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Review on Energy Storage Systems Control Methods in Microgrids

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ABSTRACT

Microgrids (MGs) are new emerging concept in electrical engineering. Apart from their many benefits, there are many problems and challenges in the integration of this concept in power systems such as their control and stability, which can be solved by Energy Storage Systems (ESSs). In this paper, an introduction to MG architecture and their challenges is initially presented. Then, important types of ESSs and a brief description of their characteristics are reviewed. Different ESSs operation configurations and their control methods are discussed as well. Different advantages and disadvantages of configurations and control methods have been discussed in the paper. A discussion about the control methods of ESSs and future trends are also presented. Investigation of different researches, shows that the control of ESSs has an effective role in different aspects of MGs such as stability, economic, etc.

1. Introduction

Nowadays, socio-economic conditions such as CO_2-emission free power generation and finite resources of fossil fuels result in the development of renewable energy resources such as wind and solar energy systems. On the other hand, these resources are more economic than fossil fuel based energy resources in some countries which encourages their integration in transmission and distribution systems [1–4]. However solar and wind energy resources have a probabilistic nature, and so, some Energy Storage Systems (ESSs) or reliable Distributed Generation (DG) units such as Fuel Cells (FCs) or Micro-Turbine (MT) should be utilized along with them to increase the energy supply reliability [5–7]. The Microgrid (MG) is a framework to realize their integration. It is a low or medium voltage-power system including controllable DGs, ESSs and loads [8,9]. Furthermore, in some MGs, the generated heat by DGs such as MT is used, which increases the system efficiency. These DGs are Combined Heat and Power (CHP) generation [10,11]. The MG geographical border might be a city, university, building, sport or traditional complex. Recently, many experimental pilot MG projects such as CERTS testbed, AUT MG testbed, UTA microgrid laboratory, British Columbia Institute of Technology microgrid. etc. have been constructed to investigate their technical aspects [12–16]. In addition some actual MGs such as Illinois Institute Technology MG [17], Bronzeville Community MG [18], are pilot large scale project in the world. A comprehensive review on the experimental and MG research set-ups has been done in [19,20]. For example in Santa Rita Jail MG, distributed energy resources management has applied [21]. Based on these review paper, it can be said that these researches and applications have mainly been focused on control of DGs in islanded and grid-connected modes [20].

MGs usually provide different advantages for consumers and power system operators such as transmission losses reduction, power quality enhancement, and system efficiency increment [22,23]. In many countries, small generators can participate in the energy market, and consumers can profit from reliable energy. On the other hand, investments for the construction of new transmission lines, substations, and bulk power generation can be postponed. The outland areas can use local power generations and independently be controlled as MG [24–29]. Fig. 1 shows the typical structure of a MG. The MG has been connected via PCC (Point of Common Coupling) to the main grid. Two ESSs and three DGs exist in this MG. One of the DGs can simultaneously produce electricity and heat. A transfer switch is placed at the PCC for mode changing. The MG could operate in two modes; connected to or islanded from the main grid. In the connected mode, the main grid can exchange power by the MG and support the MG stability. In the islanded mode, the DGs and ESSs of the MG must stabilize the MG.

The ESSs are important elements in the power system and MGs. Recently, different types of ESSs have been introduced and used. In 2017, 1.4 GW ESSs capacity has been installed in the world [31]. Battery Energy Storage Systems (BESSs), as an old, mature and still developing technology, have been used for different applications [32] such as application along with renewable energy resources [33,34], load leveling [35], electrical vehicles [36], ancillary services [37], etc. Flywheel Energy Storage System (FESS), Super Capacitor (SC) or

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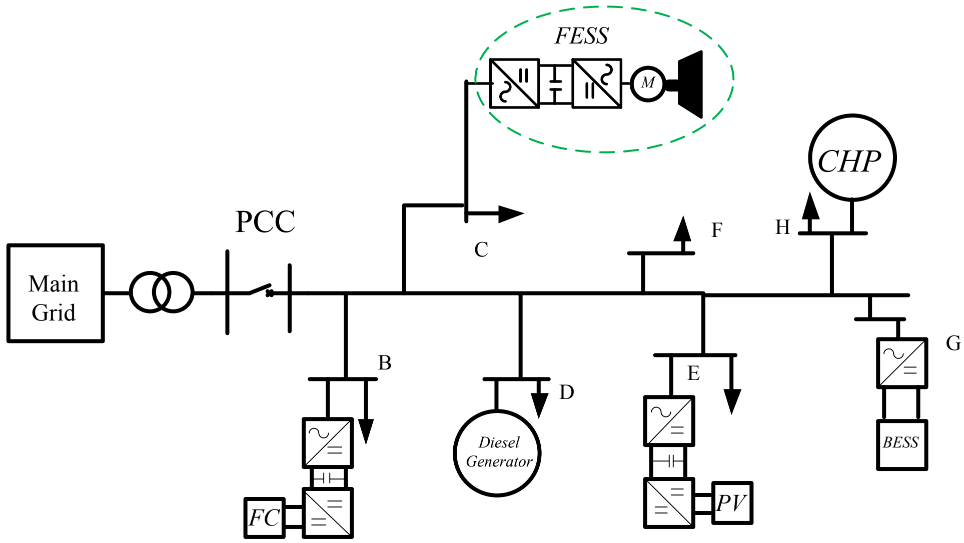

Fig. 1. A typical structure of MG [30].

