Journal of Research in Engineering and Applied Sciences

APPLICATIONS AND ASPECTS OF SUPERCAPACITOR IN IOT DEVICES AS A SUSTAINABLE ENERGY SOURCE

[1,2]Sajid Naeem, [1]AV Patil, [1]UP Shinde, [2]Abid Ali, [2]Khalid Memon and [2]Mohammed Bavluwala

[1]*MGV's LVH Research Center, ASCC Panchavati, Nashik - 422001 (Maharashtra) India*

[2]Department of Applied Sciences, Maulana Mukhtar Ahmad Nadvi Technical Campus, Malegaon – 423203, India

[1,2]Affiliated to Savitribai Phule Pune University, Pune- 411001 (Maharashtra) India

Email: {sjidnaeem@mmantc.edu.in, sne.sajid@gmail.com}

Abstract

Today, the Internet of Things (IoT) is an emerging field of recent technologies. Every field of engineering, technology, and real-time management has IoT applications such as transportation, agriculture, healthcare, manufacturing, wearable, smart grid and energy saving, smart home, smart management systems, etc. Also, AI has captured wide-area applications in the automobile industry, surveillance, security, education, entertainment, gaming, e-commerce, portable devices, robotics, biomedical instruments, etc. Electrical and electronic devices are used in IoT-based applications. They are required efficient energy to operate for a long time effectively. These types of devices required offline and online energy storage devices that charge on time or require less recharge. The supercapacitor has a high capacitor, rapid charging/discharging cyclic rate, cost-effective and eco-friendly. Our objectives are to study supercapacitors for providing energy and power supply backup to IoT devices. Electronic devices mainly operate on dc signals and electrical instruments work on signals. The supercapacitor plays an important role to supply energy which stores an extremely large amount of electrical charge. It is the future of batteries and replaces the old bulk batteries with tiny high-performance flexible sustainable supercapacitors.

Keywords: Advanced Energy Storage, Sustainability, Internet of Things (IoT), Supercapacitors, etc.

1. Introduction

Supercapacitors are demanding in the market due to their distinct characteristics such as high specific capacitance, high performance, high-power density, high energy density, good reversibility, good cyclic stability, and great lifespan. Supercaps (Supercapacitors /SC) are categorized into two types electrochemical double-layer capacitors (EDLC) and pseudocapacitors [1]. Further, it is also classified according to applications, manufacturing, and based on materials. The electrolyte solutions are used to develop electrodes having a hydrophobic surface. The effect of ionic species is associated with surface chemistry [2]. The surface morphology of the electrode is investigated for the electrochemical performance of the electrode [3]. Supercaps are the new approach to energy conversion from chemical to electrical and vice versa. SC has the potential to be used as an alternative to batteries, which are under constant development but still have a limited range of applications [4]. Supercapacitors could be a much better solution in many cases. Batteries store electrochemical energy by reversible chemical reactions of active masses, satisfying only a small part of the demand. Electrochemical batteries typically have a maximum charge/discharge cycle life of 400-500 cycles in some cases [5, 6]. The reason is that energy is lost due to heating during each cycle, limiting the battery cyclability to several hundred cycles for some batteries by convention [7]. The supercapacitor has about 95% efficiency to exhibit charge/discharge operation, because the heat loss from internal structures during each cycle is negligible in comparison with discharge and recharge time, which only lasts for several seconds or minutes (for short-circuit applications) or seconds or hours (for open circuit applications) [8]. The Internet of things is something new, which is a network of physical objects embedded with software that uses the internet as a medium to communicate [9]. It is said that there are two types of IoT: remote-controlled and autonomous [10]. The remote-controlled type of IoT requires human intervention when the IoT does not function correctly, whereas the autonomous type can control itself and perform based on preprogrammed rules [11, 12]. The IoT (Internet of Things) term is used for a physical network connected to the internet, software, sensors, actuators, and external peripherals [13]. The communication network is formed by physical objects [14]. The Internet is becoming more complex and dynamic all the time, thus driving changes and technological development, which leads to new opportunities for businesses and consumers [15]. There are a ton of devices out there that are connected to the internet, and this number is only going to grow [16]. Statistical data reflecting the use of IoT over 7 billion devices are connected and will reach 22 billion by 2025 according to a Rangers report. IoT plays important role in our lives in communication between humans and machines [17]. In the world of IoT, quantum and nanotechnology have significant applications. These technologies have already changed our lives for good in many ways. These two technologies are considered to be the next big things when it comes to the future of the Internet and technology [18]. The recent application of IoT (Internet of Things), AI (Artificial Intelligence), and ML (machine learning) are fascinating to healthcare centers and biomedical instrumentation [19]. This is mainly due to their enhanced capabilities in prediction, pattern recognition, and diagnostic analysis [20]. In healthcare, IoT-based patient monitoring and diagnostic processes are implemented. It improves the functioning of healthcare organizations to provide quality services at a low-cost and rapidly [21, 22]. Electronics and telecommunication technology are rapidly updating due to IoT and AI. Smartphones and smart devices use different types of smart sensors for AI applications [23, 24, 25].

