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Improving Energy Storage Conditions through Supercapacitor Banks: A Bibliographical Review

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— Abstract—

This literature review work presents the compilation of various studies in which the topics of energy storage systems, supercapacitors (SCs), supercapacitor banks, and switching matrices, which are considered elementary for the future of electrical systems, stand out. The storage systems allow a backup when the power supply lines fail or are not efficient enough, and have different classifications, which change depending on the types and needs of the systems. In addition to this, supercapacitors, types, and applications are described in general, as well as the characteristics that position them as a better storage option than batteries, to lay the foundations for the development of supercapacitor banks and switching matrices; the former help to enhance the characteristics of supercapacitors through different electrical arrangements, while the latter are a proposal to control the changes of supercapacitor banks in the search for control of electrical parameters.

Keywords:

Supercapacitors; energy storage systems; biomass; switching matrix; supercapacitors bank.

The electrical industry has evolved exponentially in recent decades, automating most processes and seeking to reduce environmental impact, providing greater control in industrial processes by developing energy backup systems. Energy storage systems have become novel topics of research to produce and supply electricity when there are periods of disconnection from conventional networks or to improve the response of the system. It is important to highlight that in energy storage we find two general classifications: direct means such as batteries, and indirect means including Supercapacitors and conventional capacitors. These systems are distinguished by the control of parameters such as energy and power density, efficiencies in the charge and discharge cycles of energy, and the life cycles of storage systems (Reveles, 2013).

According to research by Reveles (2013), not all storage devices are efficient for all types of systems since "the fundamental parameters that we have to consider are how much energy it can store and how fast it can deliver that energy" (Reveles, 2013, p. 29).

The high demand for electrical energy storage systems has become one of the main goals in science and engineering, seeking to obtain increasingly efficient and environmentally friendly storage systems. In recent decades, the most widely used storage system has been batteries. However, their environmental impact is very high and does not provide sufficient efficiency to the systems because their charge and discharge cycles are lower compared to other devices and, in addition, they do not deliver the power characteristics that are needed in most cases.

Attributed to the above, much more efficient alternatives began to be analyzed, such as the use of capacitors and the subsequent development of SCs.

The first are devices formed by two conductors and separated by a dielectric solution with acidic pH; while the second consists of two porous electrodes impregnated in an electrolyte and insulated from electrical contact by a separating paper; they store energy by the principle of electrochemical double layer formed at the electrode/electrolyte interface, of which we will focus the review. SCs are classified into three types: electrochemical double layer (EDLC), pseudocapacitors (Ps), and hybrids (Olán et al., 2021).

It is essential to highlight that since it contains characteristics similar to batteries, in terms of energy management, it has been necessary to develop arrangements that help improve the electrical parameters in the systems. At the same time, the development of Supercapacitors that use biomass as components has been studied to take advantage of the waste of certain products such as coconut, coffee, cocoa, bamboo, and rice, thus proposing innovative storage strategies with a reduced environmental impact in consideration of commercial ones.

The objective of this literature review document is to present the development of new technologies and improvements for energy storage, as well as their environmental impact compared to conventional batteries, documenting information about supercapacitors based on the studies of other authors embodied in articles and theses.

ENERGY STORAGE SYSTEMS

Energy storage systems are characterized by the amount of energy they store, the maximum power they supply, and the response times of charge/discharge processes related to their operation, as shown in Table 1. Based on these parameters, we can talk about large-scale storage systems, distribution systems, and power systems (Díaz, 2016).

Table 1

Classification and general characteristics of storage systems according to the amount of energy they store

Types of Energy Storage Systems	Characteristics
Large-scale storage systems	They can store energies between 10 and 8000 MWh and supply powers between 10 and 1000 MW with discharge times between 1 and 8 hours.
Distribution systems	The energy and power values range between 50 to 8000 kWh and 100 to 2000 kW respectively, reducing the discharge times by half concerning the previous ones.
Power Systems	Characterized by energy values ranging from 0.03 to 17 kWh, powers from 0.1 to 2 MW, and discharge times from 1 to 30 seconds.

