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Energy Harvesting system with battery-supercapacitor hybrid storage for highly maintenance-free remote sensing stations

***Abstract**. In this article, the usage of a Hybrid Energy Storage System concept is proposed. The proposed solution is dedicated to Energy Harvesting systems operating in remote areas, where a high level of maintenance-free operation and reliability is required. Attention is drawn to the problem of self-discharge in traditional batteries, proposing the use of batteries as a source with a much lower self-discharge rate, supported by a supercapacitor.*

***Streszczenie.** W artykule zaproponowano wykorzystanie idei Hybrydowego Systemu Magazynowania Energii. Proponowane rozwiązanie dedykowane jest systemom pozyskiwania energii, pracującym na obszarach odległych, w których wymagany jest wysoki poziom bezobsługowości, a zarazem niezawodności. Zwrócono uwagę na problem samorozładowania klasycznych akumulatorów, proponując wykorzystanie baterii jako źródła o znacznie mniejszym współczynniku samorozładowania, wspomaganego superkondensatorem. (**System pozyskiwania energii z hybrydowym magazynem energii, bateria-superkondensator dla wysoce bezobsługowych stacji zdalnego pomiaru**).*

Keywords: energy harvesting, supercapacitors, renewable energy, hybrid energy storage system.
Słowa kluczowe: pozyskiwanie energii, superkondensatory, stacje zdalnego odczytu, hybrydowe systemy magazynowania energii.

Introduction

Energy Harvesting (EH) is a set of techniques aimed at capturing and accumulating energy from various ambient sources in the environment, such as solar radiation, vibration, thermal gradients, and kinetic motion [1, 2]. This sustainable approach to power generation enables the creation of self-sustaining systems, reducing reliance on traditional energy sources [3]. However, considering the current state of technology, the need for some storage mechanism becomes essential, even for low-power and reliable electronic devices [4]. A general Energy Harvesting System structure is presented in Figure 1.

Hybrid Energy Storage Systems (HESS) ingeniously merge the strengths of batteries and supercapacitors, offering a robust solution for energy management. This integration facilitates a dynamic energy supply, with supercapacitors addressing immediate power needs through quick energy discharges, and batteries providing sustained power during longer periods of scarcity [9]. Such a setup not only boosts the operational performance but also significantly lowers maintenance needs, making HESS ideal for applications demanding high reliability with minimal upkeep [10]. This approach presents a promising avenue for improving energy systems in various sectors, ensuring reliable power supply even under fluctuating energy

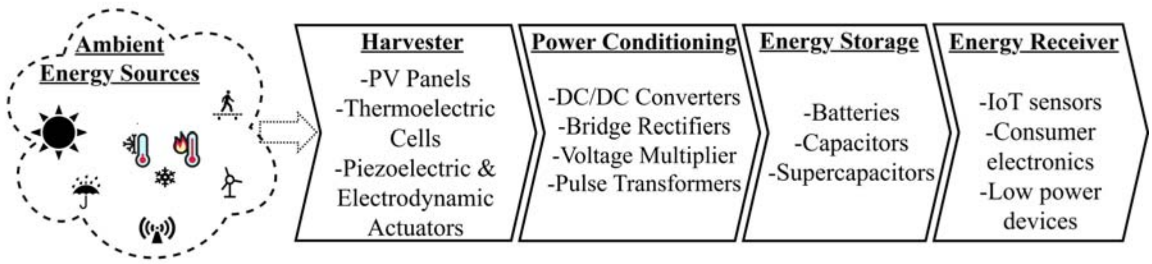

Fig. 1. General Energy Harvesting System structure

Batteries are widely used as energy storage devices due to their relatively high energy density, providing extended periods of power supply. However, in the Energy Harvesting applications that power electronic devices in remote areas, batteries need to have a low self-discharge ratio [5]. Despite their various advantages, rechargeable batteries tend to have a higher self-discharge ratio compared to disposable batteries [6]. As a consequence there is a need for replacements, which can be challenging in remote or inaccessible locations, leading to higher maintenance costs and environmental impacts. As a result the disposable battery was subjected to analysis in the article.

