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Sustainable IoT Systems Enabled by Supercapacitor Integration

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ABSTRACT

The rapid expansion of self-powered IOT systems has demanded sustainable power sources for the sensor networks. The IOT system uses different batteries which have some limitations such as lower lifespan, needs replacement with time and environmental issues. Energy harvesting systems use the different power sources like solar energy, mechanical, thermal to convert it into electrical power. However, the low power natures of these sources necessitates better energy sources with the high energy density and low environmental impact.

This chapter represents the energy harvesting systems for the Internet of things with the integration of supercapacitors. Supercapacitors are the energy storage devices which act as the replacement of batteries and have advantages such as high power density, longer lifetime, rapid charging-discharging capabilities that serve as efficient energy devices for the self-powered IOT systems. Furthermore, the chapter also analyses the current challenges of complexity of integration of energy sources, low energy efficiency and low power sources. The chapter concludes by the future research scope for the self-powered sustainable and low cost IOT systems.

1. Introduction

The Internet of Things (IoT) links computing devices, machines, everyday objects, living beings, and uniquely identified individuals into a shared network, enabling them to exchange data without direct human involvement or continuous human–computer interaction[1]. This interconnected communication framework adds considerable value to modern life by considering automating tasks also with improved efficiency, and enabling smarter decision making processes. IoT empowers devices, computing systems and it enables the transmission of information across networks without relying on human and machine input[2]. The first stage of IoT consists of sensors, smart devices, actuators and other components which collect data from the environment and then send it to other network systems. The second layer involves network gateways and data acquisition systems. These systems collect the signals from the sensors and convert them into analog signals to digital signals. These systems also perform tasks like malware detection and basic data management. The third stage of the IoT architecture is particularly critical and at this level, the first step is to pre-process the data according to its types and structure, after that it is routed to appropriate data centres[3]. This is because edge computing becomes important, as it allows processing and reduces the need to move all information to distant closers. The fourth layer consists of cloud environments and data centers, for applications such as agriculture, defense, healthcare, and others consume and analyze the data. IoT devices often handle many sensitive and personal and operational information also security purposes can lead to privacy breaches[3]. Robust security measures must be implemented such as strong encryption, secure authentication methods, and regular software updates which are very essential for protecting user data and preserving trust in IoT systems. At the same time, IoT ecosystems can grow more rapidly when more devices will be added and the major challenge to maintain scalability of systems[4]. Designing architectures is crucial for sustainable growth that can efficiently manage large numbers of devices, diverse data streams, and numerous access points. Enabling technologies have

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main components that support core IoT functions such as sensing, connectivity, data processing, and intelligent decision-making. Radio Frequency Identification (RFID) and Near Field Communication (NFC) enable automatic identification of objects and short-range wireless data transfer, which helps IoT systems that recognize the supportive items and make contactless interactions with the system. Embedded systems have some specialized computing units that are built with IoT devices which control sensors and actuators also process the collected data, and manage communication with other devices or platforms[1]. Wireless sensor networks consist of many sensor nodes that communicate via wireless links to gather and transmit data to other systems. These networks are widely used for monitoring various conditions in smart cities, agriculture areas, and industrial regions[5]. Cloud computing provides storage and processing resources for handling massive volumes of IoT data, whereas Big Data technologies support analysis, indexing, and managing these datasets[6]. Edge and fog computing parts can distribute processing closer to the source devices rather than sending all data to the centralized cloud servers[6]. This approach reduces the latency, improves real-time response, and lowers network bandwidth usage. In this context, we present a comprehensive overview of advances and enhancements in IoT systems in relation to the development of supercapacitor (SC) materials.

This chapter is structured as follows: First, the basic concepts of IoT are introduced. Next, different classes of supercapacitors are discussed, including electric double-layer capacitors (EDLCs) based on carbon, pseudocapacitive supercapacitors, and hybrid devices. Then, key performance metrics are examined and compared with those of conventional batteries. After that, the materials are required to fabricate a supercapacitor with the components electrode and electrolyte. Finally, the main challenges, integration strategies, performance parameters, and optimization approaches are summarized, along with key conclusions and general directions for future research.

2. Fundamentals of IoT Power Systems

IoT features are frequently described by the different components of the Internet of Objects (IoO) which are described here.

2.1 Interconnection

A core aspect of IoT infrastructure is connectivity. IoT devices must stay consistently connected to the network so that communication remains uninterrupted. Users and systems should be able to connect at any time and from any location which ensures the continuous interaction within the ecosystem[7].

2.2 Compatible Communication Protocols

Seamless and interoperable communication is a fundamental characteristic of the Internet of Things. As the IoT system grows the devices are becoming more tightly interconnected than ever before, which is one of the defining traits of IoT. This capability ensures that communication between the devices occurs more smoothly and efficiently. These devices connect to the internet using cloud-based services, which facilitates data exchange across different platforms. Integration enables continuous, reliable interaction between IoT gadgets and systems[8].