Note. Díaz, 2016.

These types of systems can also be classified according to the type of energy they store as shown in Table 2.

Table 2

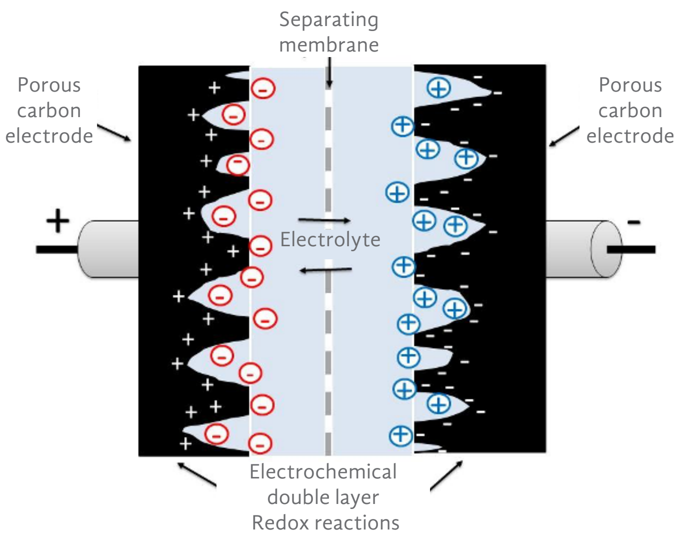
Distributed storage systems, according to the type of energy they protect

Types of Storage Systems	Características de los sistemas
Indirect electric power	- In the form of mechanical energy, such as hydraulic pumping systems (PHES), compressed air systems (CAEs), and flywheels. - In the form of chemical energy, as in the case of batteries (Mírez, 2012).
Direct electric power	- Like superconducting coils (SMES) and supercapacitors (Olán, 2020).

Note. It is important to know the storage medium to establish the most optimal one to be applied according to the energy supply needs of the system.

Supercapacitors

Supercapacitors are energy storage devices that have become a focus of attention for science because they show greater efficiency in supplying electrical energy and providing power to various systems, based on electrostatic forces (Olán et al., 2021). These devices contain two electrodes immersed in an electrolyte separated by a semipermeable material in the search to reduce the presence of short circuits without affecting the transfer of ions from the electrolyte medium (Figure 1). When a potential difference is applied to them, a charge density difference is created between their plates and the ions migrate towards the surface of the electrodes, adsorbing in the interfacial region. However, it is important to mention that these devices require electrodes made with materials of high specific area so that the capacity to accumulate charge increases, in addition to a porous structure that provides greater surface area and facilitates the conditions of displacement of the ions in the electrolyte (Olán, 2020).



Note. (Olán, 2020, p.20).

Figure 1. Representation of the internal behavior of a supercapacitor

These devices are formed mostly commercially of activated carbon that acts as electrodes, which are polarized and separated by a permeable ion that separates the electrodes in the search to avoid the presence of short circuits between the plates; it also contains an electrolytic solution forming a charge distribution along the contact surface between the carbon and the electrolyte (Muñoz, 2020).

One detail to consider regarding SCs as storage systems is that the extraction of energy in these devices is more demanding compared to batteries; this is because when SCs have delivered only 75% of their energy, their voltage has already decreased to 50%. Although SC has a higher power density, longer life cycle, and higher discharge/charge efficiency than a battery, faster charging time, wider operating temperature window, and lower internal resistance, due to their low power density, they report a maximum energy utilization efficiency of only 75% (Reveles-Miranda et al., 2017).

According to various studies shown in Table 3, the material of the active electrode in the processed electrode is the main factor influencing the performance of the SC. Three types of active electrode materials for SCs have been examined.

