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Design of a Novel Power Management Unit for Photovoltaic Powered Indoor WSN Node

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ABSTRACT

Direct cloud-enabled sensor nodes offers certain advantages over low-power wireless communication technologies but require high-power. Conventional wireless sensor nodes, which are battery-powered, have relatively low lifespan. In a battery powered direct cloud-enabled sensor nodes, the peak current needed during the data transmission process will add extra burden on the already strained battery resources and may accelerate the capacity degradation, further reducing battery life. The condition deteriorates where applications require frequent data transmission. This paper proposes a novel power management device architecture tailored to direct cloud-enabled sensor nodes' requirements for indoor applications with extended lifespan. This research also recommends using Photovoltaic energy harvesting with a hybrid storage technique consisting of a battery and supercapacitor to power the node. The work's novelty lies in the use of a supercapacitor-battery hybrid storage scheme, which provides the required peak current during the data transmission, sufficient enough to fulfill the load requirement during the data transmission process. A novel drip charge controller synchronized with the sleep period, and the active period of the sensor node is introduced. The power management unit was designed simulated and validated experimentally to verify performance with the indoor application.

Keywords: Battery-Supercapacitor hybrid storage, Indoor PV Energy harvesting, Power management unit, Direct cloud-enabled device, Wireless sensor network

1. INTRODUCTION

Wireless Sensor Network (WSN) is a collection of myriads sensor nodes in the measurement field to acquire, transmit, and receive information. WSN's reputation can be defined by being the second-largest network after the Internet [1-5]. WSN's biggest challenge in large-scale deployability is longevity constraint [6], which arises due to limited cycle-life of batteries. Low-power wireless networking systems, including LoRa and SigFox, consume less power. Nonetheless, implementations, where Security and Quality of Service (QoS) prioritize such technologies, are not feasible. Direct cloud-enabled technologies such as Narrowband Internet of Things (NB-IoT) and LTE Cat-M are also promising in these applications because they use current cellular network security and QoS [7-10]. The longevity constraint becomes more severe in direct cloud-enabled sensor nodes as they need considerable peak current. The battery performs well only when the current profile is monotonous [6]. The condition is further exacerbated by high data transfer frequency which has a negative effect on the battery electrolytes [6], accelerating the battery's capacity degradation requiring regular replacement. The above problems can be resolved to some degree by energy-autonomous sensor nodes [11 - 12, 26].

Self-sustainable WSN technology is about to be extensively used. The available energy sources in the atmosphere are photovoltaic, piezoelectric, vibration, thermoelectric, electromagnetic and acoustic noise [26-28]. However, Photovoltaic (PV) energy outperforms the other sources in terms of power density (typically 15mW/cm2) [29]. In [13], a photovoltaic-battery based Internet of Things (IoT) device is proposed using ultra-low-power sensors and wireless networking to prolong battery cycle life. To offset energy intermittency in PV powered devices, a storage buffer is required. Two types of energy storage systems are popular, Li-ion battery-based storage and electrochemical double-layer capacitor (ELDC) or Supercapacitor based storage [14].

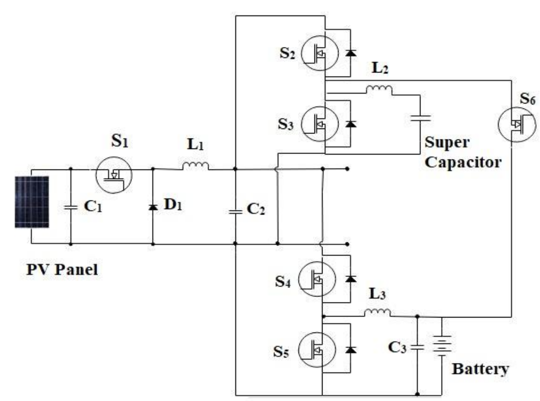
The battery has high energy density and low leakage charge, but it is paralyzed by capacity degradation with time specifically in the applications where discharge current profile consists of high-frequency high magnitude pulses [15]. Certain degradation factors such as temperature, depth of discharge often contribute to reduced battery life; however, various solutions to overcoming these degradation mechanisms have already been suggested in the literature, except for degradation due to peak current [16-20]. Another alternative storage is a supercapacitor. The key difference between the two is that the supercapacitor supports rapid charging and discharging [21-24]. Therefore, the supercapacitor is ideal for use in applications requiring high peak current. Nonetheless, the case for using the supercapacitor as a single storage medium is weakened by its low energy density and high leakage charge [14]. In [30], a battery-less sensor node based on photovoltaic energy harvesting and an ELDC as a storage buffer have been reported. The hybrid energy storage system comprises a battery and a supercapacitor and is ideally suited for non-monotonic load cycles [6]. Jing et al. reported an extensive review of battery-supercapacitor as a hybrid energy storage system and its ability to increase battery cycle life [25]. Further, Jiang et al. proposed the design of a Telos-mote photovoltaic-powered sensor node using two-stage storage buffers Li-ion battery and supercapacitor [33]. Ongaro et al. reported the power management system for photovoltaic-based WSN, using Li-ion batteries and supercapacitor as energy storage [21]. Pellitteri et al. proposed a hybrid energy storage system (HESS) for WSN powered by energy harvesting and using state-of-the-art GaN technology, which performs tests up to 15W [31]. Similarly, Joshi et al. proposed a non-MPP PV-supercapacitor energy harvester for WSN, which is stated to be cost-effective and straightforward but requires an additional battery to power the control circuit [32]. Efficient power management strategy is crucial to address disadvantages such as capacity degradation due to non-monotonous battery current and battery draining supercapacitor.

