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Power Quality in Renewable Energy Microgrids Applications with Energy Storage Technologies: Issues, Challenges and Mitigations

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Abstract

Nowadays, the electric power distribution system is undergoing a transformation. The new face of the electrical grid of the future is composed of digital technologies, renewable sources and intelligent grids of distributed generation. As we move towards the electrical grid of the future, microgrids and distributed generation systems become more important, since they are able to unify small-scale and flexible generation to clean energy and intelligent controls. The microgrids play an important role in marking electrical grids more robust in the face of disturbances, increasing their resilience. Although the microgrid concept continues in discussion in technical circles, it can be defined as an aggregation of electrical elements in low generation voltage, storage and loads (users) which are grouped in a certain bounded geographical area. The issues of a microgrid integrated with energy storage technologies has gained increasing interest and popularity worldwide as these technologies provide the reliability and availability that are required for proper operation in the system. Actual studies show that the implementation of energy storage technologies in a microgrid improves transients, capacity, increases instantaneous power and allows the introduction of renewable energy systems. However, there are still certain unsolved problems in power quality terms. This article clearly describes those problems generated by each storage technology for microgrids applications. All the ideas in this review contribute significantly to the growing effort towards developing a cost-effective and efficient energy storage technology model with a long-life cycle for sustainable implementation in microgrids.

Keywords: Distributed generation, microgrids, energy storage systems, power quality, renewable energy sources

1. Introduction

Energy storage systems (ESS) and their microgrids application play a very important role in the electricity industry since they mitigate the problem of intermittency of renewable energy sources (RES) [1–4] while improving stability of the microgrid performing auxiliary services such as the decrease in demand at peak hours, protection against blackouts and control of power quality [5–7]. ESS also help renewable energy integration by managing the energy balance during an energy crisis, therefore system stability has a significant effect on the overall electrical system by storing energy during off-peak hours at reduced cost [8–15]. Additionally, ESS can be applied for cases of energy arbitrage [16], decrease in demand at peak hours [17], load flow [18], spinning reserve [19], voltage support and regulation [20], black-start [20, 21], frequency regulation [7], power quality [22, 23], power reliability [24], changes in RES [25, 26], transmission and distribution systems modernization [27], electrical congestion mitigation [28], and off-grid services [25, 28]. That is why ESS have become widely used solutions [29–31]. In fact, to enhance the ESS capacities required by microgrid, a hybrid solution is commonly adopted [32]. However, there are still challenges in the ESS implementation for microgrid applications such as the adequate management of these technologies, power electronics, energy conversion mechanisms, reliability and some problems with the power quality derived from the intermittency of RES which affect the system frequency. To counteract these drawbacks, different solutions have been proposed that will be described in later sections where they not only improve it but also efficiently solve problems related to power control, voltage stability and the power factor.

Microgrid is defined, according to the US Department of Energy, as a group of loads, micro-sources and distributed energy resources with clearly defined electrical limits capable of being self-sufficient and operating autonomously from the distribution grid in order to ensure the continuity of the electricity supply with a high reliability factor [33]. Another microgrid concept, according to the Consortium for Electrical Reliability Technology Solutions (CERTS), is that of an entity consisting of distributed energy resources, as well as controllable electrical and thermal loads. These loads are connected to the upstream grid for power generation through photovoltaic panels, wind plants, fuel cells, diesel generators and micro-turbines with ESS [34] as seen in **Figure 1**. Simply put, an microgrid is a miniature version of the sustainable energy model that can be used to generate, distribute and control bi-directional energy flow within its operating limits in a coordinated, intelligent and efficient manner, with a focus on renewable energies integration. Microgrids can be connected and disconnected from the main grid to allow it to operate in both “grid connected mode” [35] and “island mode” [36]. Microgrid must have flexible characteristics in its operation in both modes of operation to improve the efficiency and security of the grid [37]. When the microgrid operate in “connected grid mode” can maintain a stable system frequency by exchanging power with the main grid. However, in “island mode”, the microgrid are designed as off-grid systems [38] where primary frequency control is critical. Nevertheless, “island mode” is the most prominent feature of a microgrid, which is enabled through the use of switches at the point common coupling (PCC), which allows the microgrid to disconnect from the grid in case of upstream disturbances or voltage fluctuations [39]. Microgrid comprises only a portion of the distribution grid (generally in low-voltage), located next to the substation which contains a set of electrical and/or thermal loads, DG different types, distributed storage technologies with distinct features and capabilities.

Basically, microgrids offer significant benefits for both users and the electrical grid, reducing carbon emissions through the RES diversification, economic operation by reducing transmission and distribution costs (T&D), use of DG sources less expensive, energy efficiency responding to market prices in real-time, and better power quality

Figure 1.
MG typical structure.

when managing local loads. Therefore, the objective of this review is to pre-sent the actual state of ESS and their microgrid application in terms of power quality being the main contribution of this document: an ESS critical evaluation, highlighting their operational characteristics by minimizing the risk of supply interruptions, optimizing the consumption curve and reducing the maximum power required, which generates significant economic savings in the fixed term of generated power.

2. Microgrids overview

Microgrids can be classified as: AC–microgrid, DC–microgrid, and hybrid micro-grid (DC–AC microgrid).

2.1 AC–microgrid

A typical AC–microgrid is shown in **Figure 2**. In this system, all DG that include storage devices and loads are linked to the busbars of the AC mains by an electronic power converter. However, it is possible to connect AC generators, such as micro-turbines, diesel and wind turbines, directly to the main grid without the need for converters. Alternatively, to connect DC power sources such as batteries and PV systems to the grid, a DC/AC inverter is essential. Therefore, the loads are connected in a straight line to the AC bus bar. However, AC–microgrids have several drawbacks and such a grid involves complex control and synchronization problems. However, this grid is still widely used today [40]. An important detail to mention is

Figure 2.
AC-microgrid typical structure.

that the regulation of power quality in an AC-microgrid is carried out based on the conventional distribution system and the mode of operation [41].

2.2 DC-microgrid

Most of the generators that make up an microgrid produce DC power, which must be converted to AC power to accommodate the main grid. For which, it is required to perform the DC conversion at the end of the system since some equipment requires AC power to operate. However, converting DC/AC/DC power into an AC-microgrid reduces efficiency and causes power losses. This can be remedied by using high voltage DC operation as a benchmark, as the DC-microgrid is designed to address this problem. **Figure 3** shows the structure of a DC-microgrid. Unlike an AC-microgrid, the DC-microgrid offers considerable energy savings by reducing the number of converters in a single conversion process using a single converter. The authors in [41] stated that DC-microgrid are more suitable for distribution systems in residential areas than AC distributed networks causing few power quality problems. One of the best advantages of DC-microgrid is that they solve some control problems in the microgrid, making DG timing no longer necessary and ensuring that the controls are highly dependent on the DC bus voltage. Furthermore, the primary control is considerably simpler due to the absence of reactive power flow management. Also, many modern devices are DC powered and do not have power electronics that generate harmonics. Consequently, the level of conversion in DC-microgrid is low because it skips the CA stage in the middle of the process [42]. As a conclusion to this section, the operation of a DC-microgrid is smoother than AC-microgrid since phase and frequency monitoring are not taken into account [43].

2.3 Hybrid microgrid (DC-AC microgrid)

Hybrid-microgrid consist of AC and DC grids interconnected by large-scale multi-directional converters. This system could decrease the conversion stages

Figure 3.
DC-microgrid typical structure.

(DC/AC/DC and AC/DC/AC) into individual DC-microgrids or AC-microgrids and thus reduce the occurrence of power quality issues. In these types of microgrids, the AC sources and loads are tied to the AC bus, while the DC sources and loads are tied to the DC bus. The storage system can be linked to either of the two microgrids. **Figure 4** illustrates the one-line diagram of a hybrid microgrid [44, 45]. In a hybrid microgrid, the grid-connected mode of operation will supply or use the power from the main grid to meet power generation and load demand requirements. When disturbances arise, the microgrid must isolate itself from the main grid and work in autonomous mode. In grid-connected mode of operation, the microgrid operates efficiently to ensure critical load delivery is not compromised. The transient that occurs during the switching phase must be well controlled to avoid destroying the devices in the microgrid. Therefore, power quality issues need further investigation in this case [46].

3. ESS advances in microgrid applications

ESS are classified as: mechanical, electrochemical, electrical, thermal, and hybrid. Furthermore, these systems can be classified according to the formation process and the materials used, such as batteries [47], compressed air [48], flywheels [49], super-capacitors [50], superconducting magnetic energy storage (SMES) [51], fuel cells [52] and hybrid storage [53–55], which, the latter, are the most widely applied in micro-grids. These systems will be discussed in more detail below.

3.1 Batteries

Batteries store energy in an electrochemical form, and are available in different sizes and capacities ranging from 100 W to several MW. Batteries overall estimated

Figure 4.
Hybrid microgrid typical structure.

efficiency is in the range of 58–85%, depending on the operating cycle and the type of electrochemistry within the batteries. Lead-acid, Ni-Fe, Ni-Cd, Ni-M hydride, and Li-ion batteries are the five main types of energy storage based on batteries for microgrid applications. **Figure 5** shows, schematically, a constant increase in the energy density of batteries over the years. Lead-acid battery is the most technologically mature and lowest-cost energy storage device of all available battery technologies. However, the limited charge cycle capacity of these batteries typically results in an unacceptable scenario in system economics. On the other hand, Ni-Cd and Ni-M hydride batteries offer potential advantages over lead-acid batteries as they are environmentally friendly and provide a life cycle equivalent to that of lead-acid batteries, and an increase in its capacity (between 25 and 40%). As for the Li-ion battery, it has the highest energy density, but its cost is very high [56]. From a techno-economic aspect, Ni-M hydride battery is potentially the most competent technology in terms of: output power, voltage profile and charge–discharge characteristics, while the lead-acid battery turns out to be the most economical for renewable energy applications compared to Ni-Cd, Ni-M hydride, and Li-ion batteries. In general terms, due to their long service life and relatively low costs, but with a slow response, these types of batteries are ideal for applications with low duty cycles.