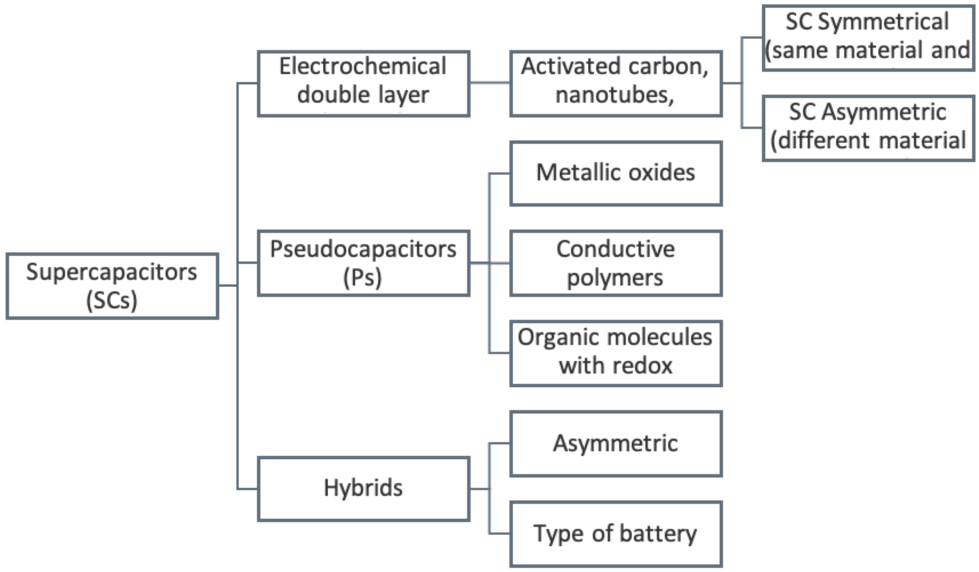
Table 3

Active electrode materials for SCs

Type of electrode	Characteristics
Activated carbons (AC)	• They show a larger surface area but lower electrical conductivity, leading to the use of conductive additives and AC in the processed electrodes. • Lower cost materials. • They can be derived from agricultural products and waste (cocoa, coconut, coffee, rice, and bamboo).
Carbon nanotube (CNT)	• It shows a high electrical conductivity but a moderate surface area due to the cylindrical shape they have. • High-cost material.
Reduced graphene oxide (rGO)	• They show a high electrical conductivity but a moderate surface area due to the restacking of the graphene layers. • High-cost material.

Note. In this table, a slight comparison is made of the general characteristics of materials used as active electrodes for SCs (Olán et al., 2021).

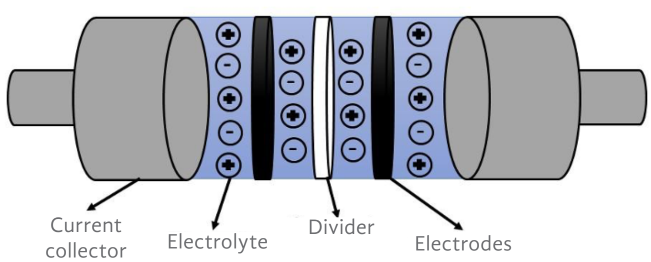
In the study of supercapacitors, classifications have been established according to the electrode used, operating principle, and design. However, the most widely accepted are three: electrochemical double-layer supercapacitors (EDLCs), pseudocapacitors (Ps), and hybrid supercapacitors. As mentioned in Figure 2.



Note. SCs are classified in this way to be able to make the appropriate choice according to the needs of the systems to be supplied (Olán, 2020).

Figure 2. Classification of supercapacitors

"Electrical double layer electrochemical supercapacitors." (Segura & Remigio, 2016) Double-layer SCs store charge mostly through the double interfacial charge effect. In this sense, this type of SC seeks to have a surface area as high as possible to capture a large amount of ions at the electrode-electrolyte interface. Generally, the larger the surface area of the electrode, the greater its capacity to accumulate charge. However, this surface must be electrochemically accessible to ions (Delgado, 2018). Although EDLCs are considered electrochemical devices, there are no chemical reactions, as they are involved in the energy storage mechanism. The energy storage mechanism is a physical phenomenon and is highly reversible. Figure 3 shows the schematic of a double-layer electrochemical supercapacitor (Segura & Remigio, 2016).