Supercapacitors are emerging as an alternative energy storage solution. They possess rapid charge and discharge capabilities, allowing for quick energy transfer. Although they have lower energy density compared to batteries, supercapacitors excel in providing bursts of power, making them ideal for high-power applications [7, 8].

Through the integration of Energy Harvesting, batteries, supercapacitors and HESS, innovative solutions can be developed to address the increasing demand for self-powered, low-power electronic devices. Such advancements hold promise for applications in remote monitoring systems, Internet of Things (IoT) devices, wireless sensor networks, and other energy-efficient technologies [12].

Energy Harvesting storage management - an overview

In the context of evolving Energy Harvesting technologies, a specific architecture of the EH system is illustrated in the Figure 2. The components within the dashed line are part of a specific integrated circuits which is used in Energy Harvesting System [13]. A various integrated circuits have subtle architectural differences based on the specific application or manufacturer [14]. The diagram presents a typical architecture suited for the IoT systems. Outside the dashed line which is connected to the

EH integrated circuit and can vary depending on the energy source, load, or storage technique.

A simplified operating principle of Energy Harvesting System is associated with collecting the Ambient Energy by the Harvester. This energy can take various forms depending on the Harvester type. For instance, a direct current from thermoelectric cells, alongside photovoltaic cells [15].

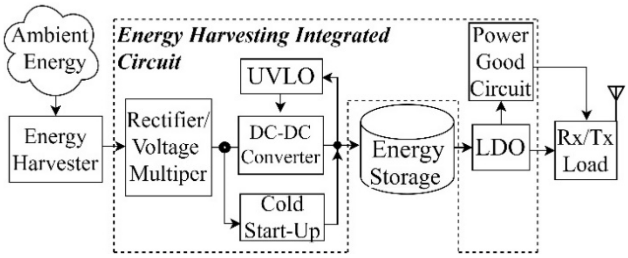

Fig. 2. Block diagram of Energy Harvesting System based on specialized Integrated Circuit [16].

Energy is directed to the rectifier and, depending on the configuration, potentially to the voltage multiplier. Subsequently, the DC-DC converter adjusts the voltage, charging the external storage. The Low-Dropout Regulator (*LDO*) ensures stable power supply for System on Chip (*SoC*), which cannot tolerate voltage fluctuations. In the systems, the "Cold start-up" module allows the system to be activated from a low energy level, which is crucial in situations with irregular energy access [17]. The Undervoltage-Lockout circuit (*UVLO*) is monitored, and the power supply is cut off if the voltage drops too low, protecting SoC-IoT circuits. Meanwhile, "*Power Good*" indicates when the voltage has reached a stable level, ensuring the safe operation of SoC-IoT circuits.

There is a multitude of architectures for energy distribution and storage in EH systems. To provide a detailed characterization of the presented solution, a classification of EH systems, focusing on energy harvesting, management, and flow, has been proposed in this chapter :

1) *Based on the number of harvested sources* [18]:

● Single-source Systems: Energy is harvested exclusively from one source in these systems. Solar cells, for instance, derive their power solely from sunlight. Managing energy in single-source systems might be straightforward, but these systems can face limitations in continuous energy supply, especially during unfavorable conditions like a cloudy day for solar cells.

● Multi-source Systems: Energy is derived from several sources in these systems, such as systems that amalgamate photovoltaic, thermoelectric, and piezoelectric converters. This distinction is paramount since energy management in single-source systems will inherently differ from multi-source ones. Notably, multi-source systems can provide a more stable and uninterrupted energy supply but necessitate more intricate management techniques.

2) *Based on energy storage technique* [19]:

● Single Storage Systems: Energy is conserved in one single reservoir in these systems, such as a battery. While this simplicity can be an advantage in terms of system design and cost, it might impose limitations on energy storage capacity and discharge rates.

● Hybrid Storage Systems: Energy is stored using a combination of mechanisms in these setups, like a battery accompanied by a supercapacitor. Hybrid systems potentially offer superior traits like rapid charging or extended operational times. However, they demand supplementary control circuits, elevating the initial system cost and introducing complexities in energy management.