A microgrid composed of RES connected by electronic power converters can experience difficulties due to the voltage and current harmonics presence. These currents can, in turn, because voltage drops in line impedances. Additionally, voltage fluctuations and harmonic distortion can cause problems such as equipment tripping, overheating, and system malfunction. Microgrid stability depends on the

Figure 5.
Increased energy density of batteries.

ability of its units to mitigate and compensate for these phenomena. It should be considered that the batteries used to simultaneously exchange active power between the same battery and the main grid will significantly improve the power quality of the microgrid. This can be done by independent cascade control of currents and active and reactive power, thus controlling the reactive power balance and thus ensuring voltage stability across the microgrid. It should be noted that batteries are also used as an active harmonic filter. In addition to the above, batteries have the ability to maintain the voltage and frequency of the microgrid within the limits prescribed by the standards, since it can provide frequency support approximately 100 times faster than conventional generators. Finally, the batteries can withstand long-term voltage variations due to higher energy density and, therefore, will considerably improve the power quality in the microgrid.

3.2 Flywheels

A flywheel stores electrical energy in the form of kinetic energy and can convert the kinetic energy, back, to electrical energy when required. The energy stored in the flywheels is usually extracted from an electrical source from the grid or from any other source of electrical energy. When the flywheel is accelerated it stores energy and decelerates when discharge, to deliver the accumulated energy. The rotating flywheel is driven by an electric machine (electric motor-generator) that performs the exchange of electric energy to kinetic energy and vice versa. The flywheel and the electric machine have a common axis of rotation, so the control of the electric machine makes it possible to control the flywheel. This flywheel consists of a massive rotating cylinder (disk) that is supported on a stator by magnetic levitation bearings [57] as seen in **Figure 6**. It is divided into two categories: low speed, that is, from 6×10^3 to $\times 10^5$ rpm (high inertia and low speed) with a mixed gearbox which provides an energy boost to short term (10–30 s) and which are the most popular in the industry [58]. The high speed, that is, $\times 10^5$ (low inertia and high speed) that use a magnetic gearbox which are used in the aerospace industry [59]. Therefore, as the rotation speed of the flywheel rotor increases, the stored energy also increases proportionally with respect to the angular momentum. This stored energy can be used to rotor torque decelerate (discharge mode) by returning the kinetic energy to the electric motor, which acts as a generator. The nominal power can reach 52 MW, with storage capacities in the range of 3–148

Figure 6.
Flywheel basic structure.

kWh. These flywheels present a self-discharge of between 2.8–21.9% per hour, with efficiencies of 88 to 96%. They have 20,000 charge and discharge cycles. Response time is milliseconds and discharge time is seconds to no more than 1 hour. Rapid charging of a system occurs in less than 15 minutes [60]. Compared to batteries, flywheels can perform better when a sudden energy deficiency occurs in the electricity generation from RES (solar or wind) [61]. A very important aspect to consider in the implementation of this type of technology is its low maintenance cost (\$22 dollars/kW-year) although the acquisition cost is generally high (\$5000 dollars/kWh). Considering the above, the flywheels become reliable and friendly devices with the CO₂ emissions reduction.

To connect the microgrid to the main grid and make it available to loads, the power quality must meet the established requirements. As part of those requirements, the frequency and voltage of the system must be kept at an acceptable level without deviations. However, voltage drop has become one of the main power quality problems that affects sensitive loads, increases line losses, increases neutral conductor overloads, and increases rotation losses in AC drives frequency. About 92% of power quality problems in microgrids are due to voltage dips and 80% of these last only 20–50 ms. Flywheels, given their excellent characteristics, can be a viable alternative to counteract this phenomenon, which can quickly add or extract power from the grid, to keep the system voltage and frequency within the acceptable range. Flywheels can also aid the penetration of wind and solar energy into electrical power systems, improving their stability. The fast response characteristics

of flywheels make them suitable in applications including renewable energies to stabilize the frequency of the main grid and can be used to supply loads in short-term failures, increasing electrical reliability and stabilizes power fluctuations. Studies have been presented where if the implementation of the flywheel is combined with an active power filter for microgrid application, the power quality is greatly improved since the filter is used to filter the harmonic distortion and the flywheel to stabilize system power and provide an uninterruptible power supply for short-term failures. Now, by combining the flywheel with a traditional battery, needs for large capacity and fast response could be met simultaneously.

3.3 Compressed air

ESS based on compressed air is one of the most promising technology to address multiple problems derived from the high penetration of RES in microgrids due to their characteristics such as less restriction in their construction, high efficiency and respect for the environment. Compressed air is another method of storing energy so that it can be used at some other time, for example during periods of high demand. For this purpose, a turbine is used to expand the compressed gas, which can be transformed into mechanical energy [62]. During the period of low power demand, the excess power drives a reversible motor or generator unit, which in turn operates a set of compressors to inject air into the storage unit. This unit is shaped like an underground cavern. However, during low power generation to meet load demand, the stored compressed air is released and then heated by a heat source. The energy from the compressed air is then transferred to the turbine. It is here that a recovery unit is used to recycle residual thermal energy, further reducing fuel consumption and efficiency. Compressed air can be built from small to large scale. Nevertheless, it is suitable for a large-scale unit involving grid applications such as load shifting, peak-hour demand drop, and voltage and frequency control. The response time of

Figure 7.
Simplified diagram of compressed aire storage system.

this system is often high and can smooth energy production in both onshore and offshore wind plants. **Figure 7** illustrates the simplified schematic of a CAES plant.

There are many challenges in implementing this system on a large scale. One of them is the adequate selection of the geographical location with natural underground caverns [63]. For microgrid applications, it has been analyzed that this technology type improves the flexibility and load displacement of the distribution grid and the microgrid itself. In off-peak hours it can be used to supply power to the loads at peak-hours to achieve the economic benefit of the microgrid.

3.4 Fuel cells

Fuel cells as a promising energy source have once again attracted the attention of academia and industry since the beginning of the 21st century because this system type is suitable for the generation of electricity free of toxic emissions and applicable in DG as it has a high energy density by weight and low energy density by volume. In terms of environmental impact, this system type is desirable, leading governments around the world to improve the prospects for the hydrogen economy [64]. The cost per unit of electricity generation for this system has decreased given the raw material resources available, for which there are three types of electrolysis technology: alkaline, polymeric electrolyte membrane and high temperature solid oxide electrolysis [65]. Among these alternatives, alkaline electrolysis turns out to be the most suitable due to its technological maturity and low cost (\$525/kW).

The fuel cells integration for microgrid applications has proven to be a promising solution, as it can provide reliable, efficient, clean and quiet energy. In general, according to the role of the fuel cell, four emerging markets can be classified for microgrid applications: primary energy, backup energy, combined heat-energy, and fuel cell vehicles. This integration has several advantages such as economic benefits, prominent energy efficiency, environmental benefits, modularity, improved reliability and power quality. With regard to the latter, in the case of insufficient electricity supply, hydrogen is converted into electrical energy by the fuel cell. That is, the fuel cell can improve the power quality aspects in microgrids and enhance local reliability by balancing power demand and supply, minimizing power fluctuations induced by RES when combined with the electrolyzer to storing and reusing excess energy in the form of hydrogen. For this, the application of hydrogen-based energy storage in a low-voltage microgrid has been studied, achieving good results, where it is proposed that hydrogen cells may have a significant potential to help microgrid in a way effective if a wide range of RES are used. Finally, this system may be economically viable for the mitigation of daily load variability at the site, therefore, additional efforts are needed from academia and industry to explore the multiple uses of hydrogen in a microgrid context such as long-term storage, hydrogen vehicle fuel production, or in combination with the production of synthetic gases. Also, this system is proposed for load displacement applications, however, this technique is expensive and its efficiency is the most critical criterion for developing this technology [66].

3.5 Supercapacitor

ESS based in supercapacitors is one of the best options for microgrid applications due to their high short-term storage capacity, wide operating temperature range, cost-effectiveness, environmental advantages, long cycle times (more than 1×10^5 cycles) and its high efficiency ranging from 84 to 97%. This technology type is also used to energy manage in the microgrid, that is, when the load in the microgrid is light or when the energy supply is ample, the supercapacitors will store energy and when the energy of the microgrid is scarce or when there is some failure

in the main grid then the supercapacitors will supply power. Furthermore, they are capable of compensating for power fluctuations derived from load transients and, therefore, can improve power quality as well as extend the useful life of distributed generators [67]. This system type is so versatile that its applications are very varied, in fact, they have great application in the communications area and aeronautics, since they present a rapid response in load leveling and power balance [68, 69]. They also have application in railways, where an efficiency of 55.5% is recorded [70]. However, this system presents several challenges such as a high daily discharge rate of approximately 5–40% and the capital cost is also high, above \$6000/kWh. To overcome these challenges, multilayer supercapacitors are proposed, consisting of materials such as carbon, graphene or paper [71] or ultra-small silicon nanoparticles based on polyaniline electrodes [72].

Nowadays, people pay more and more attention to the power quality problem. On the one hand, the microgrid must meet the quality requirements of the load power supply and ensure minimal frequency fluctuation, voltage amplitude and waveform distortion. On the other hand, the main grid establishes strict requirements, such as the power factor limit, the current harmonic distortion rate and the maximum power to incorporate the microgrid as a whole with the main grid. That is why, through the inverter control unit, supercapacitors can be adjusted to provide active and reactive power to users, in order to improve power quality. STATCOM, in conjunction with supercapacitors, is also used to improve the power quality in microgrid. Finally, for uncontrollable micro-sources such as wind and solar, fluctuations caused by the power output of generators will decrease by improving power quality. This union of the STATCOM with supercapacitors solves the dynamic power quality problems, such as the voltage drops, the harmonic currents and the instantaneous voltage interruption by the combination of the sources with ESS. **Figure 8** illustrates the principal structure of a supercapacitor.