This paper proposes a novel power management unit design for photovoltaic-powered, cloud-enabled, indoor WSN nodes with battery-supercapacitor hybrid storage. To address battery non-monotonicity, discharge current when PV power is not sufficient, a novel approach to use hybrid storage is set out. The supercapacitor is first drip charged during sleep mode with the aid of the battery and then discharged to provide peak load current during the data transmission process. A novel drip charge controller synchronized with the sleep and active time of the sensor node ensures that the supercapacitor is charged adequately before the next peak load cycle. Finally, novel power management unit was successfully simulated with the help of MATLAB simulation, and validated experimentally.

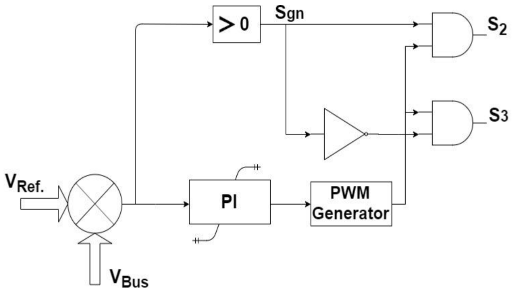
2. DESIGN OF POWER MANAGEMENT UNIT

Power Management Unit (PMU) is responsible for arranging and conditioning power during operation. It consists of Power Control Unit (PCU) and Power Management Circuit (PMC), the former implements the Power Management Algorithm (PMA) and other controllers. The PMC (fig.1 (a)) interfaces photovoltaic (PV), battery and supercapacitor through suitable DC-DC converters. Parallel active hybrid topology is implemented in this study, as it provides more efficient control for both batteries current and supercapacitor current during pulsed load current. The PMA switches between different operating modes by comparing system parameters real-time values such as input power (PIN), supercapacitor voltage (VSC) and battery voltage (VBATT) with reference values.

The PV array is primary source of energy, and its output power depends on temperature and irradiance. At a particular irradiance and temperature level a maximum power point exists. The buck converter (switch S1) shown in Figure 1(a) is connected across the panel to track the maximum power point using an MPPT controller. The switch S6 is used to realize a buck converter to drip charge the supercapacitor. While S3 can be used for the same purpose, the inclusion of an additional switch (S6) provides independent control over the battery discharging current; thereby PCU can exercise better control over it. This can be found out by observing the circuit where S6 is connected directly across battery terminals as opposed to S3 connected through the DC Bus.



(a)



(b)

Figure 1 (a) Proposed power management circuit diagram (b) controller design for supercapacitor converter