Note. The life cycle of SCs is long compared to batteries, this is due to the physical movement of the ions, which regulate the charge and discharge rates (Olán, 2020).

Figure 3. Electrochemical double-layer supercapacitor schematic

"For their part, SCs that store energy electrochemically are called pseudocapacitors, because they perform reversible oxidation-reduction or redox reaction on the electrode surface." (Segura and Remigio, 2016). Most of them are built with metal oxide electrodes such as ruthenium oxide (iridium oxide, nickel oxide, or conductive polymers are also used); they have low efficiency and very low cell voltages due to the use of aqueous electrolytes, besides being costly at the production level due to their internal composition (Romero, 2009).

Another relevant classification is that of hybrid SCs, also called asymmetrical, defined as devices that combine pseudocapacitors with double-layer capabilities, using asymmetrical electrodes. That is, in an electrode, charge separation occurs due to double-layer formation only (Yuan et al., 2012).

Table 4 shows the specific characteristics of all SCs that differentiate them from other storage devices regardless of their classification.

Table 4

General characteristics of SC to differentiate them from other storage devices

General characteristics	Description
Energy storage (energy density)	SCs can achieve an energy density of magnitude greater than that obtained by conventional batteries.
High power density	The amount of power that a device is capable of delivering/receiving per unit volume, in the case of SCs is proposed to average 10kW/kg.
Equivalent Series Low Resistance (ESR)	Compared to batteries, the internal resistance of EDLCs is much lower, allowing them to operate at very high currents with high energy efficiency.
Very fast loading and unloading	They can handle high currents, and with almost equal efficiency, both in charging and discharging.
Shelf life	According to supercapacitor manufacturers, the lifetime of supercapacitors can be estimated at 1 million charge/discharge cycles, while that of lithium-ion batteries is about 1000 cycles.
Voltage per cell	Typically EDLCs have a maximum voltage per cell of about 2.7V. Supercapacitors can work over the entire voltage range up to their maximum voltage. In addition, they can be fully unloaded without suffering any degradation, improving safety in storage.
Ease of determining charge status	The charge and discharge are practically linear, and therefore, the state of charge (SOC) is obtained directly through the measurement of the voltage at a certain moment.
Wide operating temperature range	Typically, manufacturers establish a working range of between -40 and 65°C in both loading and unloading. This range is much higher than that of lithium batteries, especially at low temperatures (according to manufacturers' data, -20 to 60°C in discharge and 0 to 45°C in charge approximately).

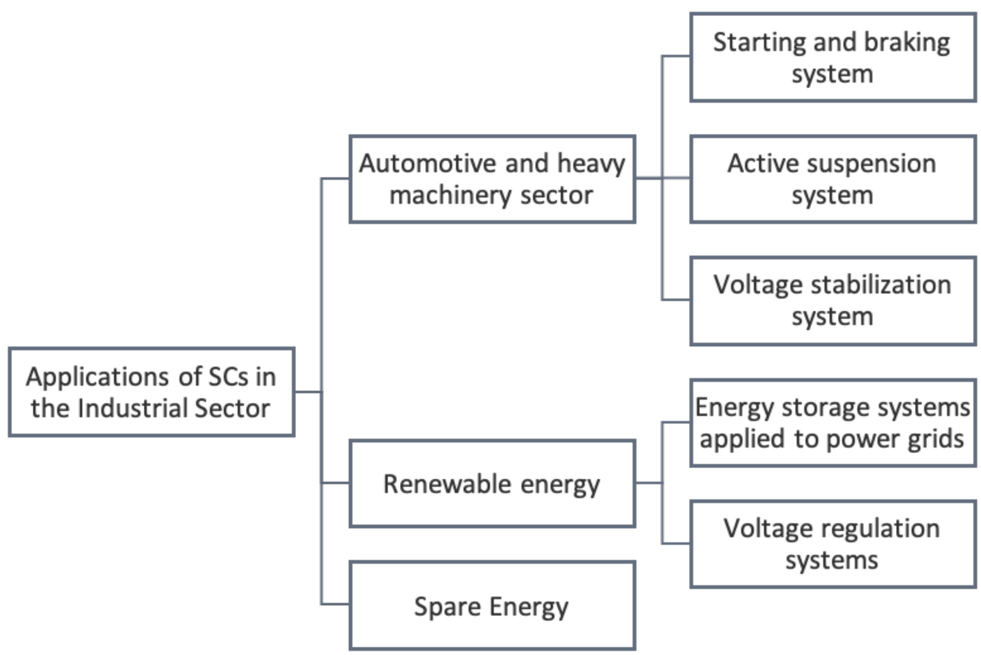
Note: These characteristics are what make a difference between direct storage devices such as batteries, and indirect storage devices such as SCs (Pradas, 2013).