Remote IoT energy storage analysis- case study

Long-range Internet of Things (IoT) technologies, supported by high-efficiency power sources and Energy Harvesting (EH) techniques, enable the connection of devices operating in remote and inaccessible areas to the internet. Examples of such devices include various types of monitoring stations that measure different physical quantities, such as:

- water levels in remote areas at risk of flooding;
- water quality in distant reservoirs and rivers;
- changes in water levels in drought-prone areas;
- changes in temperature and humidity in nature reserves;
- atmospheric precipitation in mountainous areas.

In these applications, devices must operate reliably for extended periods, often under challenging environmental conditions [20]. The role of these systems is to collect and transmit data on environmental variables that change relatively slowly - therefore, they do not require continuous real-time transmission.

The choice of a specific IoT radio technology should ensure the ability to operate in difficult propagation conditions, allowing transmission over distances of several kilometers. The selected radio interface should also be characterized by minimal power consumption. The technology that meets these requirements is LoRa (Long Range) [21]. Limited bandwidth is not an issue, as data transmission at large time intervals and the nature of the data itself do not require wide bandwidth. Furthermore, LoRa modules can be integrated with existing LoRaWAN network infrastructure through the use of LoRaWAN gateways, which provide internet access. This process enables LoRa modules to communicate over long distances with low power consumption, using the open LoRaWAN standard for wireless networks. Thanks to this integration, devices equipped with LoRa modules can transmit data to a central management system via the LoRaWAN network, enabling remote monitoring and control in IoT applications [22, 23].

Given the outlined scenario of a monitoring station situated in remote and challenging locations, which captures physical parameters that vary gradually, selecting a power supply characterized by a minimal rate of self-discharge becomes paramount. This particular attribute of the power supply guarantees sustained operation of the device over an extensive duration, crucial especially under circumstances of constrained ambient energy sources and a distinct consumption profile marked by prolonged intervals of low power usage, punctuated by occasional, significant upticks in energy demand triggered by the activation of the transmitter.

The general advantage of disposable batteries over rechargeable batteries in terms of self-discharge stems from their unidirectional chemical nature, which minimizes parasitic chemical reactions common in the reversible systems of rechargeable batteries. Within the spectrum of rechargeable batteries accessible today, Tadiran Lithium Ion (TLI) technology demonstrate the minimal self-discharge values, with an annual capacity reduction of approximately (<5% at 20°C) [24]. Conversely, LS Saft Li-$SoCl_2$ batteries stand out for their unparalleled low self-discharge coefficient, under (<1% at 20°C), annually [25].

In the context of evaluating the energy efficiency of both disposable battery and rechargeable battery. Assuming identical initial capacities $Q=2Ah$, a simplified model describing the self-discharge process based on exponential principles has been adopted. The following formula represents the total charge Q_B retained in the disposable battery over time t, taking into account the self-discharge coefficient r_B:

$$(1) \qquad Q_B = \int_0^t Q \cdot e^{-r_B \cdot t} dt = \frac{Q}{r_B} \cdot \left(1 - e^{-r_B \cdot t}\right)$$

where: Q_B - total accessible disposable battery charge, after specified time, Q - is the initial battery charge , r_B - disposable battery self-discharge coefficient (0,9% per year), t - one year time window.

The equivalent integral for the rechargeable battery is described by:

$$(2) \qquad Q_A = \int_0^t Q \cdot e^{-r_A \cdot t} dt = \frac{Q}{r_A} \cdot \left(1 - e^{-r_A \cdot t}\right)$$

where: Q_A - total accessible rechargeable battery charge, after specified time, Q - is the initial battery charge, r_A - rechargeable battery self-discharge coefficient (4,9% per year).

By solving the integrals (1) and (2) the equations are obtained that describe the remaining charge over time, given the assumed self-discharge rate. By substituting the aforementioned self-discharge coefficient for LS Saft Li-SoCl2:

$$(3) \qquad Q_B = \frac{2000}{0,009} \cdot \left(1 - e^{-0,009 \cdot 1}\right) \approx 1991 mAh$$

The equivalent equation for the Tadiran Lithium Ion (TLI) is as follows:

$$(4) \qquad Q_A = \frac{2000}{0,049} \cdot \left(1 - e^{-0,049 \cdot 1}\right) \approx 1952 mAh$$

The difference in capacity between the two energy storage devices after a given period is determined by the simple difference between the remaining charges Q_B and Q_A is expressed as an absolute value:

$$(5) \qquad \Delta Q = \left| Q_A - Q_B \right| \approx 39 mAh$$

Despite the relatively small difference between the discharge coefficients of the analysed energy storage units, the assumed conditions of not maintaining the station for a relatively long period result in a cumulative difference in the charge level of the storage units.