The main purpose of this paper is to analyze both the concept and key features of sustainable energy resources for the Internet of things and Artificial Intelligence devices, introduce their potential application areas, and the impact on human life. The Internet of Things and Artificial Intelligence technologies are increasingly becoming accessible so their use is expanding within the market. The Internet of Things (IoT) technology is developing very fast. It will replace traditional power supplies and other electrical equipment, thereby increasing the demand for sustainable energy resources. This paper discusses the origin, concept, and potential application areas of sustainable energy resources in IoT systems. Energy consumption is a key factor for Internet of Things (IoT) development. To fulfill the energy requirements for IoT devices, different research works are being carried out in recent years on the topics of energy management and power backup. The internet would be compromised if the power supply cannot be guaranteed. Therefore, to ensure effective operation, it is necessary to establish an effective energy management system.

2. Supercapacitor technology

Capacitors store electrical energy by accumulating charge on two parallel electrodes separated by a dielectric material. The capacity is the amount of charge stored in a capacitor per unit voltage applied across its plates [1,2]. The relationship between the charge (q) and voltage (V) determines whether a capacitor has either an inductance or a resistance, which would have other, potentially confusing effects. This relationship is described by equation (1), where q represents the charge stored in the capacitor, C is the capacitor value in Farads (f), and V is the capacitor voltage. The capacitance value of a capacitor is given by the dielectric permittivity ε, the distance d separating the capacitor electrodes, and the effective area of the electrodes constituting the device A, and it can be calculated using equation (2). The energy stored in a capacitor is a function of the capacitance value of the device and its terminal voltage; it can be calculated using equation (3). Where E is the energy stored in the capacitor, C is the capacitor capacitance value, and V is the capacitor terminal voltage [3,4,5].

$$q = CV \quad (1)$$

$$C = \varepsilon \frac{A}{d} \quad (2)$$

$$C = \frac{1}{2} CV^2 \quad (3)$$

A conventional dc capacitor is often used in a power circuit as an energy storage device. Capacitor technology is upgrading towards high electrical energy storage devices like supercapacitors. It has high capacity and low ESR (Equivalent Series Resistance) compared with old capacitors [6,7]. The structure of both capacitors and supercapacitors are slightly different in electrode and electrolyte. Equation (2) and equation (3) is used to measure the capacitance [8, 9,10].

2.1 Supercapacitor basic cell structure

The basic structure of the supercapacitor cell consists of three important elements such as 2 electrodes, one separator, and electrolyte material. The electrodes are made of different conducting materials like metal oxide, metal hydroxide, cobalt, etc [11]. The conducting electrodes have high surface areas and are separated by a membrane. EDLC type capacitor has high capacitance and high surface area as shown in Figure 1. It is describing the basic cell structure of a supercapacitor consisting of charged electrodes separated by a separator [12].

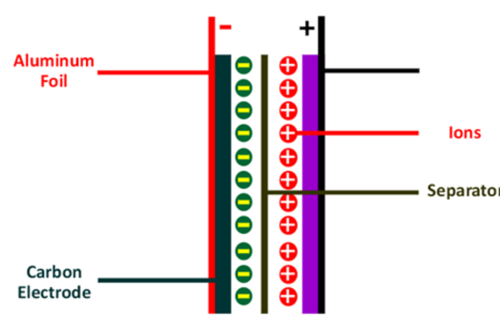

Figure 1 Double Layer Supercapacitor Cell

2.3 Electrode, Electrolyte, and Separator

2.3.1 Electrode

An electrode is a very important functional element of a supercapacitor. Various metallic electrodes are used in construction and the specific capacitance is varying depending on the materials. The cobalt hydroxide electrode is produced high specific capacitance according to recent research in the supercapacitor field [13]. Cobalt-based metal oxides and hydroxides provide high-capacitance electrodes for supercapacitors. Metal hydroxides combine high electrical conductivity and excellent stability over time. Cobalt-based metal oxides and hydroxides are used to prepare the electrodes for supercapacitors. Their high electrical conductivity and low chemical reactivity in supercapacitor applications make this an incredibly popular choice for electrodes. It offers higher energy and better capacity ratio are generally obtained with cobalt-based metal oxides or hydroxides than those with other materials, such as aluminum and copper hydroxides, nickel hydroxides, etc [14, 15].