3.6 Superconducting magnetic energy storage (SMES)

This technology type works based on the electrodynamics principle [73] where energy is stored in a magnetic field created by the DC flow in a superconducting

Figure 8.
Schematic view of supercapacitor.

magnetic through an AC–DC converter (charge mode). However, the stored energy can be delivered back to the electrical grid using a DC–AC converter (discharge mode). This ESS has the drawback of having ohmic losses which generate heat in the system and, therefore, cause thermal instability in the superconducting magnetic [74]. This type of storage is classified into two types: high-temperature superconducting magnetic (HTSM) that operate at approximately 70° K and low-temperature superconducting magnetic (LTSM) that operate at approximately 7° K. **Figure 9** shows the basic diagram of the SMES system.

LTSM is a system that presents greater technological maturity compared to the HTSM since it provides a rapid response to the charge and discharge cycles in a few milliseconds. Among its most important characteristics are: high energy density (4 kW/l) and high efficiency, around 95–98% with a long service life of approximately 30 years. This system is available on the market in a wide range of powers ranging from 0.1–10 MW. With the system advancement, the capacity of this system is expected to increase to 100 MWh in the next 10 years. However, due to the complexity of the cooling system, the material of coil manufacture and the superconducting cables, the cost of installing is high, around \$10,000/kWh [50], therefore only they are used for short-term energy storage [75]. Finally, the SMES are highly applicable in microgrids due to their flexible capacity to exchange active and reactive power and thus improve the power quality, the power factor and stabilize the frequency. They also play an important role in the RES integration such as wind generators by controlling the output power of the wind farm and improving the stability of the electrical system. Actual research on this system type is based on reducing the cost of coils and cooling systems to result in an attractive and competitive system for users.

Table 1 summarizes the most important general characteristics of the ESS for microgrid applications described in this section and **Table 2** summarizes the most important problems of the power quality generated in microgrids and the ESS that are used for mitigating those problems.

3.7 Hybrid ESS

Hybrid Energy Storage Systems (HESS) refers to the integration of two or more ESS in order to achieve greater advantages and characteristics of high power and energy in order to improve the stability and reliability of the system by minimizing the power quality problems [85]. A proposal of the above is observed in **Table 2**. HESS control strategy is usually more complicated than that of conventional ESS

Figure 9.
Principal diagram of SMES system.

ESS	Energy Density (WH/L)	Power Density (WH/L)	Nominal Power (MW)	Life time (years)	Discharge efficiency	Response time	Storage duration	Discharge time at rated power	Technological maturity
Batteries	200–500 [56, 76]	1500–10,000 [76]	0–100 [56, 76]	5–16 [76, 77]	85% [56, 77]	Milisec. [77]	Min–Days [76]	Min–Hrs. [76, 78]	Mature
Flywheels	20–80 [76]	1000–2000 [76]	0.1–20 [76]	15–20 [76, 79]	90–93% [61]	Seconds [80]	Sec–Min. [76, 81]	Sec–Min. [76]	Market
Compressed air	2–6 [62, 76]	30–60 [62, 76]	300–1000 [63, 76]	20–40 [62, 76]	70–80% [82]	Minutes [62]	Hrs–Days [76]	1–20 Hrs [76, 82]	Market
Fuel cells	500–3000 [64, 76]	500 [76]	0–58.8 [65]	5–20 [66, 76]	59% [83]	Seconds [83]	Hrs–Days [76]	Sec–24 Hrs [76]	Developing
Supercapacitors	10–30 [67, 76]	100,000 [76]	0–0.3 [67, 76, 84]	10–30 [76, 85]	95–98% [86]	Milisec. [86]	Sec–Hrs [76, 87]	Milisec–1 Hr [76, 88]	Developing
SMES	0.2–6 [76]	1000–4000 [76]	0.1–10 [76]	20–30 [76]	95% [89]	Milisec. [90]	Min–Hrs [76]	Milisec–30 Min [76, 91]	Developing

Table 1.
Actual characteristics of ESS with electrical microgrids applications.

ESS	Power quality problems	Ref.
Batteries	Harmonic distortion	[92]
	Reactive currents	[82]
	Voltage sags	[93]
Flywheels	Voltage sags	[82]
Compressed air	Voltage fluctuations	[90]
	Frequency variation	[94]
Fuel cells	Voltage unbalance	[95, 96]
Supercapacitors	Voltage sags	[87]
	Harmonic distortions	[88]
	Voltage interruptions	[88]
SMES	Voltage sags	[97]
	Resonances	[97]

Table 2.
ESS implementation for microgrids applications for the power quality problems mitigation.

High energy supplier storage device	High power supplier storage device	Ref.
Batteries	Supercapacitors	[98, 99]
	SMES	[100]
	Flywheels	[101, 102]
Compressed air	Supercapacitors	[103]
	SMES	[92]
	Flywheels	[104]
	Batteries	[93]
Fuel cells	Supercapacitors	[105–107]
	SMES	[108]
	Flywheels	[109]
	Batteries	[110]

Table 3.
Possible configuration of the Hybrid ESS.

since they consider characteristics such as: charge and discharge, response time, energy distribution, life cycle and efficiency. HESS has been a subject in which several researchers from around the world have been involved, which use various storage techniques whose proposals are listed in **Table 3**. **Figure 10** shows hybrid ESS topology for microgrid applications.

In summary, the HESS for microgrid applications showed a better performance in stabilizing the frequency compared to the conventional ESS, for example, the battery life cycle improves due to obtaining protection against high charge and discharge cycles, frequency and against very high currents. Combining the batteries with some other technology extends their useful life from 5.7 to 9.2 years.

Figure 10.
Hybrid ESS topology for microgrid applications.

4. Overview of microgrid power quality

The term power quality is typically used for a wide range of electromagnetic events generated in electrical power systems. Therefore, many researchers have focused their studies on this topic and in recent years have published important findings about the problems of power quality when connecting microgrids to the electrical grids [111]. Power quality problems have recently become important given the need for reliable power to meet customer needs and the presence and extensive use of different types of electronic and electrical appliances in the commercial and industrial sectors. **Table 4** shows the PQ problems introduced in different DG units.

Power quality is a major concern in small-scale island or monovalent microgrids due to the presence of both non-linear and unbalanced loads, which make up a larger proportion of the total microgrid load. This situation creates voltage problems such as distortion, fluctuation, and sags/swells in a relatively weak system [112]. In a microgrid operating in island mode, disturbances such as distortion or voltage unbalance are more likely to occur due to very high impedance levels as well as load distribution compared to microgrids operating in grid-connected mode. In this mode of operation, the most frequent problems are disturbances and unbalanced voltages from the grid [113]. The voltage generated by sources such as wind, solar energy and fuel cells is intermittent and therefore these sources cannot be directly connected to the grid. **Table 3** shows the power quality problems introduced in different DG units. Power quality problems are analyzed based on the development of standards which define acceptable levels of distortions and deviations in various electrical quantities, such as current, voltage, and power factor.

Power Quality Issues	Solar	Wind	Small-hydro	Diesel
Voltage (sag/swell)	×	✓	✓	✓
(Over/under) voltage	×	✓	×	✓
Voltage unbalance	✓	×	×	×
Voltage transient	×	✓	×	×
Voltage harmonics	✓	✓	✓	×
Flicker	✓	✓	×	✓
Current harmonics	✓	✓	✓	×
Interruption	✓	✓	×	×

Table 4.
Power quality issues related to generation units of microgrid.

4.1 Sag/swell issues in microgrid applications

Voltage sag represent one of the most serious power quality challenges which are mainly caused by failures and lead to power sector instability, interruption in the operation of sensitive electronic devices, which is typical in microgrids that consist of DES. On the other hand, voltage swell, whose behavior is the opposite of voltage sags, is another serious power quality problem; however, it rarely occurs [114]. As the integration of DES in microgrids increases, many standards and grid codes impose new regulations, such as the ability to withstand voltage sags (LVRT) and voltage swell (HVRT). These regulations require that the microgrids disconnect from the grids in case the voltage sags or swell has a specific duration [115]. In the case of voltage sags, the German standard dictates that the microgrids must remain connected and withstand the event by providing reactive power even if the voltage sags to 0% of its nominal value for 0.15 s; otherwise, disconnection is mandatory. Otherwise, for voltage swell, the German standard dictates that the microgrid must remain connected even if the voltage swell to 120% of its nominal value for 0.1 s; otherwise, disconnection is mandatory [116]. The voltage level and duration of both the voltage sag and swell differ from one grid code to another.

4.2 Harmonics

Non-linear loads, electronic inverters, computer controllers, and variable speed motors that generate harmonics are applicable for microgrids. Most electrical system handle harmonics down to a specific amount; however, once the number of harmonics is large, it will cause communication failures, excessive line losses, overheating and tripping of the circuit breaker [117]. For this reason, many studies have been carried out in low voltage systems to analyze the power quality with respect to harmonic distortion problem. Considering that an microgrid is a low-voltage grid, then harmonic distortion as a severe power quality problem is an important problem for this type of system, and it should be investigated and addressed [118]. The sources that make up the microgrid consist mainly of RES with a power electronics device that produces harmonics in the system. Therefore, microgrids must reduce the emission of harmonics in accordance with what is dictated by current standards and codes [119].

As the specifications for the integration of microgrids into the main grids progress, various criteria about harmonic distortion is also implemented to ensure that the voltage and current are compatible with the grids as much as possible. Therefore, some requirements have been imposed on the limits of total and individual harmonic distortion (THD) for microgrids connected to the main electrical

grid [120–122]. For current THD (THD_i), all requirements, standards and grid codes are similar, that is, it should be less than 5%. UK standards (EREC G83) are more stringent and require $THD_i < 3\%$ [123]. Regarding the voltage THD (THD_v), the literature indicates that most countries follow the IEEE or IEC standards [124], in which the THD_v should not exceed 5% in a microgrid.