When analysing the load profile of battery-powered communication devices that use LoRa technology, accurately determining the time needed for data transmission is crucial. Understanding this parameter is essential to evaluate the impact of transmission cycles on the device's overall energy consumption. To calculate the data transmission time, the formula (6) is employed, incorporating key LoRa transmission parameters that have a direct influence on the transmission time and, consequently, on the energy profile of the load:

$$(6) \quad t_{TX} = \frac{2^{SF}\left(N_{PR} + \frac{4,25 + N_{PY} + 8 + \max\left\{2SF;16\right\} - 4CR}{4(SF - 2DE)}\right)}{BW}$$

where: t_{TX} - data transmission time [s], SF - Spreading Factor [bit], BW - Bandwidth [Hz], DE - Data Rate Optimization [bit], CR - Coding Rate [bit], $max\{2SF;16\}$ - selects the larger value between 2 times the Spreading Factor (SF) and "16", Npy - user data amount in a frame, Npr - preamble length.

To establish the most reliable transmission, parameter values are selected to optimize interference resistance and extend range. For example, this may mean using higher SF values (e.g., SF=12), the maximum available bandwidth, and an increased coding rate (e.g., CR=4). Choosing these parameters ensures the highest possible transmission reliability, which is crucial in critical applications or challenging environmental conditions, at the cost of longer transmission times and higher energy consumption [26]. The following parameter values were selected to determine the most reliable LoRa transmission:

●Spreading Factor (SF): 12, the maximum value for LoRa, providing the greatest range and interference resilience but also extending transmission time.

●Coding Rate (CR): 4, which enhances transmission reliability by adding redundancy but also affects the transmission time.

●Data Rate Optimization (DE): 0, in LoRa technology, is a setting where '1' enables enhancements for reliable low-speed data transmission, and '0' disables them, optimizing for higher speeds.

●Bandwidth (BW): 125 kHz, a common value for many LoRa applications, offering a good balance between range and transmission speed.

● Payload (Npy): The data content carried by a LoRa frame, often encoded in a number of symbols. For instance, a payload might consist of sensor information and system data encoded within 4 symbols, depending on the transmission settings such as Spreading Factor (SF) and Coding Rate (CR).

● Preamble Length (Npr): Indicates the number of symbols used for the preamble, which is essential for receiver synchronization. An 8-symbol preamble length is an example value that might be chosen to balance transmission reliability with efficiency.

The estimated transmission time can be determined by substituting the above example values into formula (6), which calculates the duration based on the specified parameters :

$$(7) \quad t_{TX} = \frac{2^{12}\left(8 + \frac{4,25 + 4 + 8 + \max\left\{24;16\right\} - 16}{4 \cdot (12-1)}\right)}{125000} \approx 282 ms$$

Knowing the duration of the data frame, it's equally important to understand the current consumption of the radio transmitter. According to the datasheet of the LoRa module-Semtech SX1276 [27], the minimum current draw for the radio transmitter is 20mA ($I_{TX} = 20mA$) and it depends on varies with the chosen transmission power. Opting for the minimum transmission power to conserve battery life is advisable, especially since the reduced power output can be offset by employing antennas with directional gain.

$$(8) \quad Q_{TX} = I_{TX} \cdot t_{TX} \cdot N = 20mA \cdot 282ms \cdot 365 \approx 573\text{mAh}$$

where: t_{TX} - average LoRa message transmission time, I_{TX} - average current consumption during transmission, N - 365 days in the year.

Figure 3 shows how the current spikes when a transmission starts, and this increase is added on top of the usual current used in Idle Mode. This spike is short but shows how much extra energy is needed for sending data. To fully understand the system's energy use, we need to look at how much power the microcontroller (MCU), sensors, and LoRa module use when they're just waiting around, not doing much. These parts are the baseline, or the minimum, the system always needs to keep going. Knowing this helps figure out the total energy the system needs and how to manage it better.