"SC can be used to complete the electric power capacity of batteries in numerous applications. They can be used to store energy and provide power demand peaks in power electronic systems " (Reveles-Miranda et al., 2017).

Due to the energy advantages such as availability to handle the high voltage, current, and temperature values; short charge/discharge cycles, and optimal maintenance availability in a simple way. In addition to all the above and as a practical representation of the aforementioned qualities, the following are the most widespread applications of supercapacitors:

- Development of converters integrating supercapacitors applying the principles of power electronics for the aforementioned purpose.
- Development of systems that allow having an energy back-up integrating the use of supercapacitors.
- Development of a system that allows improving charging autonomy with the integration of supercapacitors to improve the charging times of the aforementioned system (Méndez et al., 2020).

Figure 4 shows applications of SCs in the industrial sector, in which the use of this type of storage system is more efficient (Technologies, 2020).

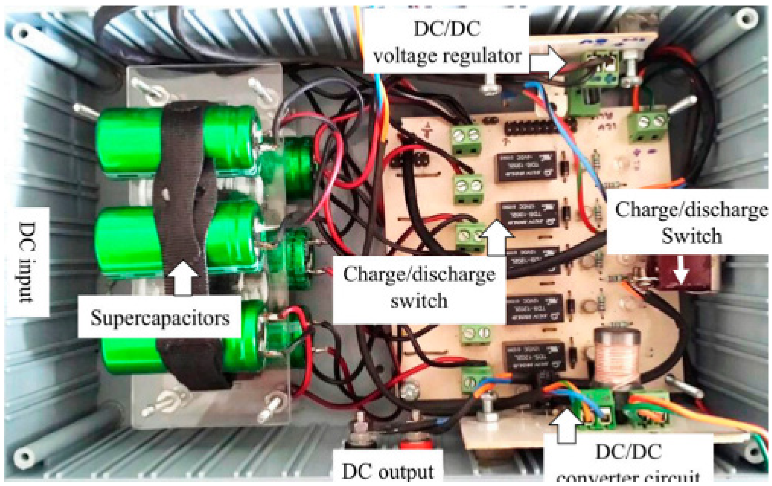


Note. (Technologies, 2020).

Figure 4. Applications of SCs in the industry

Supercapacitor Bank

A capacitor bank is an electrical equipment with a metal structure that contains two or more identical capacitors and is grouped fixedly (Figure 5). However, this type of system makes use of various arrangements with which we can enhance various electrical parameters depending on the specifications of the SCs we are using (Domínguez, 2012).



Note. Supercapacitor Bank carried out the study of arrangements applied in a Supercapacitor Bank to enhance electrical parameters (Reveles-Miranda et al., 2017).

They are used to correct the power factor (the ratio of the active power to the apparent power) of a commercial or industrial environment that uses several electric motors and transformers. This first point is important since in the industry, if the power factor is not corrected, there may be a penalty and a negative effect on the operation of the systems, as shown in Table 5 in detail: characteristics, types of capacitors, and which are the most used of the same (García, 2022).

Table 5

Comparative description of the operation of capacitor banks

Characteristics of capacitor banks		
Having control of the power factor helps the efficiency of energy consumption and the operation of some systems (Arredondo-Ferrer et al., 2022).	It stabilizes and adapts the voltage when a deficiency in electrical current levels occurs (Rayon, 2018).	Improves voltage profile, long service life, and cheaper capacitor bank maintenance (Garcia, 2022).