2.3 Identity of Objects

Identity is a key characteristic for people and objects. Just as every person has a unique identity, every connected device can be assigned a distinct identifier. For instance, each smartphone has a unique IMEI number, and most smart devices are labelled with individual identifiers. Such unique markings make it easier to recognize and manage devices and individuals over the internet. As a result, object identity is considered one of the most critical features of IoT[9].

2.4 Expansion Capability

Scalability has become a more important feature in IoT system design with an increase in the number of connected devices. In technical terms, scalability refers to a system ability to grow in size or capacity without degrading its performance[10]. By leveraging IoT's scalable architecture, organizations can adjust their systems to meet operational needs. For example, hotels can use IoT to monitor room occupancy and the usage of amenities by different guests in real time.

2.5 Dynamic or Self-Adjusting Behaviour

The dynamic or self-adapting nature of IoT is another essential feature. IoT systems must be able to respond autonomously for environment changes and evolving requirements. For example, early cameras were designed mainly to capture still images[11]. Modern cameras, however, automatically adjust image settings based on lighting conditions, demonstrating how IoT enabled systems can self-adapt to improve performance.

3. Fundamentals of Supercapacitors

3.1 Storage Mechanisms

To store electrical energy, capacitors accumulate charge on two parallel electrodes separated by a separator referred to as dielectric substance. Capacitor capacity is the amount of charge stored for each unit of voltage applied to its plates. The connection between charge (q) and voltage (V) defines if a capacitor exhibits resistance or inductance between the plates. This relationship is represented in Equation (1), where V denotes the voltage across the capacitor, C represents the value of the capacitor in Farads (F), and q indicates the charge held within the capacitor. The value of capacitance of a capacitor can be calculated using Eq.2, which depends on the dielectric permittivity, the effective area of the electrodes in device A, and the distance d between the capacitor electrodes.

Equation (3) allows for calculating the energy held in a capacitor, which is influenced by the capacitance of the device and the terminal voltage.

Where V represents the voltage at the capacitor terminals, C denotes the capacitance of the capacitor, and E indicates the energy stored within the capacitor

$$Q=CV \quad \ldots\ldots\ldots\ldots\ldots(1)$$

$$C=\varepsilon A/d \quad \ldots\ldots\ldots\ldots\ldots(2)$$

$$E=1/2CV^2 \quad \ldots\ldots\ldots\ldots\ldots(3)$$

3.2 Types of Supercapacitors

3.2.1 Electric Double-Layer Capacitors (EDLCs)

Supercapacitors are typically composed of two electrodes, an electrolyte, and a separator that helps to prevent short circuits. The electric double layer (EDL) formed at the electrode and electrolyte interface which is considered as the primary source of capacitance in electrochemical supercapacitors[13].

The electrochemical double-layer concept provides the information regarding the electrochemical behaviour at these interfaces. It describes the procedure when an electrode is in contact with the electrolyte during charging, where charge separation occurs. The capacitance is strongly influenced by the electrode surface area in contact with the electrolyte, with larger surface areas that enables much higher capacitance values.

Helmholtz was the first scientist to describe charge separation at the interface of electrolyte and electrode. They suggested that charges can accumulate on the electrode surfaces, leading to the formation of two closely spaced layers of opposite polarity. Unlike the simple view of non-specific adsorption, this model allows for ion adsorption directly on the electrode surface. According to Helmholtz, the EDL stores charge through electrostatic attraction, similar to a molecular-scale dielectric[13].

Building on Helmholtz's idea, the Gouy–Chapman model (1910) proposed that capacitance depends on the applied voltage and the ion concentration in the electrolyte. In this model, the electric field weakens as it extends into the electrolyte, and a double layer of oppositely charged ions forms at the boundary between the electrode and the electrolyte due to Coulombic forces[14]. This double layer acts as an effective barrier that traps charge within the storage system. The total charge on the electrode surface is then determined by both the double-layer capacitance and the applied voltage. The development of electrochemical supercapacitors is largely based on the electric double-layer capacitor (EDLC) concept[15].

3.2.2 Pseudocapacitors

The term "pseudocapacitive" originates from a Greek word meaning "to hold" or "to retain." In this type of supercapacitor, charge storage arises from faradaic processes, such as redox reactions occurring at the electrode–electrolyte interface. These reversible electrochemical reactions allow pseudocapacitors to store more charge than EDLCs.