2.3.2 Electrolytes

Traditional electrolytes are quaternary ammonium salts that produce a high electrochemical potential (pH) and, consequently, slightly alkaline solutions that limit their use in most commercial formulations. Organic electrolytes have a dissociation voltage (more than 2.5V) [16]. The electrolyte is responsible to migrate the charges (electrons) in the aqueous, organic dissociation, and organometallic type solution [17]. The dissociation of organic, aqueous, and organometallic electrolytes is all caused by the migration of electrons. Electrolytes which dissociate in an aqueous solution will generally be ionic, including cations and anions of various sizes that can easily form cations and anions in water [18]. Organic electrolytes may also contain multivalent cations, including those with tetravalent properties. Salt like organic electrolyte is hard to dissolve molecules and form inter-species in the solution. The organic electrolyte has a higher energy density, higher conductivity, and similar electrochemical stability [19, 20].

2.3.3 Separator

Separators are the most important element of EDLCs. They remove the electrolyte and carry out the economical separation of the hydrogel [21]. Therefore, the separator is a significant portion of the entire structure. The high-performance separators have applications in low-voltage (1–10 V), high-voltage (above 100 V), and high-temperature supercapacitors. The separator can be made of paper, glass fiber, or ceramic [22]. Depending on the application it is required to obtain the optimum efficiency level. The performance of separators can be evaluated through several tests such as calorimetry, capacity measurement, or eddy current investigation [23]. An EDLC is a solid-electrode separation cell that uses solid separators to separate ions based on their ability to conduct electricity [24, 25].

2.4 Taxonomy of Supercapacitors

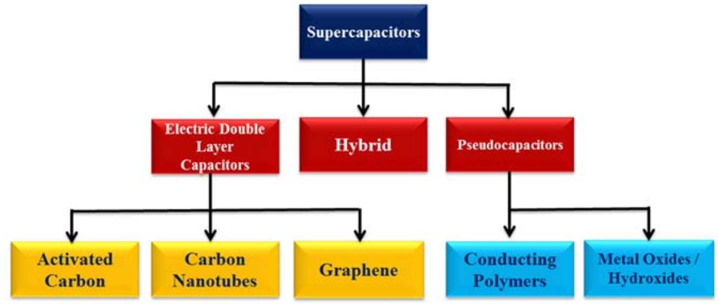

Figure 2 Taxonomy of supercapacitors (Self-made)

Supercapacitors are categorized into three types EDLC, Hybridge, and Pseudo capacitors as shown in Figure 2 Supercapacitors are differentiated according to materials, manufacturing, electrodes, and their applications [26]. EDLC has three types Activated Carbon, Carbon Nanotubes, and Graphene based supercapacitors. Other side, pseudo capacitors are two types of conducting polymers and metal oxide / hydroxide-based supercapacitors for the advanced energy storage device [27, 28]. The fundamentals of capacitors are shown in Figure 3 such as Electrostatic Capacitor, Electrolyte Capacitor, and Electrical Double-Layer Capacitors.

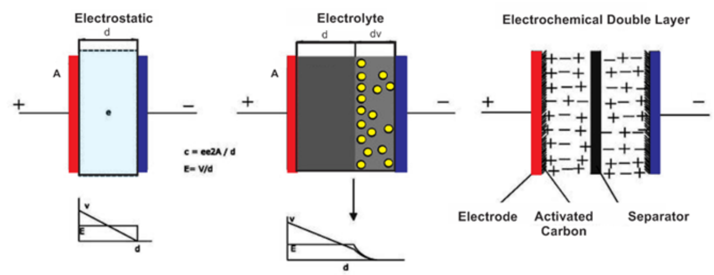

Figure 3 Schematic of Electrostatic capacitor, Electrolytic capacitor, and Electrical double-layered capacitor (Self-made)