Table 6

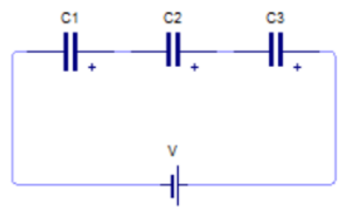
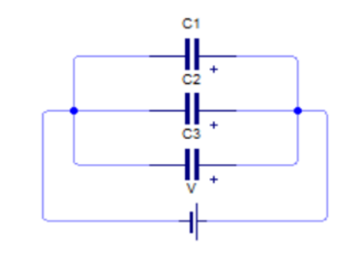
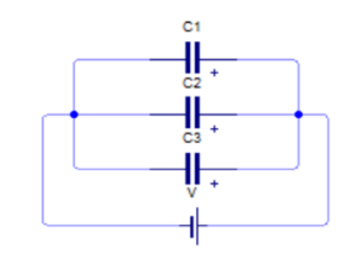
Classification and characteristics of capacitors for the realization of a capacitor bank balancing network connection

Types of capacitors	Characteristics	Authors
Ceramic capacitors	It is one of the most used and well-known capacitors in the field of electronics and electricity. It features a dielectric made of different types of ceramics. The dielectric constant of these devices is usually higher than average.	(Vilela *et al.*, 2017).
Electrolytic capacitors	In its interior, there is an electrolyte that functions as a cathode and anode, having the outstanding characteristic of receiving very large currents. They can explode if they have polarity and are not connected correctly.	(García, 2022).
Air capacitors	It is composed of parallel conductive plates and uses air as a dielectric. They are used when there is a lower consumption of electrical energy.	(Fornaro *et al.*, 2012).
Mica capacitors	Capacitors are more resistant since their dielectric is made of mica; this material has the characteristic of low energy loss, and the use of this type of capacitor is more efficient when there are high voltages.	(Vilela *et al.*, 2017).
Aluminum capacitors	This capacitor is often used in the capacitor bank. It is made of aluminum and boric acid-based electrolyte and is also used for audio systems.	(Méndez *et al.*, 2020).
Paper capacitors	The dielectric is made of kerosene paper, Bakelite, or some other material that prevents humidity. Two paper plates are used in conjunction with aluminum.	(Vilela *et al.*, 2017).

Depending on requirements, series, parallel, or mixed connections can be made. The series connection of a supercapacitor is made by connecting a set of the negative part to the positive part of a capacitor. When a higher rated voltage is required from a supercapacitor it is necessary to make a series connection since the total voltage is the sum of each of the supercapacitors and the current is equal in each. A disadvantage of using the series connection is that the capacitance decreases (Table 7a). In turn, when applying a parallel connection, the capacitance of each supercapacitor is added (Table 7b); the voltage is equal to that of a single supercapacitor, and the current is summed (Tippens et al., 2007). Finally, it should be considered that to make a supercapacitor arrangement for an application with higher voltage demand and at the same time maintain its capacitance (Table 7c), it is necessary to make a mixed connection, that is, to connect capacitors both in series and in parallel (Escribano, 2020).

Table 7

Comparison of array types to enhance the electrical parameters of SCs

Comparación de los arreglos de las conexiones de los SC´s	
a) Series	
b) Paralelo	
c) Mixto	

Nota. (Tippens *et al.*, 2007)

Switching matrix

A switching matrix is a circuit that involves having all the levels of a supercapacitor bank (SCB) and controlling the changes between the levels of the bank to take advantage of the characteristics of the SCs (Table 8).