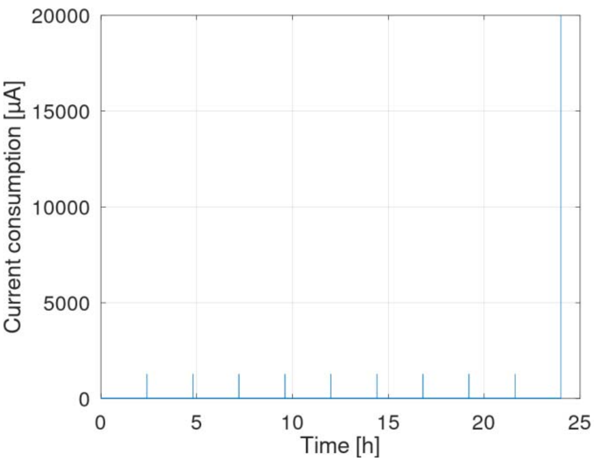

Fig. 3. Average Daily Current Draw of the LoRa Remote Measurement Station Under Analysis

●The LoRa module current consumption in hibernate mode is 1,5 μA ($I_{LoRa\_hib}=1{,}5\ \mu A$) [27].

●An ultra low power microcontroller selected for analysis is ADuCM4050, draws a minimal current of 0,78 μA ($I_{mcu\_hib}=0{,}78\ \mu A$) and 1,27 mA during active mode ($I_{mcu\_act}=1{,}27\ mA$) [28]. This current might be additionally reduced by several orders of magnitude through changing the clock source and its division using the PLL system [29].

●A temperature sensor- BME280 based on the datasheet [30] is assumed to have a hibernate mode current draw of 0,1 μA ($I_{sens\_hib}=0{,}1\ \mu A$) and 1μA in active mode ($I_{sens\_act}=1\ \mu A$). Another component of power consumption is the duration of active current draw by the sensor, which, based on the datasheet, is determined to be 11,5 ms ($T_{act}=11{,}5\ ms$).

By aggregating the power consumed during the active measurement phase with the quiescent power draw, a comprehensive view of the daily energy consumption has been acquired. Multiplying this daily usage by the number of days in a year yields the annual charge extracted from the battery, encompassing all operational states of the monitoring station. This evaluation is pivotal for ensuring that the power source selected can sustain the system's operations over the intended lifespan without the need for maintenance or battery replacement. The total annual charge drawn from the battery is described by the formula below:

(9) $$Q_{stan} = (N_{mes}\cdot(I_{act}\cdot T_{act}) + I_{hib}\cdot(T_{day} - N_{meas}\cdot T_{act}))N$$

where: I_{act} - average current draw during active mode (I_{mcu_act} + I_{sens_act}), T_{act} - operation time with higher power consumption, N_{mes} - daily number of measurements, I_{hib} - current draw in the sleep phase (I_{sens_hib} + I_{mcu_hib}+ I_{LoRa_hib}), T_{day} - 24h during the day, N - 365 days in the year.

By substituting the above values into formula (9), we obtain an annual battery charge consumption of 20,9 mAh ($Q_{stan}=20{,}9\ mAh$).

The total annual discharge from the selected energy storage, due to the continuous operation of the MCU, sensor, and the idle current of the LoRa module, is significantly lower than the discharge caused by the sporadic but more intense operation of the LoRa radio transmitter, even when the most energy-efficient transmission settings are used. The calculated discharge, closely approximates the battery's self-discharge rate, and is simultaneously almost two times greater than the self-discharge rate of the accumulator analysed for the purposes of this article. This observation underscores the importance of careful selection of the energy storage solution in remote sensing applications. It highlights the need for a balanced approach that considers not only the operational energy requirements but also the intrinsic self-discharge characteristics of the chosen power source. Such a strategy ensures long-term sustainability and reliability of remote monitoring systems, particularly in applications where maintenance opportunities are limited.