3. Electrochemical deposition technique

Supercapacitors can be important to sustainable energy storage in various electronic devices. Supercapacitors' development has been characterized by rapid progress over the last decade, and consequently, many new materials are introduced [1-5]. The supercapacitor is one of the most innovative energy storage alternatives in the world today, currently attracting significant interest from industry and academia alike. Supercaps are a novel type of electrochemical and electrical energy-saving device. They provide fast charge discharge, have an energy density higher than batteries, and can be used to charge small electronic devices [6,7]. $Co(OH)_2$ thin films have been investigated and studied for electrode fabrication and their applications in advanced electrical energy storage devices called supercapacitors. We have successfully studied the electrochemical deposition of 0.1M compound $CoCl_2$ and $Co(NO_3)_2$ on stainless steel (SS) substrates in double-distilled water at room temperature. In addition, electrochemical characteristics of cobalt hydroxide thin films were investigated to predict their application in sustainable energy conversion and storage, such as supercapacitors. It is known that the stabilities of supercapacitor parameters such as electrolyte capacitance, electrode materials, structural properties, and thicknesses. Electrochemical studies on these parameters are necessary for designing attractive and efficient supercapacitor devices.

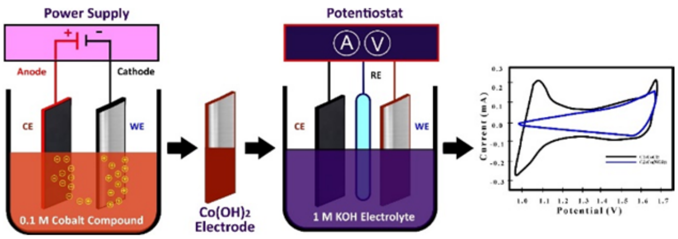

Figure 4 Electrochemical deposition to prepare Co(OH)2 thin film onto stainless steel (SS) substrate

4. Advanced energy storage devices

Nowadays, the most challenging is to sustain renewable energy sources and control on increase in utilization. Solar and wind energy are the primary sources of renewable energy [15]. SCs offer many advantages over batteries such as high energy density, superior energy density at low temperatures, excellent cycling durability, and fast charge rates [16]. However, since they are based on many thousands of individual capacitors stacked in parallel, SCs suffer from relatively slow charge/discharge rates [17]. These factors restrict the practical application of SCs in consumer electronics applications due to their comparatively low capacity [18]. Electrical energy storage like batteries, advanced batteries, and supercapacitors offer a high cyclic rate and lifespan (>1,000,000 cycles). These types of energy storage devices have low maintenance and are cost-effective [19]. The supercapacitor is manufactured by Nippon Electric Company and Ultracapacitor is manufactured by Pinnacle Research Institute where the first patent was filed by General Electric in the year 1957 [20]. Recently, supercapacitors are demonstrated to have high specific capacitance and high energy density. It is small in size, lighter in weight, and expensive [21]. Their performance is further enhanced by a smooth charging curve, making supercapacitors a promising alternative to batteries. Compared to alkaline batteries and fuel cells, the supercapacitor has excellent cycling stability and can charge faster than batteries or fuel cells [22].

Table 1 lists the main differences between battery and supercapacitor technologies and describes how each type of device can be used to store electrical energy [31]. A supercapacitor is an electrochemical device that stores power. Supercapacitors may be used as battery replacements because they do not face rate limitations. They have superior cycling stability while offering a higher energy density compared to batteries [32].

No	Devices	Voltage Range (V)	Capacitance (F)	Company	Country
1	BestCap	3.50-12.0	0.022-0.56	AVX	USA
2	BoostCap	2.5	1.60-2600	Maxwell	USA
9	Capacitor modules	12.0-52.0	100-8000	ESMA	Russia
11	Capattery	5.50-11.0	0.01-1.50	Evans	USA
5	Dynacap	2.50-6.80	0.033-100	ELNA	USA
4	EDLC	2.7	10.0-5000	NessCap	South Korea
3	GoldCap	2.30-5.50	0.10-2000	Panasonic	Japan
12	Kapower	12	1000	Kold Ban	USA
8	PowerStor	2.50-5.00	0.470-50.0	Copper	USA
6	Supercapacitor	3.50-12.	0 0.01-6.50	NEC	Japan
7	Supercapacitor	2.25-4.50	0.090-2.80	Cap-XX	Australia
10	Ultracapacitor	2.30-2.50	5.00-5000	EPCOS	USA