4.3 Voltage unbalance and fluctuation

Voltage unbalance is the most frequently occurring power quality phenomenon. The voltage unbalance factor (VUF), which is the ratio between the positive and negative sequence of voltage components, is used to measure the degree of unbalance in the system [125]. Voltage unbalance can have adverse effects on microgrids power electronics as well as power system devices. Power systems will suffer a greater number of losses and will be less stable in unbalanced conditions; therefore, it is essential to have a balanced system, especially with the diversity of sources that make up the microgrid [126]. In addition to the above, certain criteria have been established in the grid codes and standards to guarantee a stable and balanced integration of the microgrids to the main grid to limit the VUF. For example, IEEE Std [127] does not allow the VUF to exceed 3%. The IEC standard requires that all distribution generators keep the VUF below 2% [121]. The requirements of China and Germany state that the VUF should not exceed 2% [128, 129]. The Canadian Standards Association (CAN/CSA–C61000–2–2) established 2% as the maximum allowable VUF limit; for the case of unbalanced loads, 3% is allowed [130]. Generally, global standards indicate that the acceptable limit of VUF should be between 1% and 2% [131].

Fluctuations in microgrids are known as slow switch voltage variations or stable operations. Typically, voltage fluctuation in microgrids occurs due to changes in solar irradiation, wind speed, battery charge/discharge, and charge variations [132]. An essential detail to mention is that voltage fluctuations can be caused by sources whose output power changes widely over time.

5. Power quality mitigation devices, methods, and control strategies in microgrid applications

Power quality plays an increasingly important role in both energy supply and demand. With the participation of private companies in the distribution systems, it is expected that the power quality will be the deciding factor for consumers. Due to the increasing application of switching devices, power quality is likely to deteriorate. For this reason, this situation has drawn the attention of researchers to identify and suggest mitigation strategies for power quality problems to improve the microgrid performance.

5.1 Electronic controllers

Numerous studies reveal that advanced control technologies have been adopted to reduce the negative effects caused by the main grid connected to DG, undeniably improving aspects of power quality. Photovoltaic systems with voltage monitoring controllers have been established based on various control theories, achieving a significant improvement in the transition process during the connection of the photovoltaic systems that make up the microgrid [133]. Also, in the wind energy area, fuzzy logic-based controllers have been designed to control the inverter and PMSG (permanent magnet synchronous generator) operation, however, this could cause

oscillations near the operating point [134]. The smart solution concept has been introduced to mitigate the grid-side converter voltage ripple and improve certain aspects of power quality as well as the efficiency of the grid connected to a photo-voltaic system for microgrid application [135]. Finally, the experimental proposal of a magnetic flux control applied to a variable reactor integrated to a power quality controller has generated good results which validate the controller's capacity by mitigating a large percentage of harmonic penetration.

5.2 Dynamic voltage restorers (DVR)

A DVR is used to mitigate power quality problems in microgrids, mainly voltage sags and swell, thus improving the power quality of microgrids containing PV and batteries [136]. However, there are still some limitations in terms of LVRT. Therefore, in [137] they use an optimization technique to improve the performance of the DVR and thus solve the problem of voltage sags in microgrids using fuzzy logic. The effectiveness of this method reduced the VUF to less than 1%, while the current and voltage THD was reduced to less than 5%, as indicated in the current grid codes. Overall, DVR is one of the best devices to mitigate power quality issues when the microgrid is connected to the main grid. Finally, the equivalent circuit of the DVR is shown in **Figure 11**.

5.3 STATCOM and SVC

STATCOM and SVC are other devices used to solve power quality problems. These two devices, shown in **Figure 12**, are flexible AC transmission system devices and have been widely used in recent years to solve many power quality problems mainly due to RES integration, such as LVRT, to overcome voltage swell in PV systems [138] and wind systems [139]. The authors compared the efficacy of SVC and STATCOM in addressing voltage sag problems and found that STATCOM contributes more to the transient margin compared to SVC. In [140], STATCOM was used

Figure 11.
DVR – integrated microgrid system to mitigate power quality issues.

Figure 12. Typical configuration of: (a) STATCOM and (b) SVC used for power quality mitigation in microgrid systems.

to mitigate voltage fluctuations at high penetration DER for microgrid applications. Furthermore, STATCOM was used to mitigate voltage fluctuation and compensate for reactive power in microgrids in [141].

Another study demonstrated the ability of STATCOMs to reduce power fluctuation in microgrids and increase voltage regulation and power factor of the system. Regarding the mitigation of harmonics and THD in microgrids that use numerous RES such as wind turbines, diesel generators, fuel cells, microturbines and photovoltaic systems, the STATCOM reduced the harmonics according to the IEEE 1547 [142] standards. From the previous studies, it is concluded that STATCOM has a high ability to mitigate voltage fluctuation and improve the voltage profile in microgrids while mitigating voltage sags/swell to a lesser extent. The SVC was used in microgrids to improve the power quality of the grid and to increase the efficiency of the system during voltage sag. The authors in [143] used it for the same purpose in a microgrid

operating in island mode where it showed good performance. However, during severe brownout events, the SVC performs worse than the DVR and STATCOM.

5.4 FACTS

A Flexible AC Transmission System (FACTS) is a system composed of static equipment used for the transmission of electrical energy in AC. This device is intended to improve the controllability and increase the power transfer capacity of the main grid. Relevant studies incorporate a distribution static compensator (D-STATCOM), which injects a reactive component to provide rapid voltage regulation at the load terminal while maintaining an almost unity power factor ($PF=1$) [144]. IR (Intelligent Detection & Reconnection Technique), with a UPQC (Unified Power Quality Conditioner), is used for secondary control of the direct current link integrated to ESS. In addition, this technique compensates for voltage interruptions, reactive power, voltage drops, and harmonic distortion [145].

5.5 Unified power quality conditioner (UPQC)

The UPQC is the complete hybrid filter configuration and is identified as a multi-functional power conditioner used to compensate for different voltage disturbances, correct voltage fluctuations and prevent the entry of harmonic currents in the electrical grid. Originally, it was designed to mitigate disturbances that affect the performance of sensitive and/or critical loads and thus improve the power quality of the electrical system. The UPQC is a combination of serial and parallel controllers connected by a common DC bus, as shown in **Figure 13**. The parallel controller can generate or absorb reactive power at the point of connection. However, the serial controller is linked with the microgrid to control the parameters of line [146]. In [147], the fuzzy logic technique was implemented in a UPQC to minimize harmonic voltages and harmonic currents. The results show that the overall harmonic distortion was reduced from 8.93% to 3.34%. In [148] the design

Figure 13.
Typical configuration of: (a) STATCOM and (b) SVC used for power quality.

Factors	DSTATCOM	SVC	DVR	UPQC
Rating	Low rating	Low	High rating	Higher ratings are available
Speed of operation	Less than DVR	Less than DVR	Fast	Faster
Compensation method	Shunt compensation	Shunt	Series compensation	Both series and shunt
Active/reactive power	Reactive	Reactive	Active/reactive	Both
Harmonics	Less	Less	Much less	Least
Problems addressed	Sag, swell	Sag, swell	Sag, harmonics, fluctuation, swell	Swell, sag, harmonics, transient, unbalance and flicker
Cost	Normal	Average	High	Higher
Complexity	High	High	High	Higher

Table 5.
Comparison of various custom power devices.

of a suitable UPQC implemented in a microgrid is proposed to improve the harmonic distortion. The results show that the measured voltage sag occurs from 0.2 to 0.3 s with a THD of 2.69%. The analysis of the harmonic spectrum of the current without considering the UPQC shows a THD of 33.26%. Using UPQC you get a current THD of 3.11%, which meets IEEE 519–1992 standards of less than 5%. The UPQC is used in to mitigate the sags/swell in a microgrid consisting of a hybrid PV/ wind system by injection or absorption of reactive current. Mitigation of voltage sag and reduction of THD using the UPQC device using an adaptive neuro-fuzzy inference system (ANFIS). In [149], a UPQC is designed to power quality improve, and its performance was evaluated for various non-linear loads. Results show that UPQC reduced THD_i and THD_v when ANN control techniques were used to improve overall performance. THD is reduced from 12.6% to 3.7% and from 7.34% to 3.7% for voltage and current, respectively. Although UPQC is widely used to mitigate harmonics, the authors in [150] introduced UPQC to mitigate voltage unbalance in the microgrid connected to the grid. The results illustrate that the UPQC can detect the incidence of voltage unbalance and reduce the VUF to less than 2%, as established by grid codes.

Finally, based on the literature described, **Table 5** illustrates a comparison between the most popular devices used to mitigate power quality problems in microgrids. The comparison was made in terms of cost, maturity and performance. Overall, the DVR is superior to SVC and STATCOM in terms of voltage sags and/or swell, voltage fluctuations and unbalances, while the UPQC offers the best protection for sensitive loads from low quality sources.

5.6 Mitigation techniques

To improve power quality and, consequently, microgrid performance, harmonic mitigation techniques are implemented which can be: passive techniques, multi-pulse rectifier techniques, and active harmonic cancellation techniques. For low-power industrial applications, traditional harmonic mitigation techniques such as AC–DC inductors are used due to their low cost, reliability, and

simplicity [151], as well as passive harmonic mitigation techniques to analyze grid disturbances. In the latter, harmonic mitigation depends, to a great extent, on the grid configuration [152].

Additionally, methods have been implemented for estimating the positive sequence phase angle based on the Discrete Fourier Transform [153] where the transient response of a single cycle that is immune to harmonics, electromagnetic noise, unbalance voltage, and frequency variations in microgrid applications. The implementation of “shunt” type active power filters is another way to improve the power quality of a microgrid at distribution level using intelligent learning algorithms [154]. Another way to counteract power quality problems due to the RES incorporation is through active power filter control methods where the inverter injects the power generated by the renewable source into the main grid (it works as an active power filter and injects power into the main grid). Basically, the inverter operates in two modes, (a) mode 1: it injects power generated by RES, improving the power quality, and (b) mode 2: no power is generated and acts as a “shunt” type active power filter [155].