Table 8
Comparison of switching matrix applications in different storage systems

Authors	Year	Objective	Results
Freddy Chan, Jorge Aguilar, Víctor Sánchez, Emmanuel Torres and Marlos Alpuche	2019	"Switching matrix applied to a photovoltaic system (SFVI) to reconfigure both photovoltaic modules, inverters, and connected loads under certain operating conditions, generation, and electrical energy consumption."	Experimental evaluation of the performance under different generation conditions and for different types of loads connected to the grid is developed. The system has reconfiguration capabilities for various situations, such as inverter failures, phase overloads, line unbalances, consumption increases, short circuits, etc. The system is capable of adapting to various operating conditions (Ramiro et al., 2019).
María Guadalupe Reveles-Miranda, Manuel Israel Flota-Bañuelos, Freddy Chan-Puc, and Daniella Pacheco-Catalán	2017	Basic Switching Cell (BSC) that allows reconnection of the SCs to increase the storage bank power delivery time to a constant voltage level within a set interval to ensure uniform power draw from each SC with deep charge/discharge cycles.	By implementing the switching matrix, the average energy extracted was increased to 98.87%. The discharge patterns show that the proposed reconfigurations increase the discharge time in all cases. (Reveles-Miranda et al., 2017b).
Pietro Romano, Roberto Candela, Marzia Cardinale, Vincenzo Li Vigni, Domenico Musso, Eleonora Riva Sanseverino	2013	"Reconfiguration system that enhances the power extracted by a photovoltaic generator under non-uniform solar irradiance conditions using a flexible switch array topology to maximize the power generated in real time under various mismatch conditions."	The fully reconfigurable dynamic electrical system (DES) for photovoltaic generators allowed satisfactory power gain both in the case of non-uniform irradiance and in the case of fixed obstacles (Romano et al., 2013).

CONCLUSION

In today's industry, the development of new energy storage technologies has been considered of vital importance due to the increasing automation of production systems since these types of systems require that the devices are properly electrically powered, and in turn, deliver the necessary electrical characteristics to ensure that the process is carried out correctly, such as power, charge/discharge times, and amperage. SCs represent an alternative solution for energy storage because they are more stable devices compared to conventional batteries, and thanks to several studies have been proposed configurations that allow them to conserve electrical parameters such as voltage, power, amperage, and better conditions in the charge/discharge cycles; in addition to this, the activated carbon that composes the electrodes of the SC's can be made of biomass (coconut, cocoa, bamboo, coffee, and rice), which would represent an environmentally friendly alternative with a longer life cycle compared to commercial ones. Among the improvements proposed with the use of SCs, we find the development of supercapacitor banks, defined as a series of SCs connected by electrical arrangements (series, parallel or mixed) that allow improving the voltage and amperage parameters, stabilizing the systems, to enhance the electrical parameters. However, these banks require control according to their applications; from which the switching matrices are presented, these have the particularity of allowing to change the parameters delivered according to the needs of the system that is being fed; this is a topic that is under research development and proposes revolutionary changes for the electrical industry.

REFERENCES

Arredondo-Ferrer, E., Buitrago-Sierra, R., & López, D. (2022). Hierarchical carbonaceous materials derived from spent coffee grounds for application in supercapacitors. *Revista de La Academia Colombiana de Ciencias Exactas, Fisicas y Naturales, 46*(178), 233–247. https://doi.org/10.18257/raccefyn.1585

Delgado Fernández, S. (2018). Estudio de viabilidad acerca del uso de un sistema de almacenamiento basado en hidrogeno como alternativa al almacenamiento en batería de una instalación fotovoltaica aislada para abastecer a una vivienda.

Díaz Baizán, P. (2016). *Supercondensadores híbridos asimétricos con especies redox inorgánicas.* Tesis doctoral.

Domínguez Ponce, A. (2012). *Diseño y construcción de un banco de pruebas para baterías y supercapacitores*.

Escribano Reyes, M. (2020). *Modelo y control de un banco de supercapacitores con convertidor*.

Fornaro, P., Talpone, J. I., Moré, J., & Riva, D. (2012). *Diseño y construcción de un banco de supercapacitores*. 1–12.

García Hilario, J. C. (16 de agosto de 2022). Bancos de Capacitores, Ejemplos, Usos y Beneficios. Capacitores.net. https://capacitores.net/bancos-de-capacitores/Que-debo-conocer-de-los-bancos-de-capacitores.