Table 1 List of Supercapacitor Manufacturers [32]

No	Parameters	Supercapacitor	Battery
1	Energy density	Low	High
2	Power density	High	Low
3	Charge-discharge Cycle	10^5-10^6	500-1000
4	Self-discharge	Days to Week	Months
5	Lifetime	5-10 years	3-5 years
6	Cell Potential	1.2-3.8V	2.5-4.2V

Table 1 General comparison between supercapacitor and battery [35]

Table 2 shows the important parameters of the supercapacitor and battery. The supercapacitor has high power density while the batter has low energy density [35].

5. Roles of supercapacitor in power resources and backup

Supercapacitors are a safe, reliable, and durable energy source. They can be used to power devices like sensors, water pumps, batteries, medical equipment, crop cultivation, and more. Following are several examples of Sc applications in various domains.

5.1 Real-Time Clocks (RTC)

A real-time clock is a device that keeps track of time and date, in addition to the correct date, time, and day. Generally, the RTC is on-chip or part of a chip with the processor. It may be used for various functions including timing, system control, and calibration of other systems for proper functioning. Batteries are a common feature of many electronic devices. Temporarily removing or replacing a battery can cause the device to lose power, resulting in degraded performance and reduced productivity. But with the advent of batteries that can be replaced quickly, long-time backup power has been achieved. You can then protect your investment in electronics and communicate with coworkers across the globe while knowing that you have saved yourself from the consequences of battery death.

5.2 Emergency lighting, flashlights, Audio System, and Taxi Meter

In car audio systems, Supercapacitor can power the radio station memory and accumulated fare data. In taxi meters, SC serves as the power backup in case of a power failure by powering emergency lighting. When power is off or goes fail for hours at that time the emergency lights (LEDs) are used for lighting purpose. The supercapacitors are used to provide electricity at night events for brightening and decorations.

5.3 Hospital and medical instruments

There are a lot of biomedical instruments and machines which are operated on a power supply (DC). It has a power back resource also to keep the instrument working during the diagnostic and operation process. Electronic machine-like ECG, EEG, MRI, etc. are required to display, data processing and storage units and have power back to the work machine without any interruption of electricity. Supercapacitors are also used in portable devices and handheld terminals.

5.4 Remote solar-powered installations

SC power supplies are ideal backup power sources for mission-critical systems that require reliability. SC has a long lifespan and it is very useful to store solar energy in the form of electrical energy. Further, it is converted and transferred to the industries' applications. It is a more reliable and renewable energy source based on supercapacitors.

5.5 Electronics Gadgets

Tiny electronic gadgets are the need of the market and lifestyle. These types of electronic devices are portable, small in size and have long time battery backup. These power sources are the supercapacitors that make it possible for consumers. Sc-based electronic devices such as digital hand watches, wireless headphones, wireless audio systems, flashlights, etc.

5.6 Transportation and Automotive Industry

The transportation, automobile, and automotive industries are transforming from fuel to electricity. Electricity-based vehicles, cars, buses, planes, and other types of transport objects are working on electricity. The major source of electricity is solar system and SC-based power supply storage. The luxurious vehicles are fully automated and have a comfortable bake system to door opening and closing automatically.

5.7 Consumer electronics and home appliances

Most consumer electronics products and home appliances are replacing the wire with wireless. It is possible due to SC and advanced electrical energy storage devices. Consumer electronics are having power supply sources inbuilt such as smartphones, toys, digital clocks, laptops, tabs, minicomputers, smart watches, personal digital assistance, etc. These devices are cost-effective, reliable, and have long-life battery backup due to SC.

5.8 Uninterrupted power supply (UPS)

Supercapacitor-powered UPS offers ultra-high-power density, reliability, and ease of integration. SC is used in UPS to provide and maintain the continuous electricity supply to electronic appliances such as computers, TV, printer, scanner, etc. UPS is a need for offices, organizations, and companies to work online and 24X7 for customer satisfaction.

5.9 Other applications

Today, Supercapacitors are used in every sector such as banking, airport, transportation, control tower, communication network, IT parks, textile industries, agriculture, and more. It is filling the gap between conventional power supply and battery-based systems. It is also replacing bulk energy storage and costly devices with an effective source of energy.