6. Issues and challenges of the ESS for microgrid applications

Carbon emission drives the world to replace conventional power generation with as much renewable generation as possible. However, when integrating the energy generated by RES to the grid, problems are generated in the power quality, for which new techniques must be evaluated to mitigate these problems and thus improve the microgrids performance that contain RES. The power quality concept is not strictly defined yet for microgrid application. Therefore, the responsibility for maintaining a good electrical environment rests with the dealer, the manufacturer and the user. As previously mentioned, DG generates power quality problems: power flow variation which causes voltage and frequency deviations, voltage and current unbalance, power factor poor, harmonic distortion, voltage flickers as well as voltage drops, among others. Faced with these problems, ESS play a key role when meeting different needs of this kind. Depending on the application field, there are three general cases: (i) storage for power quality improvement, (ii) emergency storage and (iii) storage for grid management. In the first case, the power quality can be improved with systems that give up the accumulated energy in the shortest possible time (seconds), as is the case with supercapacitors that with up to 95% efficiency and barely 5% of daily self-discharge losses, they are capable of storing an unusually high energy density. On the other hand, emergency storage is designed to provide energy, activating in a matter of minutes and remaining in operation to ensure continuity of supply. This is the case with flywheels coupled to generators, which allow short-term energy storage with efficiencies of up to 85%. However, being mechanical systems, this figure drops by up to 40% after just one day of storage due to friction losses. The kinetic energy they store is designed to be returned through generators to support sudden changes in electricity demand. Finally, storage for grid management, which are systems that allow the prolonged storage of large amounts of energy and that are capable of gradually transferring it to support the management of the grid itself. This is the type of energy storage that allows renewable energy to be stored for later use in a manageable way. As can be seen, there are still niches of opportunity for the research field regarding the development of ESSs and their microgrid application to meet the requirements of international standards in the power quality area. The most important challenges faced by ESSs and their microgrid application are listed below.

6.1 Suppression of power fluctuations

RES, such as wind and solar, are often unstable energy sources. The power production of the wind turbines and solar panels is intermittent due to climatic variations such as clouds on the photovoltaic panels or the wake effect of the wind turbine as well as the shadow effect of the tower. Knowing that microgrid is not as strong as the grid, power fluctuations cause power quality problems, specifically notable variations in grid frequency and voltage, making microgrid unstable.

6.2 LVRT capability

When some incidents occur in the microgrid or in the main grid, the voltage can drop suddenly and cause some GD sources to disconnect, ceasing to produce power. If a certain GD source in the microgrid trips due to voltage dips, this can cause other GD sources to disconnect from the main grid and cause a cascading power outage. Therefore, GD sources, such as wind turbines or solar panels, are required to remain connected to the grid during the presence of voltage sags, that is, they have the ability to operate in low-voltage conditions. According to [156], by integrating the ESS into the microgrid, the capacity of wind generators to operate in voltage dips can be improved.

6.3 Spinning reserve

Power generation is highly dependent on weather conditions, which are constantly changing. As a result, power shortages can occur more frequently into the microgrid. Therefore, the spinning reserve issue is very important for the microgrid operation. With the ESS implementation, most of the spinning reserve requirements in the generators for microgrid applications will be able to be met, that is, with the help of the ESS, the generators will be able to operate closer to their nominal value. Also, ESS can react faster than many generators, so power shortages can be quickly recovered. The most important problem with spinning reserve technology is determining how much power to reserve. Both the reliability and economics of the microgrid must be considered when deciding the amount of spinning reserve. This will undoubtedly improve the microgrid performance and power quality aspects [157].

7. Conclusion

Actually, ESS and the availability of mitigation methods are an alternative solution for the potential use of RES for microgrid applications. Many researchers are involved in the development of ESSs and their microgrid applications to manage the energy balance by storing it during off-peak hours at reduced cost. Therefore, an optimal ESS model is the key to a successful storage future. However, efficient development of ESSs for microgrid applications is a challenge in power quality terms. Numerous studies and reviews about ESS are limited to analyzing the types, characteristics, configurations as well as the operational advantages and disadvantages, but very little is addressed to the issue of improving the power quality into microgrids through the ESS. Therefore, the key contribution of this study has been the exhaustive analysis of the ESS actual state for microgrid applications as well as the issues and challenges they face in meeting power quality standards. This review proposes some technical and operational suggestions:

- Advanced research is required to improve the capabilities of ESSs for microgrid applications in terms of materials, size, cost and efficiency considering the adequate functionality of the system and its acceptance in the market.
- An advanced power electronics system in conjunction with ESSs could help overcome switching challenges and power quality issues into microgrids, addressing issues such as overheating, harmonic distortion, and charge–discharge for efficient operation of the system.
- Development of appropriate techniques for the ESS optimal sizing and thus ensure efficient operation in terms of: energy arbitrage, energy backup, energy demand at peak hours and voltage support.
- Advanced research is required on the integration of ESSs for microgrid applications, addressing the issue of complexity in synchronization, improving the performance of integration or operation in “island” mode.

These suggestions would be notable contributions towards the maturity of ESSs, which are expected to dominate the electricity market in the future. In addition, from this review, some important and specific recommendations relevant to power quality mitigation issues and techniques are summarized below for further improvement:

- Further studies should consider more RES to conform to microgrids, such as hydropower, biomass and geothermal, along with non-RES such as diesel generator to show the effects of a wide variety of sources on energy quality.
- Devices such as DVR and UPQC must use a fast and accurate method to detect power quality problems in microgrids.
- In the future, generalized validation and benchmarking methods can be applied for mitigation of power quality in microgrids using optimization methods that take into account uncertain climatic conditions.
- International system operators should adopt a single or constant limit for each integration requirement to reduce differences between current technical requirements and thus harmonize power quality requirements in microgrids.

The above recommendations may be the most important contributions towards improving the power quality in microgrids, especially with renewable generation sources, which are expected to dominate the energy market in the near future. Future studies based on the results of this review may also help to address current drawbacks of microgrids in developing new standards and preventing new power quality problems.

Conflict of interest

The authors declare no conflict of interest.

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References

- [1] “EPRI–DOE of Energy Storage for Transmission and Distribution Applications,” EPRI, and the U.S. Department of Energy, Palo Alto and Washington, CA and DC, 2003, EPRI–DOE no. 1001834.
- [2] S. B. groupe Energie, “Energy Storage Technologies for Wind Power Integration,” Tech. Rep., Université Libre de Bruxelles, Faculté des Sciences Appliquées, 2010.
- [3] “EPRI–DOE Handbook Supplement of Energy Storage for Grid Connected Wind Generation Applications,” EPRI, and the U.S. Department of Energy, Palo Alto and Washington, CA and DC, 2004, EPRI–DOE no. 1008703.
- [4] Manz D, Schelenz O, Chandra R, Bose S, de Rooji M, Bebic J. Enhanced Reliability of Photovoltaic Systems with Energy Storage and Controls, Tech. Rep., National Renewable Energy Laboratory, 2008.
- [5] Ton D, Peek GH, Hanley C, Boyes J. Solar Energy grid Integration Systems Energy Storage (SEGIS-ES), Sandia Nat. Labs, 2008.
- [6] F. Diaz F, Bianchi FD, Sumper A, Gomis O. Control of a Flywheel Energy Storage System for Power Smoothing in Wind Power Plants, *IEEE Transaction on Energy Conversion*, 2014;**29**:204-214.
- [7] Guerrero JM, Loh PC, Lee TL, Chandorkar M. Advanced control architectures for intelligent microgrids Part II: Power quality, energy storage, and AC/DC microgrids, *IEEE Trans. Ind. Electron.*, 2013;**60**:1263-1270.
- [8] Liu F, Liu J, Zhang H, Xue D. Stability Issues of Z+Z Type Cascade System in Hybrid Energy Storage System (HESS), *IEEE Trans. Power Electron.* 2014;**29**: 5846-5859.
- [9] Wang P, Xiao J, Setyawan L. Hierarchical Control of Hybrid Energy Storage System in DC Microgrids, *IEEE Trans. Ind. Electron.* 2015;**99**:1-15.
- [10] Han J, Solanki SK, Solanki K. Coordinated predictive control of a wind/battery microgrid system, *IEEE J. Emerg. Sel. Top. Power Electron.* 2013; **1**:296-305.
- [11] Tan X, Li Q, Wang H. Advanced and trends of energy storage technology in Microgrids, *Int. J. Electr. Power Energy Syst.* 2013;**44**:179-191.
- [12] Bhuiyan FA, Yazdani A. Energy storage technologies for grid-connected and off-grid power system applications, 2012 IEEE Electr. Power Energy Conf. EPEC 2012, 2012:303-310.
- [13] Katsanevakis M, Stewart RA, Lu J. Aggregated applications and benefits of energy storage systems with application-specific control methods: A review. *Renewable Sustainable Energy Review.* 2017;**75**:719-741.
- [14] Rohit AK, Rangnekar S. An overview of energy storage and its importance in Indian renewable energy sector, *Journal of Energy Storage.* 2017;**13**: 447-456.
- [15] Lasseter RH. MicroGrids. 2002;305-308.
- [16] Bragard M, Soltan N, Thomas S, Doncker RW. The balance of renewable sources and user demands in grids: Power electronics for modular battery energy storage systems. *IEEE Trans. Power Electron.* 2010;**25**:3049-3056.
- [17] Levron Y, Shmilovitz D. Power systems optimal peak-shaving applying secondary storage. *Electr. Power Syst. Res.* 2012;**89**:80-84.