2.1 Power Management Algorithm

Power Management Algorithm (PMA) renders requisite intelligence. This is at the core of any control activity during system operation. It also lets the system operate optimally under varying environmental conditions. Figure 2 displays the flowchart for the proposed Power Management Algorithm (PMA). The PMA operates in Mode 1 to Mode 4 where Mode-1 and Mode-2 are subsumed under the Day mode and are referred as Day Mode-1 and Day Mode-2, and Mode-3 and Mode-4 are subsumed under the Dark mode. Originally, all storage is believed to be depleted, and the state of the system corresponds to sleep state. It is booted out of this state only if PV power breaches a threshold value the operating mode corresponds to Day Mode-1. During this mode, PV power is directed to the supercapacitor and load. The supercapacitor converter is operated in a bi-directional mode to account for PV power intermittency, where the power exceeding the load demand is guided to the supercapacitor as shown by the division block in Figure 2 and the deficit power is drawn from the supercapacitor as an additional component (PSCAP) ensuring that the load demand is met at each moment. This is achieved by controlling the dc bus voltage by the supercapacitor controller. The rationale behind implementing this mode is the supercapacitor's virtual independence from the charging current profile. Therefore, it is first charged with non-monotonous PV current to accumulate sufficient energy to charge the battery with the desired charging profile in the subsequent mode. Day Mode 2 subsumes battery charging operation.

The Power Control Unit (PCU) tracks the supercapacitor voltage continuously to prevent overcharging and switches the process to Day Mode-2 when it exceeds a threshold value of 2.5 V. After reaching Day Mode-2, the MPPT controller is disabled (overvoltage protection). The combination of PSD and PSCAP will fulfill the battery charging requirement and load demand and will disable the battery charging controller after VB exceeds 3.7 V. In case, power from the PV side is below the threshold value, the system switches to dark mode where a flag is used to synchronize the supercapacitor's charge or discharge time with sleep and active periods, respectively. If the flag is high, the system switches to Dark Mode-3 which corresponds to the peak power period of the load cycle. In this mode, the supercapacitor is chosen to power the load. If the flag status is low, the battery while supplying the sleep current also charges the Supercapacitor for a period until it accumulates sufficient energy to meet the peak power required during the next cycle.

2.2 Various DC-DC Converter and Controller design

A unidirectional buck converter fig. 1(a) is used to interface the PV panel with the DC bus. At steady state, the relationship between the output voltage and the input voltage is governed by equation 1.

$$VBUS = D \times VPV \qquad 0 \leqslant D \leqslant 1 \qquad (1)$$

Where D is the duty cycle ratio of the converter, VBUS is DC bus voltage (controlled by the supercapacitor Controller), and VPV is PV voltage. A MPPT controller implementing Perturb & Observe (P&O) algorithm is used to control the switch S1.

In Figure 1(a), a bi-directional converter connected across the battery is shown. The battery is charged by activating the switch S4 and simultaneously deactivating the switch S5, converter topology is a buck, looking from the side of the DC bus. Switching S5 and deactivating S4 would initiate discharging.

As shown in Figure 1(a), a bi-directional controller connected across the supercapacitor. Bi-directional power flow conversion is achieved using S2 and S3 switches. Under charging conditions, when Isc > 0 (as shown in figure 1(b)), the DC-DC converter acts as a buck converter, looking from the DC Bus side. A switch S3 is deactivated and S2 routes the surplus power to the supercapacitor. While discharging, S2 is deactivated and S3 is switched, the power flow directions from supercapacitor to DC bus. The converter is working as a boost converter, looking from the supercapacitor side. Equation 2 controls a steady-state relationship between VDC and VSC voltages.

$$VBUS/VSC = 1/(D-1) \qquad 0<D<1 \qquad (2)$$

Figure 1(b) displays a PI controller which was used to control the DC Bus voltage to the reference value. The status of a logic signal (Sgn) determines the deactivation or working status of S2 and S3, thus contributing to the controller's improved dynamic response, particularly during load and discharge transitions.