6 Major Applications of IoT

IoT is a system of technological devices that takes advantage of network connectivity to connect objects or sensor networks, this infrastructure which can collect and exchange data (e.g., weather reports) over an established network. The main principle behind IoT is to allow different types of devices to work together harmoniously by sharing data, reducing manual tasks, and improving effectiveness at low cost as well as increasing productivity.

6.1 Smart City, Transportation, and GPS

The impacts of smart city are significant as it is a large part of the IT industry. IoT-based smart homes, smart offices, and smart cities are concepts to live in a better environment where all objects are connected to the internet and can communicate with each other. The facilities are provided in-house for the owner to control the home appliances. Also, smart transportation and traffic control are using IoT to guide the citizens. IoT-based shipping and product delivery on time is possible. It helps the consumer to monitor their goods which are ordered from various locations. Global positioning system (GPS) is very useful to travelers and in mapping the place to place.

6.1 Computerized Maintenance Management

The increase in physical assets, as well as their technological state, has led to an actual change in the way they are managed. Enterprise Asset Management (EAM) and Computerized Maintenance Management Systems (CMMS) are used in the sensors, control system, application software, and internet. These systems provide better management for users and service providers. The applications of these tools are in malls, canteens, service centers, retail, and warehouses.

6.2 Healthcare Sector and Wearable Devices

Today, healthcare centers and hospitals are using IoT-based patient monitoring systems. The patients are diagnosed by the doctor and reports are generated by the computer. Further, the essential parameters are continuously monitored by IoT-based applications.

6.3 Smart Grid and Energy Storage

The electricity supply, storage, and distribution networks are monitored by the IoT. IoT provides electricity management solutions to electricity companies and manufacturers. It is easy to communicate with users and service providers. It also helps to find the fault and repairing at that node. IoT allows sharing of the status of on-gride and off-gride conditions to the controller. It has supercapacitors and advanced electrical energy storage devices which are the source of power backup. Nowadays, electrical energy suppliers are producing energy from natural resources such as windmills, solar panels, etc.

6.4 Smart Water Supply Management System

The Internet of Things (IoT) based water supply distribution and management system are implemented in various cities. It is one of the applications of IoT to deal with a proper water management system to control the waste of drinking water. IoT has allowed companies to collect, process, and analyze data to provide better value for their consumers. This allows the company to understand its customers' behaviors and consequently build a relationship that is based on trust and mutual benefit. Similarly, IoT has allowed water companies to monitor data relating to the consumption patterns of their consumers. Consumers can now track their water consumption on a webpage or via mobile applications. These web pages (mobile applications) can be accessed via smartphones or tablets as well as computers.

6.5 Agriculture and Greenhouses

The use of IoT enables farmers to automate the processes on their farms. Intelligent devices serve as wearables, while sensors play a major role in environmental monitoring, controlling and automating processes, and saving energy. The agricultural industry is the 5th largest industrial sector of the world's GDP. The global agriculture sector employs over 1 billion people and plays a vital role in the food security of millions of people. However, due to various reasons such as climate change, increasing demand for natural resources, and increasing population, agricultural activity has been suggested as one of the solutions to relieve stress on natural resources and thereby improve productivity. Greenhouses are designed to provide a controlled environment (environmental parameters) to increase crop production.

7 Conclusion

Supercapacitors are the future of electrical energy storage devices. It is used in all sectors such as electrical vehicles, portable devices, wearable gadgets, home appliances, consumer electronics, robotics, automotive electronics, and IoT devices. IoT-based devices required a power supply and energy backup to work without interruption. It is possible due to supercapacitors which provide a continuous supply to the system for a long duration. The major applications of IoT are in healthcare, agriculture, metrological, transportation, home appliances, consumer electronics, and more. Supercapacitors are flexible and can be used in many ways. Supercapacitors offers give power to connected devices that are running on low voltage and can't obtain energy by themselves. Electronic devices mainly operate on dc signals and electrical instruments work on signals. The supercapacitor plays an important role to supply energy which stores an extremely large amount of electrical charge. It is the future of batteries and replaces the old bulk batteries with tiny high-performance flexible sustainable supercapacitors."

Declarations:

Competing interests:

The authors have no relevant financial or non-financial interests to disclose. The authors have no conflicts of interest to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Authors' contributions:

SN has done the literature review work and summarized the supercapacitor technology and its applications in IoT devices. AV did comparative study of all types of electrical energy storage devices. UP have supervised and contributed in manuscript writing. AB, KM and MB have contributed in paper writing and proofreading. All authors read and approved the final manuscript.