- [18] Mohd A, et al., Challenges in integrating distributed Energy storage systems into future smart grid. 2008 IEEE Int. Symp. Ind. Electron. 2008:1627-1632.
- [19] Díaz F, Sumper A, Gomis O, Villafáfila A. A review of energy storage technologies for wind power applications. *Renew. Sustainable Energy Review*. 2012;**16**:2154-2171.
- [20] Huff G, et al., DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA, Rep. SAND2013- ..., no. July, p. 340, 2013.
- [21] Feltes JW, Grande-Moran C. Black start studies for system restoration. IEEE Power Energy Soc. 2008 Gen. Meet. Convers. Deliv. Electr. Energy 21st Century, PES, pp. 1-8, 2008.
- [22] Atwa YM, El-Saadany EF, Salama MMA, Seethapathy R. Optimal Renewable Resources Mix for Distribution System Energy Loss Minimization. *IEEE Trans. Power Systems*. vol. 2010;**1**:360-370.
- [23] Mundackal J, Varghese AC, Sreekala P, Reshmi V. Grid power quality improvement and battery energy storage in wind energy systems. 2013 Annu. Int. Conf. Emerg. Res. Areas 2013 Int. Conf. Microelectron. Commun. *Renew. Energy*, 1-6, 2013.
- [24] Carrasco JM, et al., Power Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey. *IEEE Trans. on Industrial Electronics*. 2006;**53**:1002-1016.
- [25] Hill CA, Such MC, Chen D, Gonzalez J, Grady WM. Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation. *IEEE Trans. Smart Grid*. 2012;**3**:850-857.
- [26] Subburaj AS, Pushpakaran BN, Bayne SB. Overview of grid connected renewable energy based battery projects in USA. *Renew. Sustain. Energy Reviews*. 2015; **45**:219-234.
- [27] Leou R. Electrical Power and Energy Systems An economic analysis model for the energy storage system applied to a distribution substation. *Int. J. Electr. Power Energy Syst*. 2012;**34**: 132-137.
- [28] Saez A. Analysis and Comparison of Battery Energy Storage Technologies for Grid Applications. IEEE Grenoble Conference, June 2013.
- [29] US State Department, "US Climate Action Report," 2014.
- [30] J. G. J. (PBL) Olivier, G. (EC-J. Janssens-Maenhout, M. (EC-J. Muntean, J. A. H. W. (PBL) Peters, "Trends in Global CO₂ Emissions: 2016 Report," *PBL Netherlands Environ. Assess. Agency Eur. Comm. Jt. Res. Cent.*, pp. 86, 2016.
- [31] Hacker F, Harthan R, Matthes F, Zimmer W. Environmental impacts and impact on the electricity market of a large scale introduction of electric cars in Europe—Critical Review of Literature," *ETC/ACC Tech. Pap.*, vol. 4, pp. 56-90, 2009.
- [32] Conti S, Nicolosi R, Rizzo SA, Zeineldin HH. Optimal dispatching of distributed generators and storage systems for MV islanded microgrids. *IEEE Transaction Power Delivery*. 2012;**27**: 1243-1251.
- [33] Etxeberria A, Vechiu I, Camblong H, Vinassa JM. Comparison of three topologies and controls of a hybrid energy storage system for microgrids. *Energy Convers. Management*. 2012;**54**:113-121.
- [34] Department of Energy Office of Electricity Delivery and Energy Reliability. *Summary Report: 2012 DOE Microgrid Workshop*. 2014.

- [35] Colet A, Ruiz A, Gomis O, Alvarez A, Sudria A. Centralized and distributed active and reactive power control of a utility connected microgrid using IEC61850. *IEEE Syst. J.* 2012;**6**: 58-67.
- [36] Aghamohammadi MR, Abdolahinia H. A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded Microgrid. *Int. J. Electr. Power Energy Syst.* 2014;**54**:325-333.
- [37] Daneshi H, Khorashadi H. Microgrid energy management system: A study of reliability and economic issues. *IEEE Power and Energy Society General Meeting*, pp. 1-5, 2012.
- [38] Trujillo CL, Velasco D, Figueres E, Garcerá G. Analysis of active islanding detection methods for grid-connected microinverters for renewable energy processing. *Appl. Energy*, 2010;**87**: 3591-3605.
- [39] Ma T, Yang H, Lu L. A feasibility study of a stand-alone hybrid solar-wind-battery system for a remote island. *Appl. Energy*. 2014;**121**:149-158.
- [40] Rajesh KS, Dash SS, Rajagopal R, Sridhar R. A review on control of AC microgrid, *Renew. Sustain. Energy Rev.* 2017;**71**:814-819.
- [41] Zuo S, Davoudi A, Song Y, Lewis FL. Distributed finite-time voltage and frequency restoration in islanded AC microgrids, *IEEE Trans. Ind. Electron.*, 2016;**63**:5988-5997.
- [42] Veneri O. *Technologies and Applications for Smart Charging of Electric and Plug-in Hybrid Vehicles*. 1st ed. Cham, Switzerland: Springer, 2017, pp. 39-64.
- [43] Mohamad AMEI, Mohamed YARI, Investigation and assessment of stabilization solutions for DC microgrid with dynamic loads. *IEEE Trans Smart Grid*, 2019;**10**:5735-5747.
- [44] Lotfi H, Khodaei A. AC versus DC microgrid planning, *IEEE Trans. Smart Grid*, 2017;**8**:296-304.
- [45] Ma T, Cintuglu MH, Mohammed O.A. Control of a hybrid AC/DC microgrid involving energy storage and pulsed loads, *IEEE Trans. Ind. Appl.*, 2017 ;**53**:567-575.
- [46] Mehrizi-Sani A. Iravani R. Potential-function based control of a microgrid in islanded and grid-connected modes. *IEEE Trans. Power Syst.*, 2010; **25**:1883-1891.
- [47] Alsaidan I, Khodaei A, Gao W. A comprehensive battery energy storage optimal sizing model for microgrid applications. *IEEE Trans. Power System*. 2018;**33**:3968-3980.
- [48] Ibrahim H, Belmokhtar H, Ghandour M. Investigation of usage of compressed air energy storage for power generation system improving—Application in a microgrid integrating wind energy. *Energy Procedia*, 2015;**73**:305-316.
- [49] Arani AAK, Karami H, Gharehpetian HB, Hejazi MSA. Review of flywheel energy storage systems structures and applications in power systems and microgrids. *Renewable Sustainable Energy Reviews*. 2017; **69**:9-18.
- [50] Inthamoussou FA, Pegueroles J, Bianchi FD. Control of a supercapacitor energy storage system for microgrid applications. *IEEE Trans. Energy Convers.* 2013;**28**:690-697.
- [51] Nguyen TT, Yoo HJ, Kim HM. Applying model predictive control to SMES system in microgrids for eddy current losses reduction. *IEEE Trans Appl. Superconduct.* 2016; **26**:1-25.
- [52] Konstantinopoulos SA, Anastasiad AG, Vokas GA, Kondylis GP, Polyzakis A. Optimal management

of hydrogen storage in stochastic smart microgrid operation. *Int. J. Hydrogen Energy*. 2017;**43**:490-499.

[53] Hannan MA, Hoque MM, Mohamed A, Ayob A. Review of energy storage systems for electric vehicle applications: Issues and challenges. *Renew. Sustain. Energy Review*. 2017;**69**:771-789.

[54] Oriti G, Julian AL, Anglani N, Hernandez GD. Novel hybrid energy storage control for single-phase energy management system in a remote islanded microgrid. in *Proc. IEEE Energy Conversion Congr. Expo. (ECCE)*, Oct. 2017, pp. 1552-1559.

[55] Guney MS, Tepe Y. Classification and assessment of energy storage systems. *Renew Sustain. Energy Reviews*. 2017;**75**:1187-1197.

[56] Garimela N, Nair NKC. Assessment of battery energy storage systems for small-scale renewable energy integration. In: *IEEE TENCON*, pp. 1-6, 2009.

[57] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: A critical review. *Prog. Nat. Sci.*, 2009;**19**:291-312.

[58] Hadjipaschalis I, Poullikkas A, Efthimiou V. Overview of current and future energy storage technologies for electric power applications. *Renew. Sustainable Energy Reviews*., 2009;**-13**:1513-1522.

[59] Abdin Z, Khalilpour KR. Single and Polystorage Technologies for Renewable based Hybrid Energy Systems. In *Polygeneration with Polystorage for Chemical and Energy Hubs*, pp. 77-131, 2019.

[60] Faisal M, Hannan MA, Ker PJ, Hussain A, Mansor MB, Blaabjerg F. Review of energy storage system technologies in microgrid applications:

Issues and challenges. *IEEE Access*, 2018; **6**:35143-35164.

[61] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appliyng Energy*, 2015;**137**:511-536.

[62] Liu H, He Q, Borgia A, Pan L, Oldenburg CM. Thermodynamic analysis of a compressed carbon dioxide energy storage system using two saline aquifers at different depths as storage reservoirs. *Energy Convers. Manage.*, 2016;**127**:149-159.

[63] Yao E, Wang H, Wang L, Xi G, Maréchal F. Thermoeconomic optimization of a combined cooling, heating and power system based on small scale compressed air energy storage. *Energy Convers. Manage.*, 2016;**118**: 377-386.

[64] Niaz S, Manzoor T, Pandith AH. Hydrogen storage: Materials, methods and perspectives. *Renew. Sustain. Ene Reviews*., 2015; **50**:457-469.

[65] Bhandari R, Trudewind CA, Zapp P. Life cycle assessment of hydrogen production via electrolysis—A review. *Journal Cleaner Prod.*, 2014; **85**:151-163.

[66] Kousksou T, Bruel P, Jamil A, El Rhafiki T, Zeraouli Y. Energy storage: Applications and challenges. *Sol. Energy Mater. Sol. Cells*, 2014;**120**: 59-80.

[67] Kusko A, DeDad J. Stored energy—short-term and long-term energy storage methods for standby electric power systems. *IEEE Trans. Industrial Applications*. 2007;**13**:66-72.

[68] Crider JM, Sudhoff SD. Reducing impact of pulsed power loads on microgrid power systems. *IEEE Trans. Smart Grid*. 2010;**1**: 270-277.