Méndez, E. F., Arrobo, E. V. y Morocho, A. F. (2020). Supercapacitores como aporte al desarrollo energético eléctrico, análisis comparativo mediante herramientas computacionales de simulación aplicadas. *Espacios*, 41, 29.

Mírez Tarrillo, J. (2012). *Sistemas de almacenamiento de energía*. 1–9.

Muñoz Menéndez, D. A. (2020). *Modelado y validación experimental de un banco de supercapacitores y baterías con propósitos de diagnóstico de fallas fuera de línea*.

Olán Ramos, M., del Ángel Meraz, E., Rojo, J. M., Pacheco-Catalán, D. E., Pantoja Castro, M. A., & Mora Ortiz, R. S. (2021). Activated carbons from coconut shell and NiO-based composites for energy storage systems. *Journal of Materials Science: Materials in Electronics, 32*(4), 4872–4884. https://doi.org/10.1007/s10854-020-05227-0

Olán Ramos, M. (2020). *Diseño de materiales de almacenamiento de energía fabricados a partir de cáscara de coco*.

Pradas Luengo, A. (2013). *Sistema de ensayo y caracterización de supercondensadores. Estudio de supercondensadores sometidos a radiación ionizante*.

Ramiro, I., Carrillo, A. A., de Finanzas, S., Comercialización, Y., Teresita, M. C., Chan, I., Secretaria Técnica, E., De, J., Vicente, I. I., Coronado, R., de Edición, J., Producción, Y., De, M. A. L., Luz, L. A., Vázquez, R., Digital, E., Rosa, P. L., Montero, P., de Resguardo, J., ... Publicaciones,

D. E. (2019). *Revista del centro de Graduados e Investigación Instituto tecnológico de Mérida. Centro de Investigación de Graduados e Investigación TECNM MÉRIDA*, 1–100.

Rayón López, N. (2018). *"Supercapacitores electroquímicos ensamblados con electrodos de carbón activado y nanocompuestos de WO3 obtenido con energía solar"*.

Reveles Miranda, M. G. (2013). *Diseño y elaboración de un módulo de supercondensadores con configuración flexible para el incremento de tiempo de descarga a voltaje constante.*

Reveles-Miranda, M. G., Flota-Bañuelos, M. I., Chan-Puc, F., & Pacheco-Catalán, D. (2017a). Experimental evaluation of a switching matrix applied in a bank of supercapacitors. *Energies, 10*(12). https://doi.org/10.3390/en10122077

Reveles-Miranda, M. G., Flota-Bañuelos, M. I., Chan-Puc, F., & Pacheco-Catalán, D. (2017b). Experimental evaluation of a switching matrix applied in a bank of supercapacitors. *Energies, 10*(12). https://doi.org/10.3390/en10122077

Romano, P., Candela, R., Cardinale, M., Li Vigni, V., Musso, D., & Riva Sanseverino, E. (2013). Optimization of photovoltaic energy production through an efficient switching matrix. *Journal of Sustainable Development of Energy, Water and Environment Systems, 1*(3), 227–236. https://doi.org/10.13044/j.sdewes.2013.01.0017

Segura, C. and Remigio, J. (2016). Modelación y simulación de un sistema híbrido de almacenamiento de energía eléctrica para la propulsión de embarcaciones tipo taxis en puerto ayora. Master's thesis, Quito.

Technologies, M. (2020). Ultracapacitors application.

Tippens, P. E., Orozco, J. H. C., and Ruiz, Á. C. G. (2007). Física: conceptos y aplicaciones. Number Sirsi) i9789701035146. McGraw-Hill Interamericana.

Vilela, J. A., De, E. A., & Fabro, G. (2017). *Conversor forward para carga de bancos de supercapacitores*. 1–4.

Yuan, L., Xiao, X., Ding, T., Zhong, J., Zhang, X., Shen, Y., Hu, B., Huang, Y., Zhou, J., and Wang, Z. L. (2012). Paper-based supercapacitors for self-powered nanosystems. *Angewandte Chemie International Edition, 51*(20). 4934–4938.