Acknowledgment

I would like to thank Dr. AV Patil (Research Guide) for supervising the research work on supercapacitors and their applications in IoT and AI devices. I am also expressing our gratitude to Dr. U.P. Shinde (Research Director) of MGV's LVH ASCC Research Center, Panchavati, Nashik (Maharashtra) India.

References

[1] B.E. Conway, 1999, Electrochemical Supercapacitors - Scientific Fundamentals and Technological Applications. New York: Kluwer.
[2] H.E. Becker, U.S., 1957, Patent 2800616, General Electric.
[3] J.R. Miller and P. Simon, 2008, 'Fundamentals of electrochemical capacitor design and operation', The Electrochemical Society Interface.
[4] Dr. Ovidiu Vermesan SINTEF, Norway, Dr. Peter Friess EU, Belgium, 2013, "Internet of Things: Converging Technologies

for Smart Environments and Integrated Ecosystems", river publishers' series in communications.

[5] Dr. Ovidiu Vermesan SINTEF, Norway, Dr. Peter FriessEU, Belgium, 2014, "Internet of Things–From Research and Innovation to Market Deployment", river publishers' series in communications.

[6] Ranger S., 2020, "What is the IoT? Everything you need to know about the Internet of Things right now."

[7] Kumar, S., Tiwari, P., & Zymbler, M. 2019, "Internet of Things is a revolutionary approach for future technology enhancement: a review. Journal Of Big Data, 6(1).

[8} Gatsis, K., & Pappas, G., 2017, "Wireless Control for the IoT." Proceedings of the Second International Conference on Internet-Of-Things Design And Implementation.

[9] Lee, S.; Lee, D., 2020, Healthcare wearable devices: An analysis of key factors for continuous use intention. Serv. Bus. 14, 503–531.

[10] Yoon, S.; Lee, D., 2019, Artificial Intelligence and Robots in Healthcare: What are the Success Factors for Technology-based Service Encounters? Int. J. Healthc. Manag., 12, 218–225.

[11] Ramesh, A.; Kambhampati, C.; Monson, J.; Drew, P., 2004, Artificial Intelligence in Medicine. Ann. R. Coll. Surg. Engl. 86, 334–338.

[12] Safavi, K.; Kalis, B., 2019, How AI can Change the Future of Health Care. Harv. Bus. Rev.

[13] J.-Y. Lee, W.-C.Lin, and Y.-H. Huang, 2014, "A lightweight authentication protocol for internet of things," in Int'l Symposium on Next-Generation Electronics (ISNE), 1-2.

[14] Y. Xie and D. Wang, 2014, "An Item-Level Access Control Framework for Inter-System Security in the Internet of Things," in Applied Mechanics and Materials, 1430-1432,

[15] Han, J., Wei, W., Zhang, C., et al. 2018, Engineering graphenes from the nano- to the macroscale for electrochemical energy storage. Electrochem. Energy Rev. 1, 139–168. https://doi.org/10.1007/s41918-018-0006-z

[16] I'm, H., Gunjakar, J.L., Inamdar, A., et al., 2018, Direct growth of 2D nickel hydroxide nanosheets intercalated with polyoxovanadate anions as a binder-free supercapacitor electrode. Nanoscale 10, 8953–8961. https://doi.org/10.1039/C7NR09626G

[17] Dong, J., Lu, G., Wu, F., et al., 2018, Facile synthesis of a nitrogen-doped graphene fower-like MnO2 nanocomposite and its application in supercapacitors. Appl. Surf. Sci. 427, 986–993 https://doi.org/10.1016/j.apsusc.2017.07.291

[18] Dubai, D.P., Chodankar, N.R., Kim, D.H., et al., 2018, Towards flexible solid-state supercapacitors for smart and wearable electronics. Chem. Soc. Rev. 47, 2065–2129. https://doi.org/10.1039/C7CS00505A

[19] Song, Q.S., Li, Y.Y., Chan, S.L.I., 2005, Physical and electrochemical characteristics of nanostructured nickel hydroxide powder. J. Appl. Electrochem. 35, 157–162. https://doi.org/10.1007/s10800-004-6301-x

[20] Cao, L., Xu, F., Liang, Y.Y., et al. 2004, Preparation of the novel nanocomposite Co(OH)2/ultra-stable Y zeolite and its application as a supercapacitor with high energy density. Adv. Mater. 16, 1853–1857. https://doi.org/10.1002/adma.200400183