Compared with EDLCs, pseudocapacitors generally offer higher energy density and better charge storage capacity, but at the cost of lower power density. Materials commonly used in pseudocapacitive systems include transition metal oxides, layered hydroxides, metal sulfides, and certain conducting polymers. Despite their superior performance, pseudocapacitors remain in relatively early stages of commercialization, partly because of the limited variety of suitable electrode materials. So far, ruthenium-based materials have shown the best results, but their high production cost makes widespread use impractical[16].

3.2.3 Hybrid Supercapacitors

Hybrid supercapacitors are designed to combine the advantages of different storage mechanisms. They exhibit significantly higher energy density than conventional EDLCs and behave more like battery-type devices, while still retaining some capacitor-like characteristics. This category includes systems that integrate features of both EDLCs and pseudocapacitors, often using an asymmetric configuration[17].

In hybrid designs, the energy is stored through a combination of electrostatic and faradaic processes, which improves overall performance. However, the slower electrochemical reactions at the electrode surface can limit power delivery and long-term stability, even though energy density is higher. Compared with traditional supercapacitors and batteries, hybrid systems often show better electrochemical performance in terms of both energy and power density. Common electrode materials for hybrid supercapacitors include carbon-based structures, metal oxides, metal vanadates, and other composite materials[18].

3.3 Key Performance Parameters and Comparison with Conventional Batteries

Balancing the use of renewable energy sources while preventing their over consumption is one of the most pressing challenges today. Among renewable technologies, solar and wind power are the two dominant sources. Supercapacitors (SCs) offer several advantages over conventional batteries, including high power density, good performance at low temperatures, excellent cycling durability, and fast charging capabilities. However, because SCs typically consist of many individual capacitors connected in parallel, their charge and discharge rates are relatively slower compared to ideal expectations. These limitations, along with their generally lower capacity, restrict the practical use of SCs in many consumer electronics applications[19].

Electrical energy storage systems that can endure a very high number of cycles (often exceeding 1,000,000) include traditional batteries, advanced batteries, and supercapacitors. These devices are generally low-cost and require minimal maintenance. Supercapacitors were first commercialized by Nippon Electric Company, while ultracapacitors were developed by the Pinnacle Research Institute. The first patent for such technology was filed by General Electric in 1957.

TABLE 1
Key characteristics of supercapacitors and batteries

Parameters	Supercapacitor	Battery
Energy density	Low	high
Power density	high	Low
Charge-discharge cycle	10^5-10^6	500-1000
Self-discharge	Days to weeks	Months

Lifetime	5-10 years	3-5 Years
Cell potential	1.2-3.8V	2.5 to 4.2 V

Recent studies have shown that supercapacitors can achieve high specific capacitance and favorable energy density. They are also lightweight, compact, and relatively expensive compared to some alternatives. Their excellent performance and nearly flat charging profile, supercapacitors are considered promising candidates to partially replace batteries in certain applications. They can be charged more quickly and offer superior cycle stability when compared with fuel cells and alkaline batteries[20]. Key characteristics of supercapacitors and batteries are summarized in Table 1.

According to Musolino, the supercapacitor has a high power density but a low energy density[21].

4. Materials and Technological Advances

4.1 Electrode Materials

One of the important parts of a supercapacitor is the electrode. When we build a supercapacitor we use electrodes made of metal. The capacitance of these electrodes is different depending on the materials we use. Now scientists are studying supercapacitors and they found that electrodes made of cobalt hydroxide have very high capacitance. We use cobalt-based metal oxides and hydroxides to make electrodes for supercapacitors because they have good electrical conductivity. These materials are very stable and are considered to be useful. Cobalt-based metal hydroxides and oxides are great for making supercapacitor electrodes because they conduct electricity well and are not very reactive. Compared to materials like nickel hydroxides, aluminum hydroxides and copper hydroxides, cobalt-based metal oxides and hydroxides are better because they have higher energy and capacity ratios[22].

4.2 Electrolytes for Supercapacitors

We usually use electrolytes in commercial supercapacitors but they have some limitations. These electrolytes are ammonium salts and they have high electrochemical potential. This means they are slightly alkaline. The voltage at which these electrolytes dissociate is very high over 2.5V. The electrolyte controls the movement of electrons in the supercapacitor. We have types of electrolytes like organic, aqueous and organometallic electrolytes. Ionic electrolytes are usually the ones that dissociate in water. They have cations and anions of sizes. Organic electrolytes can also have multivalent cations. These electrolytes are very good because they have energy density, conductivity and electrochemical stability[23].

4.3 Separator

The separator is an important part of the supercapacitor. It separates the hydrogel and removes the electrolyte from the electrode material. We need high-performance separators for supercapacitors that work at voltage, high voltage and high temperature. We can use ceramic, paper or glass fiber separators. The type of separator we use depends on the application. We can test the performance of the separator using methods like calorimetry, capacity measurement and eddy current analysis. The separator is like an electrode separation cell that uses solid separators to separate ions based on how well they conduct electricity[24].