- [69] Farhadi M, Mohammed O. Energy storage technologies for high-power applications. *IEEE Trans. Ind. Appl.*, 2016;**52**:1953-1961.
- [70] Zhang X, Zhang Z, Pan H, Salman W, Yuan Y, Liu Y. A portable high-efficiency electromagnetic energy harvesting system using supercapacitors for renewable energy applications in railroads. *Energy Convers. Manage.*, 2016;**118**:287-294.
- [71] Dubal DP, Ayyad O, Ruiz V, Gómez P. Hybrid energy storage: The merging of battery and supercapacitor chemistries. *Chem. Soc. Rev.*, 2015; **44**:1777-1790.
- [72] Liu Q, Nayfeh MH, Yau ST. Supercapacitor electrodes based on polyaniline–silicon particle composite. *Journal Power Sources*, 2010;**195**: 3956 –3959.
- [73] Gong K, Shi J, Liu Y, Wang Z, Ren L, Zhang Y. Application of SMES in the microgrid based on fuzzy control. *IEEE Trans. Appl. Supercond.* 2016; **26**:1-5.
- [74] Ridgers TJ, Boucey C, Frambach JP, et al., Challenges in integrating distributed energy storage systems into future smart grid. *IEEE radio and Wireless, Symposium*, 2008, pp. 547-550.
- [75] Molina MG, Mercado PE. Power flow stabilization and control of microgrid with wind generation by superconducting magnetic energy storage. *IEEE Trans. Power Electron.* 2011; **26**:910-922.
- [76] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: A critical review. *Prog. Nat. Sci.*, 2009;**19**:291-312.
- [77] Walsh F. Progress & challenges in the development of flow battery Technology. In: *The 1st Int. Flow Battery Forum (IFNF)*: pp. 1-8, 2010.
- [78] Xu L, Miao Z, Fan L, Gurlaskie G. Unbalance and Harmonic Mitigation using Battery Inverts. *IEEE 2015 North American Power Symposium (NAPS)*, Charlotte, USA, 2015.
- [79] Faisal M, Hannan MA, Ker PJ, Hussain A, Mansor MB, Blaabjerg F. Review of energy storage system technologies in microgrid applications: Issues and challenges. *IEEE Access*, 2018;**6**:35143-35164.
- [80] Arghandeh R, Pipattanasomporn M, Rahman S. Flywheel Energy Storage System for Ride-Through Applications in a Facility Microgrid. *IEEE Trans. on Smart Grid.*, 2012;**3**:1955-1962.
- [81] Samineni S, Johnson BK, Hess HL, Law JD. Modeling and analysis of a flywheel energy storage system for voltage sag correction. *IEEE Trans. Ind. Appl.*, 2006;**42**:42-52.
- [82] Westering W, Hellendoorn H. Low voltage power grid congestion reduction using a community battery: design principles, control and experimental validation. *Electrical Power and Energy Systems*. 2020;**114**:1-9.
- [83] Igrahim H, Belmokhtar K, Ghandour M. Investigation of usage of Compressed Air Energy Storage for Power Generation System Improving–Application in a Microgrid Integrating Wind Energy. *9th Int. Renewable Energy Storage Conf., IRES*, pp. 305-316, 2015.
- [84] Goharshenasan P, Joorabian M, Seifossadat SG. A new proposal for the design of hybrid AC/DC microgrids toward high power quality. *Turkish Journal of Electrical Engineering & Computer Sciences*, 2017; **25**:4033-4049.
- [85] Hemmati R, Saboori H. Emergence of hybrid energy storage systems in renewable energy and transport applications—A review. *Renew. Sustain. Energy Reviews.*, 2016; **65**:11-23.

- [86] Dou X, Quan X, Wu Z, Hu M, Sun J, Yang K, Xu M. Improved Control Strategy for Microgrid Ultracapacitor Energy Storage System. *Energy*, 2014;7:8095-8115.
- [87] Sharma R, Suhag S. Supercapacitor utilization for power smoothening and stability improvement of a hybrid energy system in a weak grid environment. *Turkish Journal of Electrical Engineering & Computer Sciences*, 2018;26:347-362.
- [88] Cericola D, Novák P, Wokaun A, Kötzt R. Hybridization of electrochemical capacitors and rechargeable batteries—an experimenttal analysis. *J. Power Sources*, 2011;196:10305-10313.
- [89] Peng, et. al., Application of superconducting magnetic energy storage in microgrid containing new energy. *IOP Conference series: Materials Science and Engineering*, vol. 382, 2018.
- [90] Morandi A, Trevisani L, Negrini F, Ribani PL, Fabbri M. Feasibility of superconducting magnetic energy storage on board of ground vehicles with present state of the art superconductors. *IEEE Transaction Appl. Supercond.*, 2012;22:1558-1569.
- [91] Suzuki S, Baba J, Shutoh K, Masada E. Effective applications of superconducting magnetic energy storage (SMES) to load leveling for high speed transportation system. *IEEE Trans. Appl. Supercond.*, 2004;14: 713-716.
- [92] Teleke S, Baran M, Huang A, Bhattacharya S, Anderson L. Control strategies for battery energy storage for wind farm dispatching. *IEEE Trans. on Energy Convers.*, 2009;24: 725 –732.
- [93] Nelson R. Power requirements for batteries in hybrid electric vehicles. *J. Power Sources*, 2000;91:2-26.
- [94] Latha R, Palanivel S, Kanakaraj J. Frequency control of Microgrid based on Compressed Air Energy Storage System. *Distribute Generation and Alternative Energy Journal*, 2013;27:8-19.
- [95] Shi R, Zhang X, Xu H, Liu F, Li W, Mao F, Yu Y. A Method for Microgrid connected Fuel Cell Inverters Seamless Transitions between Voltage Source and Current Source Modes. 9th International Conference on Power Electronics–ECCE, Seoul, Korea, vol. 63, pp. 1-5, 2015.
- [96] Vigneysh T, Kumarappan N, Arulraj R. Operation and control of wind/fuel cell based hybrid microgrid in grid connected mode. *IEEE International Multi-Conference on Automation, Computing, Communication, Control and Compressed Sensing, India*, pp. 754-758, 2013.
- [97] Ngamroo I, Karaipoom T. Improving Low-Voltage Ride-Through Performance and Alleviating Power Fluctuation of DFIG Wind Turbine in DC Microgrid by Optimal SMES with Fault Current Limiting Function. *IEEE Trans. on Appl. Superconduct.*, 2014; 24:1-16.
- [98] Bolborici V, Dawson FP, Lian KK. Hybrid energy storage systems: connecting batteries in parallel with ultracapacitors for higher power density. *IEEE Ind. Applying Mag.*, 2014;20:31-40.
- [99] Gao L, Douglas R, Liu S. Power enhancement of an actively controlled battery/ultracapacitor hybrid. *IEEE Transaction Power Electronic*, 2005;20:263-243.
- [100] Ise T, Kita M, Taguchi A. A hybrid energy storage with a SMES and secondary battery. *IEEE Trans. Appl. Supercond*, 2005;15:1915-1918.
- [101] Briat O, Vinassa JM, Lajnef W, Azzopardi S, Woïrgard E. Principle, design and experimental validation of a

flywheel-battery hybrid source for heavy-duty electric vehicles. *IET Electr Power Appl*, 2007;**1**:665-674.

[102] Prodromidis GN, Coutelieris FA, Simulations of economic and technical feasibility of battery and flywheel hybrid energy storage systems in autonomous projects. *Renewable Energy*, 2012;**39**:149-153.

[103] Lemofouet S, Rufer A. A hybrid energy storage system based on compressed air and supercapacitors with maximum efficiency point tracking. *IEEE Trans. Ind. Electron.*, 2006;**53**:1105-1115.

[104] Zhao P, Dai Y, Wang J. Design and thermodynamic analysis of a hybrid energy storage system based on A – CAES (adiabatic compressed air energy storage) and FESS (flywheel energy storage system) for wind power application. *Energy*, 2014;**70**: 674-684.

[105] Wu Y, Gao H. Optimization of fuel cell and supercapacitor for fuel-cell Electric vehicles. *IEEE Trans. Veh. Technol.*, 2006;**55**:1748-1755.

[106] Zhu GR, Loo KH, Lai YM, Tse CK. Quasi-maximum efficiency point tracking for direct methanol fuel cell in DMFC/supercapacitor hybrid energy system. *IEEE Trans. Energy Convers.*, 2012;**27**:561-571.

[107] Martín IS, Ursúa A, Sanchis P. Integration of fuel cells and supercapacitors in electrical microgrids: Analysis, modelling and experimental validation. *Int. Journal Hydrogen Energy*, 2013; **38**:11655-11671.

[108] Loui H, Strunz K. Superconducting Magnetic Energy Storage for energy cache control in modular distributed hydrogenelectric energy systems. *IEEE Trans. Appl. Supercond.*, 2007; **17**:361-364.

[109] Lee H, Shin BY, Han S, Jung S, Park B, Jang G. Compensation for the power fluctuation of the large scale wind farm using hybrid energy storage applications. *IEEE Trans. Appl. Supercond.*, 2012;**22**: 57019.

[110] Zandi M, Payman A, Martin JP, Pierfederici S, Davat B, MeibodyTabar F. Energy management of a fuel cell/ supercapacitor/battery power source for electric vehicular applications. *IEEE Trans. Veh. Technol.*, 2011;**60**: 433-443.

[111] Palizban O, Kauhaniemi K, Guerrero J. M. Microgrids in active network management—Part II: System operation, power quality and protection, *Renew. Sustain. Energy Rev.* 2014;**36**: 440-451.

[112] Li YW, He J. Distribution system harmonic compensation methods An overview of DG-interfacing inverters. *IEEE Ind. Electron. Mag.*, 2014;**8**:18-31.

[113] Kow K W, Wong YW, Rajkumar RK. Power quality analysis for PV grid connected system using PSCAD/EMTDC. *Int. J. Renew. Energy Res.*, 2015;**5**:121 –132.

