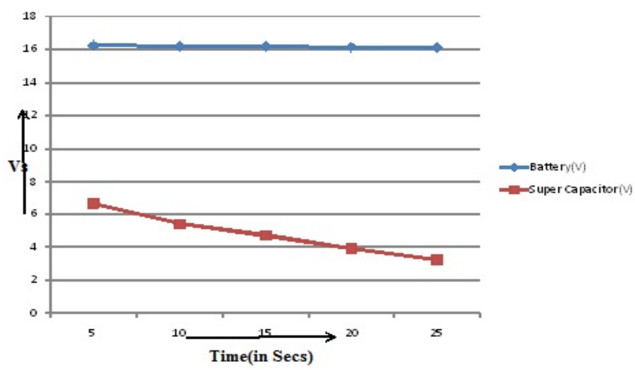

Fig 10.The Final output voltages across the load by the energy harvesting system

VI. CONCLUSION

An experimental solar energy harvesting systems to power sensor nodes virtually makes the wireless sensor network indefinitely self sustaining. The high power density and free availability of solar harvesting system makes it more preferred than its nearest energy harvesting alternative.

The system energy storage module which is hybrid combination of a set of Ultracapacitors shunted with alkaline battery used as a back-up energy source eliminates the need to frequent replacement of batteries. High power, long shelf and cycle life performance of Ultracapacitor and its purely reversible linear charge and discharge process can release energy much faster (with more power) than a battery. Hence can be cycled hundreds of thousands of times without deep effect on performance. The experiment setup worked impressively, producing constant voltage to power the Nodes for long hours. This is tested for both indoor and outdoor conditions with optimized output. But this setup is more feasible for Base or router node rather than the data collecting nodes because of lack of miniaturization.

As the PV cell technology continues to improve and costs continue to drop a micro solar energy harvesting becomes a practically viable option for long-term powering of remote WSN devices.

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