[21] Bose, S., Kuila, T., Mishra, A.K., et al., 2012, Carbon-based nanostructured materials and their composites as supercapacitor electrodes. J. Mater. Chem. 22, 767–784. https://doi.org/10.1039/C1JM14468E

[22] Yuan, J., Tang, S., Zhu, Z., et al., 2017, Facile synthesis of high-performance Ni(OH)2/expanded graphite electrodes for asymmetric supercapacitors. J. Mater. Sci.: Mater. Electron. 28, 18022–18030. https://doi.org/10.1007/s10854-017-7745-1

[23] Wang, R., Sui, Y., Huang, S., et al., 2018, High-performance flexible all-solid-state asymmetric supercapacitors from nanostructured electrodes prepared by oxidation-assisted dealloying protocol. Chem. Eng. J. 331, 527–535. https://doi.org/10.1016/j. cej.2017.09.004

[24] Sharma, V., Singh, I., Chandra, A., 2018¸ Hollow nanostructures of metal oxides as next-generation electrode materials for supercapacitors. Sci. Rep. 8, 1307. https://doi.org/10.1038/s41598-018-19815-y

[25] Conway, B.E., Pell, W.G., 2003, Double-layer and pseudocapacitance types of electrochemical capacitors and their applications to the development of hybrid devices. J. Solid State Electrochem. 7, 637–644. https://doi.org/10.1007/s10008-003-0395-7

[26] Miller, J.R., 2006, Electrochemical capacitor thermal management issues at high-rate cycling. Electrochim. Acta 52, 1703–1708. https://doi.org/10.1016/j.electacta.2006.02.056

[27] Sugimoto, W., Yokoshima, K., Murakami, Y., et al.: Charge storage mechanism of nanostructured anhydrous and hydrous ruthenium-based oxides. Electrochim. Acta 52, 1742–1748 (2006). https://doi.org/10.1016/j.electacta.2006.02.054

[28] Chen, Z., Augustyn, V., Wen, J., et al., 2011, High-performance supercapacitors based on intertwined CNT/V2O5 nanowire nanocomposites. Adv. Mater. 23, 791–795. https://doi.org/10.1002/adma.201003658

[29] Paleo, A.J., Staiti, P., Brigandì, A., et al., 2018**,** Supercapacitors based on AC/MnO2 deposited onto dip-coated carbon nanofiber cotton fabric electrodes. Energy Storage Mater. 12, 204–215. https://doi.org/10.1016/j.ensm.2017.12.013

[30] Du, C., Pan, N., 2006, High power density supercapacitor electrodes of carbon nanotube films by electrophoretic deposition. Nanotechnology 17, 5314–5318. https://doi. org/10.1088/0957-4484/17/21/005

[31] Park, J.H., Kim, S., Park, O.O., et al., 2006,Improved asymmetric electrochemical capacitor using Zn–Co co-doped Ni(OH)2 positive electrode material. Appl. Phys. An 82, 593–597. https://doi.org/10.1007/s00339-005-3400-4

[32] Kotz, R., Carlen, M., 2000, Principles and applications of electrochemical capacitors. Electrochim. Acta 45, 2483–2498.

[33] Winter, M., Brodd, R.J.: What are batteries, fuel cells, and supercapacitors? Chem. Rev. 104, 4245–4269 (2004). doi.org/10.1021/cr020730k

[34] Yu, G., Xie, X., Pan, L., et al., 2013, Hybrid nanostructured materials for high-performance electrochemical capacitors. Nano Energy 2, 213–234. https://doi.org/10.1016/j.nanoe n.2012.10.006

[35] Zhi, M., Xiang, C., Li, J., et al., 2013, Nanostructured carbon-metal oxide composite electrodes for supercapacitors: a review. Nanoscale 5, 72–88. https://doi.org/10.1039/C2NR3 2040A

[36] Bello, A., Makgopa, K., Fabiane, M., et al.: Chemical adsorption of NiO nanostructures on nickel foam-graphene for supercapacitor applications. J. Mater. Sci. 48, 6707–6712 (2013). https://doi.org/10.1007/s10853-013-7471-x

[37] Pawan S., and T.S. Bhatti, 2018, A review on electro- chemical double-layer capacitors, Energy Conversion and Management, vol. 51, pp. 2901-2912.