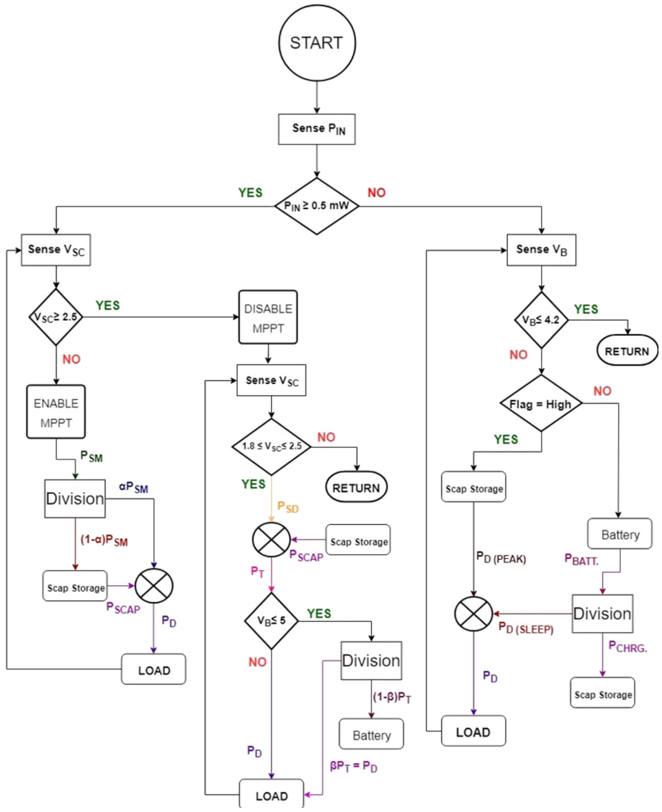


Figure 2 Power Management Algorithm (PMA)

Abbreviations

PIN = Input Power, VSC = Supercapacitor Voltage, VB = Battery Voltage, PSD = Input photovoltaic power when MPPT controller is in Off state, PD = Power requirement of Load, PT = Summation of PSD and PSCAP, PD (Sleep) = Power required by load during sleep mode, PD (Peak) = Peak power demand of load, PBATT = Power discharged by battery during dark mode, PCHRG = Charging power of supercapacitor during dark mode, α = a variable that depends on load cycle and input power, PSM = Input photovoltaic power while operating at maximum power point, PSCAP = Power discharged by supercapacitor to compensate for any deficit power on load bus, β = a variable that depends only on load cycle

3. RESULT AND DISCUSSION

On the MATLAB-Simulink platform, the Power Management Unit (PMU) with associated control system was modeled, and validated experimentally.

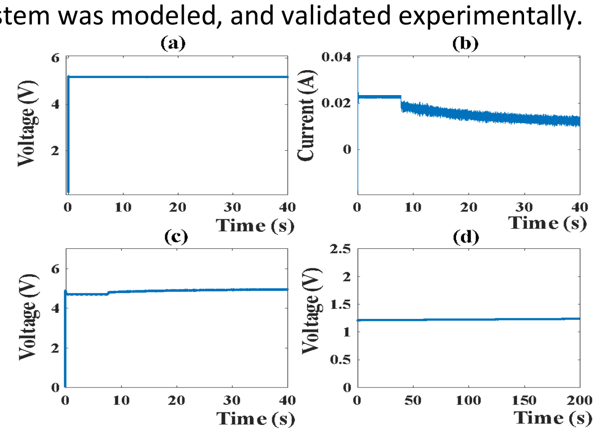


Figure 3 Simulation results for the system operating in Day Mode-1, (a) PV voltage, (b) PV current, (c) Load Voltage, (d) Supercapacitor voltage

Figure 3 displays system variables while system operation was Day Mode-1. Figure 3(a) is a plot for PV panel voltage at MPP and Figure 3(b) illustrates the PV current. From the simulation result figure 3(a), 3(b) it can be observed that the MPPT algorithm is insensitive to smaller variations in illumination, as the MPP voltage stays more or less the same while the PV current fluctuates in a narrow range.

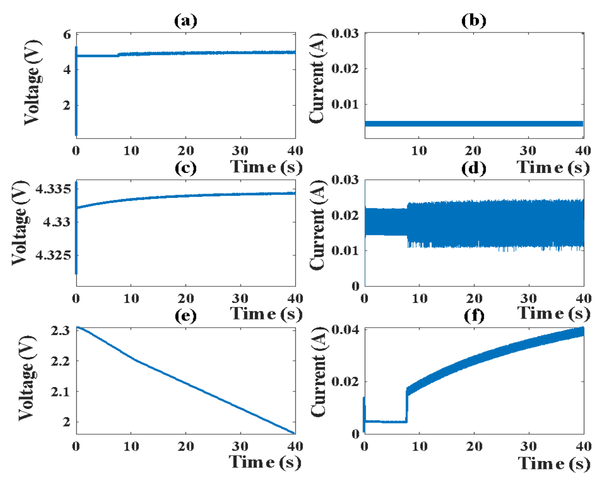
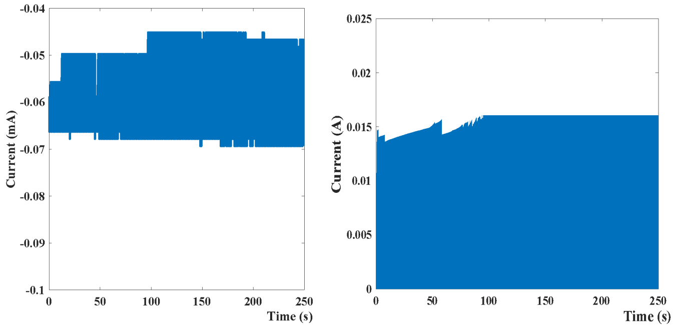