5. Integration of Supercapacitors in IoT Systems

Nowadays energy harvesting technologies are becoming very popular. They need an energy storage device to deal with their limited power and intermittent characteristics. We can use batteries. They have limited cycle life and that is not good because replacing them is expensive. Supercapacitors are becoming popular because they provide a lot of power for data transfer and they have a long cycle life. But supercapacitors have a limitation. They take up a lot of space on printed circuit boards[25].

5.1 IOT and Energy harvesting

The term "Internet of Things" or IoT is becoming very popular. It refers to a network of connected physical things. IoT is like a network of objects that can be addressed uniquely. They communicate using standard protocols. We can imagine new applications like health monitoring, smart homes, logistics and industrial manufacturing. All these applications have one thing in common. They are all very energy-constrained. This is a problem for power components and power management techniques. Current battery technology is not good enough for IoT devices because they need to be small and have a long lifetime. Energy harvesting is one solution. We can use energy sources like thermal, solar, vibration and radiofrequency to charge an energy storage device like a battery or supercapacitor. This can help extend the lifetime of IoT devices and even make them work independently[26].

Current uses, for Wireless Sensor Networks include fields. We can use panels, piezoresistors or RF rectifiers to convert environmental energy into electric energy.

5.2 Integrating Supercapacitors as a power supply

Power sources pose many challenges to specific biomedical applications. Biomedical sensors generally incorporate batteries, which grant the circuit a self-contained, closed, and sealed structure. Their short lifespan, long charging times, and high toxicity make them less desirable for future applications [8]. Recent advances in supercapacitors (supercap) have unlocked different opportunities for powering biomedical devices. Although supercapacitors have a low energy density, they have a very fast charging time and virtually unlimited shelf life without the toxic heavy metals. Supercapacitors have a very high power density and are easy to use and integrate in Uninterruptible Power Supply (UPS) Systems[27]. Supercapacitors have been used in Uninterruptible Power Supplies to provide and maintain a constant power supply to electronic devices, for instance, computers, televisions, printers, scanners, and so on. The company requires that all offices, shops and enterprises are operational all the time, that is, seven days a week on twenty four hours a day basis in order to serve the customer well.

6. Challenges and Limitations

Typically, applications that fall under the Internet of Things (IoT) will involve many component systems. As such, the cloud or fog will build a number of the IoT application components. Components that provide the end users access to the IoT systems will typically be built as a separate web, mobile, or desktop application. On the other hand, data collection and real-time data analysis features will be built into the IoT devices. Furthermore, IoT applications can be located in different and quite large geographical locations. The conventional method that centralizes all the software components for a single system may be insufficient to address the distribution of the applications. In addition, it is often very difficult to design and implement a distributed system that can operate in a coordinated manner with decentralized components.

When multiple IoT applications use services from real world objects, an interdependency problem can arise. Take the example of two IoT applications operating simultaneously in a home: a health-care application that monitors residents' vital signs, and an energy management application that optimizes the energy consumption of home appliances[28]. These applications use data from the home's sensors to implement the application in a cost effective manner and to limit channel contention. However, integrating the two applications is complicated since each application will have its own assumptions of the world, and each will typically lack awareness of the other application. For example, the home health-care application may decide to turn on all the lights when it detects that a resident is in a state of depression[29].

As IoT applications are embedded into daily life, including some applications in critical contexts where there's little tolerance for errors, it is essential to evaluate the overall quality of the system. It needs to be carefully evaluated before deploying to ensure that it is high quality. One of the main issues in evaluating quality is that performance is contingent on the performance of many elements as well as the performance of the underlying technology. This makes assessing quality criteria like performance a great challenge[30].

7. Conclusion and Future perspective

This chapter deals with the integration of supercapacitors in IoT systems. Supercapacitors store electricity in a system. Compared to batteries, supercapacitors are superior in having longer life and better charge-discharge cycling. IoT system frameworks are being used in numerous areas including healthcare, transportation, and agriculture. This chapter discusses the significance of energy harvesting in IoT systems and the quality of energy sources available to IoT systems. Following this, the IoT frameworks are described, and the challenges and optimizations are discussed.

It then focuses on the obstacles to the development of IoT applications and analyzes existing IoT frameworks specially targeted to IoT application development and their advantages and disadvantages. Based on this analysis, a large number of development frameworks have been introduced for the purpose of aiding the development of IoT applications, with most of these frameworks being in the early stages of development and having different structures, yet many frameworks have been created. The majority of these frameworks focus on the rapid development of IoT applications with little to no focus on the resulting application quality. Therefore, to develop high-quality IoT applications, development frameworks of this nature must incorporate quality assurance control. In addition, new heterogeneous devices and technologies will need to be integrated into these systems and dynamically configured.

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