Hybrid Storage System Proposal

Considering the limitations of self-discharge phenomenon of rechargeable batteries in the analyzed load profile, the subsequent chapter introduces a system based on the Hybrid Energy Storage System combining the disposable battery with a supercapacitor. The supercapacitor serves as the component capable of capturing ambient energy, compensating for the Battery's incapability to recharge, and ensuring an energy efficient management in the system.

A general block diagram of the proposed Hybrid Energy Storage System is presented in Figure 4. To the general EH (Fig. 3), a selector and an energy storage monitoring System Integrated Circuit (IC) were added. The system is characterized by the exceptionally high number of charge and discharge cycles of the supercapacitor, the absence of parameter changes during prolonged periods of undercharging, and the ability to rapidly deliver and absorb energy. On the other hand, batteries are known for providing a relatively high energy density with minimal self-discharge, compensating for the significant self-discharge and limited energy density of the supercapacitor, factors that considerably limit its capabilities as a standalone storage in systems demanding high reliability and maintenance-free.

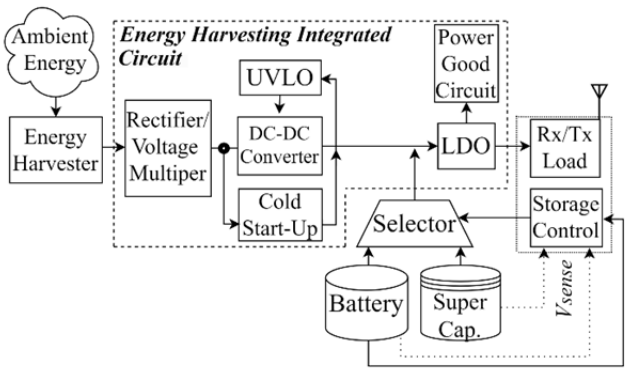

Fig. 4. Energy Harvesting System with proposed battery-supercapacitor HESS – block diagram.

There are various Integrated Circuit designs on the market dedicated to Energy Harvesting. From a storage management perspective, two IC architectures can be distinguished: single storage and multiple storage. Depending on the architecture the presented switching method takes a slightly different form. Both mechanisms are presented in Figure 5. Figure 5a illustrates the proposed switching method in the dual storage IC [31]. In this scenario there is only one single switch on the battery side. Based on the information from the V_{sense} feedback lines, the Storage Control circuit determines the state of the battery switch (*SWbat*). By turning off the switch a current consumption is then limited into the self discharge only. Supercapacitor is connected permanently into the dedicated line, in this case V_{store}, hence it doesn't require separate switch. The IC is capable of autonomously charging the supercapacitor and drawing current from it. Figure 5b presents the adaptation of the proposed method into a single storage IC [32]. In this scenario each storage needs to have separate switch. Like in Single Storage (Fig.5a) the Storage Control circuit based on feedback lines V_{sense} determines the state of the switches.

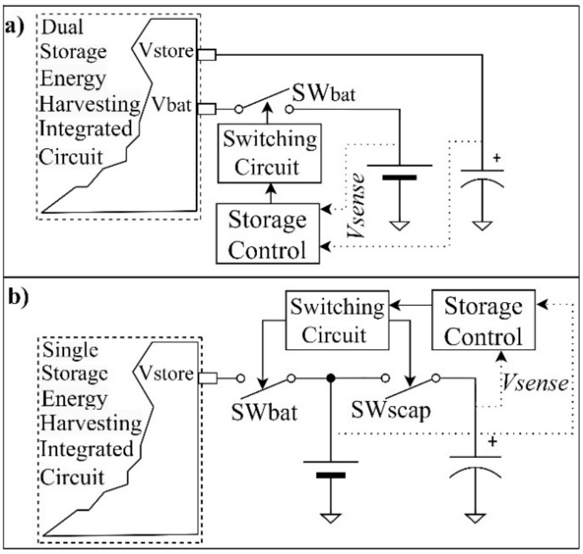

Fig. 5. Block diagram of proposed HESS implementation. a) Single Energy Storage IC. b) Dual Energy Storage IC.