Figure 4 Simulation results for the system operating in Day Mode-2, (a) PV voltage, (b) PV current, (c) Battery voltage, (d) Battery charging current, (e) Supercapacitor voltage and (f) Supercapacitor discharging current



(a) (b)

Figure 5 Simulation results for the Dark Mode-3,4, (a) Peak load current (b) Battery discharge current

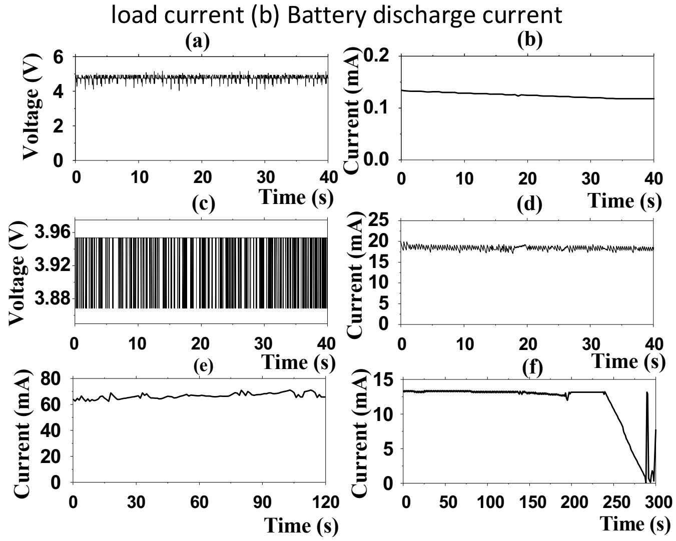


Figure 6 Experimental results for the system operating under the Day Mode-2, (a) PV and Load voltage, (b) PV current, (c) Battery voltage, (d) Battery charging current, (e) Peak Load current, (f) Battery discharge current

A capture of the DC Bus voltage held at the desired value of 5 Volts is shown in Figure 3(c), Figure 3(d) shows the Supercapacitor voltage of 1 to 1.33V in 200 seconds, demonstrating the super capacitor’s fast charging capability. The process switches to Mode 2 after the supercapacitor voltage exceeds a magnitude of 2.5 volts, simulation and experimental results plots for the corresponding operating mode are shown in Figure 4. Figure 4(a) displays PV voltage. As the MPPT controller is disabled during this mode, the same voltage appears across the DC bus, Figure 4(b) shows the PV current, Figure 4(c) and 4(d) respectively reflects battery voltage and charging current. Figure 4(b) and 4(d) show that a constant charging current is maintained for batteries under low illumination, showing the supercapacitor 's function as a power conditioning buffer, the supercapacitor voltage and current plots shown in Figure 4(e) and 4(f) respectively. Figure 5(a) shows the active mode load current plot and Figure 5(b) shows the sleep mode battery discharge current, and Figure 3 to 5 validates the effectiveness of the control system design and offers an insight into the circuit operation under different modes. In addition, the simulated model is validated with lab experiments and Experimental results for the system operating under the Day Mode-2 is shown in Figure 5. The measured test revealed good alignment with simulated performance. This indicates the efficacy of the proposed design.

4. CONCLUSION

The novel power management unit design for directly cloud-enabled indoor WSN nodes with hybrid battery-supercapacitor storage is introduced. These sensor nodes offer certain advantages over other low-power wireless communication technologies, but consume more peak current. This higher pulsating current leads to degradation of battery capacity, resulting in further reduction of battery life. The proposed power management unit is specially designed for applications which require frequent data transmission. To maximize battery life, battery-supercapacitor hybrid storage was implemented. First, a PCU is designed for efficient energy routing and ensuring the system operates optimally under varying externalities. The supercapacitor is used to relieve the battery from frequently occurring peak current. The innovation of the proposed research lies in the use of supercapacitor to provide the necessary peak current during the data transmission process when power from PV is not available; to realize this, a drip charge controller synchronized with the node's sleep and active period was implemented. Simulation and experiment results show the proposed design's effectiveness as battery charge and discharge are free from intermittent peaks, which can prevent capacity degradation acceleration and thus shorten the cycle life.

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