[114] Hu WX, Xiao XY, Zheng ZX. Voltage sag/swell waveform analysis method based on multidimension characterization. *IET Gener., Transmiss. Distrib.*, 2020;**14**:486-493.

[115] Zheng F, Chen Y, Zhang Y, Lin Y, Guo M. Low voltage ride through capability improvement of microgrid using a hybrid coordination control strategy. *Journal Renew. Sustain. Energy*, 2019;**11**:034102.

[116] Erlich I, Bachmann U. Grid code requirements concerning connection and operation of wind turbines in Germany. in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2005:1253-1257.

- [117] Alwaz N, Raza S, Ali S, Bhatti MKL, Zahra S. Harmonic power sharing and power quality improvement of droop controller based low voltage islanded microgrid, presented at the Int. Symp. Recent Adv. Electr. Eng. (RAEE), Aug. 2019, pp. 1-6.
- [118] Astorga OAM, Silveira JL, and J. C. Damato, The influence of harmonics from non-linear loads in the measuring transformers of electrical substations, in *Laboratory of High Voltage and Electric Power Quality, Optimization Group of Energy Systems*, vol. 1, no. 4. São Paulo, Brazil: Sao Paulo State Univ., 2006, pp. 275-280.
- [119] Blooming TM, Carnovale DJ. Application of IEEE STD 519-1992 harmonic limits, in *Proc. Conf. Rec. Annu. Pulp Paper Ind. Tech. Conf.*, Jun. 2006, pp. 1-9.
- [120] Cho N, Lee H, Bhat R, Heo K. Analysis of harmonic hosting capacity of IEEE Std. 519 with IEC 61000-3-6 in distribution systems, presented at the IEEE PES GTD Grand Int. Conf. Expo. Asia (GTD Asia), 2019, pp. 730-734.
- [121] Cleveland FM. IEC 61850-7-420 communications standard for distributed energy resources (DER), presented at the IEEE Power Energy Soc. Gen. Meeting-Convers. Del. Elect. Energ 21st Century, Jul. 2008, pp. 1-4.
- [122] *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems-Amendment 1*, IEEE Standard 1547, Inst. Elect. Electron. Eng., New York, NY, USA, 2014.
- [123] Wu YK, Lin JH, Lin HJ. Standards and guidelines for grid-connected photovoltaic generation systems: A review and comparison. *IEEE Trans. Ind. Appl.*, 2017;53:3205-3216.
- [124] Gao DW, Muljadi E, Tian T, Miller M, Wang W. Comparison of standards and technical requirements of grid-connected wind power plants in China and the United States. Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-5D00-64225, 2016.
- [125] Kim YJ. Development and analysis of a sensitivity matrix of a three-phase voltage unbalance factor, *IEEE Trans. Power Syst.*, 2018;33:3192-3195.
- [126] Savaghebi M, Jalilian A, Vasquez JC, Guerrero JM, Secondary control scheme for voltage unbalance compensation in an islanded droopcontrolled microgrid, *IEEE Trans. Smart Grid*, 2012;3:797-807.
- [127] State Grid Corporation of China. Technical rule for PV power station connected to power grid, Chin. Enterprise Standards, Tech. Rep. GB/T 19964, 2012.
- [128] Wu YK, Lin JH, Lin HJ. Standards and guidelines for grid-connected photovoltaic generation systems: A review and comparison, *IEEE Trans. Ind. Appl.*, 2017;53:3205-3216.
- [129] Troester E. New German grid codes for connecting PV systems to the medium voltage power grid, presented at the 2nd Int. Workshop Concentrating Photovoltaic Power Plants, Opt. Design, Prod., Grid Connection, 2009, pp. 9-10.
- [130] *Interconnection of Distributed Resources and Electricity Supply Systems*, Canadian Standards Association, Standard CSA C22.3 No. 9-08-R2015, 2015. Accessed: Mar. 29, 2020. [Online]. Available: <https://www.csagroup.org>
- [131] Ghassemi F, Perry M. *Review of Voltage Unbalance Limit in the GB Grid Code CC.6.1.5 (b)*. Accessed: March. 11, 2021. [Online]. Available: <https://www.nationalgrid.com>.
- [132] Xu L, Miao Z, Fan L, Gurlaskie G. Unbalance and Harmonic Mitigation

using Battery Inverts. IEEE 2015 North American Power Symposium (NAPS), Charlotte, USA, 2015.

[133] Li D, Zhu ZQ. A Novel Integrated Power Quality Controller for Microgrid. IEEE Trans. on Ind. Electron., 2015;**62**:2848-2858.

[134] Bajpai RS, Gupta R. Voltage and power flow control of grid connected wind generation system using D-STATCOM. IEEE Power Energy Soc. Gen. Meeting—Convers. 21st Century, Jul. 2008, pp. 1-6.

[135] Castilla M, Miret J, Matas J, de Vicuna LG, Guerrero JM. Linear current control scheme with series resonant harmonic compensator for single phase grid connected photovoltaic inverters. IEEE Transactions on Industrial Electronics, 2008;**55**: 2724-2733.

[136] Ghahderijani MM, Castilla M, de Vicuña LG, Camacho A, Martínez JT. Voltage sag mitigation in a PV-based industrial microgrid during grid faults, presented at the 26th IEEE Int. Symp. Ind. Electron. (ISIE), 2017, pp. 186-191.

[137] Li Z, Li W, Pan T. An optimized compensation strategy of DVR for microgrid voltage sag. Protection Control Mod. Power Syst, 2016;**1**:1-8.

[138] Al-Shetwi AQ, Sujod MZ. Modeling and control of grid-connected photovoltaic power plant with fault ride through capability. J. Sol. Energy Eng., 2018;**140**:021001-021009.

[139] Molinas M, AreSuul J, Undeland T. Low voltage ride through of wind farm with cage generators: STATCOM versus SVC. IEEE Trans. Power Electron., 2008;**23**:1104-1117.

[140] Lee TL, Hu SH, Chan YH. DSTAT-COM with positive-sequence admittance and negative-sequence conductance to mitigate voltage fluctuations in high-level penetration of

distributed-generation systems, IEEE Trans. Ind. Electron., 2013;**60**: 1417-1428.

[141] Chaudhari P, Rane P, Bawankar A, Shete P, Kalange K, Moghe A, Panda J, Kadrolkar A, Gaikwad K, Bhor N, Nikam V. Design and implementation of STATCOM for reactive power compensation and voltage fluctuation mitigation in microgrid, presented at the IEEE Int. Conf. Signal Process., Informat., Commun. Energy Syst. (SPICES), Feb. 2015, pp. 1-5.

[142] Goyal M., John B, Ghosh A. Harmonic mitigation in an islanded microgrid using a DSTATCOM, presented at the IEEE PES Asia-Pacific Power Energy Eng. Conf. (APPEEC), Nov. 2015, pp. 1-5.

[143] Yang X, Du Y, Su J, Chang L, Shi Y, Lai J. An optimal secondary voltage control strategy for an islanded multibus microgrid, IEEE J. Emerg. Sel. Topics Power Electron., 2016;**4**: 1236-1246.

[144] Bajpai RS, Gupta R. Voltage and power flow control of grid connected wind generation system using DSTAT-COM. IEEE Power Energy Soc. Gen. Meeting—Convers. 21st Century, Jul. 2008, pp. 1-6.

[145] Castilla M, Miret J, Matas J, de Vicuna LG, Guerrero JM. Linear current control scheme with series resonant harmonic compensator for single phase grid connected photovoltaic inverters. IEEE Transactions on Industrial Electronics, 2008;**55**: 2724-2733.

[146] Khadem SK, Basu M, Conlon MF. Integration of UPQC for power quality improvement in distributed generation network—A review, presented at the 2nd IEEE PES Int. Conf. Exhib. Innov. Smart Grid Technol., Dec. 2011, pp. 1-5.

[147] Rasheed A, Keshava G. Improvement of power quality for

microgrid using fuzzy based UPQC controller, Indian J. Sci. Technol., 2015;**8**:1-5.

[148] Senthil Kumar A, Rajasekar S, Raj PADV. Power quality profile enhancement of utility connected microgrid system using ANFIS-UPQC, Procedia Technol., 2015;**21**:112-119.

[149] Singh MD, Mehta RK, Singh AK. Performance assessment of current source converter based UPQC for power quality improvement with simple control strategies, J. Elect. Syst., 2019;**15**:276-290.

[150] Hoseinnia S, Akhbari M, Hamzeh M, Guerrero JM. A control scheme for voltage unbalance compensation in an islanded microgrid, Electric Power Syst. Res., 2019;**177**: 106016.

[151] Dai L, Chen W, Yang X, Zheng M, Yang Y, Wang R. A Multi-Function Common Mode Choke Based on Active CM EMI Filters for AC/DC Power Converter. IEEE Access, 2019;**7**: 43534-43546.

[152] Hernandez E, Madrigal M. A step forward in the modeling of the Doubly Fed Induction Machine for harmonic analysis. IEEE Trans. on Energy Conv., 2014;**29**:149-157.

[153] Baradarani F, Zadaash E, Zamani MA. A Phase-Angle Estimation Method for Synchronization of Grid Connected Power Electronic Converters. IEEE Trans. on Power Deliv., 2015;**30**:827-835.

[154] Senthilkumar A, et. al., Mitigation of Harmonic Distortion in Microgrid System Using Neural Learning Algorithm Based Shunt Active Power Filter. Smart Grid Technol. Elsevier, 2015;**21**:147-154.

[155] Mehta G, Singh S. Power quality improvement through grid integration of renewable energy sources. IETE Journal of Research, 2013;**59**: 210-218.

[156] Ling Q, Lu Y. An Integration of supercapacitor storage research for improving low voltage ride through in power grid with wind turbine. In: Presented at the power and energy engineering conference, APPEEC Shanghai, China: Asia-Pacific; 2012.

[157] Wang MQ, Gooi HB. Spinning reserve estimation in microgrids. IEEE Trans. Power Systems, 2011;**26**: 1164-1174.