The control algorithm for the proposed HESS implementation (Fig. 5) has been illustrated in the Figure 6. A continuous monitoring of the supercapacitor's voltage serves as a real-time indicator of its charge state. This measurement is crucial, as it informs the system's immediate energy dispensation demand. Foreseeing future energy requirements, especially with impending activations of power-intensive components such as the LoRa transmitter, is a pivotal feature of this algorithm. By predicting upcoming high-energy events, the system can judiciously choose to sustain the battery's reserve, even when the supercapacitor appears sufficiently charged. This precautionary measure ensures that the supercapacitor's quick discharge curve does not lead to abrupt power deficits during critical operations

Sequential switching is a critical aspect of this algorithm, ensuring uninterrupted power supply. Should the supercapacitor's voltage fall below a predefined threshold, the battery is connected first, thus securing an energy source before the supercapacitor is disconnected. This step is vital to avoid any instances where the system is left without power, however momentarily.

The algorithm takes a detailed approach to managing energy, not just by tracking the current charge but also by considering how the system behaves, like how the supercapacitor discharges and the expected patterns of energy use. This careful energy management boosts the system's stability and reliability, which is crucial for remote setups where fixing issues isn't easy, and keeping the system running smoothly is critical. Thanks to this smart energy control algorithm, remote sensing stations can work effectively for longer, making the most of both disposable batteries and supercapacitors to keep their monitoring going without breaks. This way, the algorithm ensures the system can handle varying energy needs and keeps it running reliably, even in hard-to-reach places.

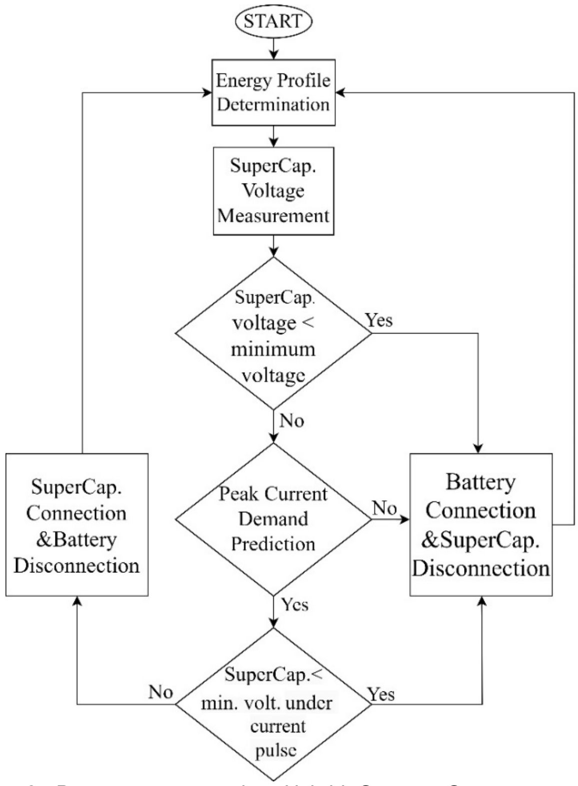

Fig. 6. Battery-supercapacitor Hybrid Storage System-operation algorithm

Conclusions

This article presents a new approach to Hybrid Energy Storage Systems (HESS) designed for remote monitoring stations of slowly changing phenomena, emphasizing the integration of disposable batteries with supercapacitors to create a maintenance-free, reliable power source. This system is particularly suited for areas where accessibility is limited, and the longevity of power sources is crucial. The core idea revolves around utilizing disposable batteries known for their low self-discharge rates, complemented by supercapacitors for their ability to quickly charge and discharge, catering to sudden spikes in energy demand.

The proposed HESS addresses the challenge of energy management in remote locations by ensuring a continuous and stable power supply, even under varying environmental conditions. The conceptual framework outlines an intelligent algorithm that dynamically switches between the supercapacitor and the battery based on the real-time energy needs and the supercapacitor's charge state. This approach not only safeguards the system against power interruptions but also optimizes the energy utilization by predicting future demands, especially during high-consumption activities like data transmission. By carefully balancing the advantages of both storage types, the HESS aims to extend the operational lifespan of remote stations, reducing the need for frequent maintenance visits.

A practical application of the proposed solution is reserved for future work, which includes the selection of low-loss MOSFETs as *SWbat* and *SWscap* switches.

Moreover, methods related to switching in capacitive load scenarios are currently under practical implementation.

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