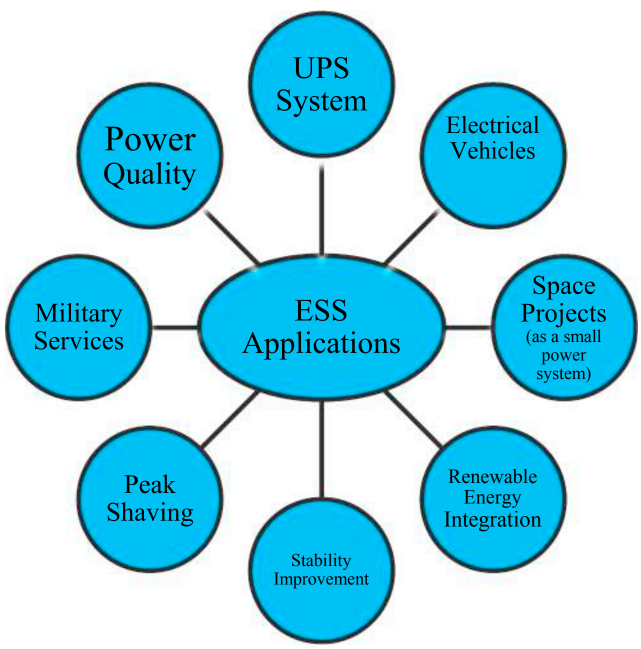

Fig. 2. Some applications of ESSs [45–49].

ultracapacitor, Super Magnetic Energy Storage (SMES), and Compressed Air Energy Storage (CAES) are some other important ESSs, which have special applications and structures [30,38–44]. Some applications of ESSs in MGs and power systems have been shown in Fig. 2.

Usually, the ESSs generate DC voltage, and so, power electronics interfaces are needed to connect them to the AC power system and AC MG [50–53]. In addition, some energy consumers may use DC electrical power. Power electronics interfaces, made of semiconductor switches, provide more controllability for ESSs [54,55]. For example, a DC/DC convertor should usually be used for altering the DC voltage level of a BESS, a DC/AC convertor which is called inverter, is used to connect a SC to the MG, a AC/DC converter which is called rectifier, is used for DC loads and AC/DC/AC (or back-to-back) converters are used for the FESS [56–61].

In order to have a stable MG, these converters should properly be controlled. It means that, in an AC MG, the voltage and frequency should be maintained in a specified range [62,63] and in a DC MG, the voltages should be adjusted using the current feedbacks [64,65]. Therefore, in AC MG, at least a voltage source-type DG should be used, and the convertors of this type of DGs are controlled as Voltage Source Convertor (VSC). In this situation, other DGs can operate in the current source mode and other convertors are called Current Source Convertors (CSCs) [66–68].

This paper reviews different control strategies applied to several types of ESSs. Firstly, different ESS types are reviewed and categorized in the next section. Different control strategies applied on DGs of MGs are described in Section 3 and some specialized techniques for ESSs are explained in Section 4. A discussion about ESSs and their control strategies and future viewpoints are presented in Section 5. Finally, a conclusion of the paper is made in the last section.

2. Description of different ESSs

In spite of advances in technology, electrical energy cannot be stored in electrical form in large-scale capacities. To store electrical energy, it should be stored as gravitational, adiabatic, mechanical, chemical, thermal, magnetic or other forms [40,69–79]. The energy storage system can be classified considering their power and energy density, life cycle, ramp rate, etc. Until now, none of the ESSs can suitably satisfy the power system requirement.

Fig. 3 classifies different ESSs based on their primary source of energy. Table 1 lists their important characteristics and describes some advantages and disadvantages. As it can be seen in Fig. 3, the ESSs are divided into 5 groups of electrical, mechanical, thermal, electrochemical and magnetic.

Today, the most famous ESS in the worldwide is the BESS [81,82]. It is an electrochemical ESS which produces or absorbs electrical power via a chemical reaction. Each battery is made of several stacks. To achieve high power and energy density, several BESSs should be connected in parallel and series [83]. There are several types of BESS such as lead-acid, nickel, sodium-sulfur, lithium ion, metal-air batteries, etc. [84–86]. In addition to the BESS, some of hydrogen-based generation units such as some types of Fuel Cell (FC) can be classified as the chemical ESSs. In this case, the existence of the hydrogen reservoir provides the possibility of the electricity generation when it is required [79,87].

The pumped-hydro storage power plants can be considered as ESS with large energy density used in the power system for decades [40,88]. This system stores water in two reservoirs; high and low height reservoirs. When electrical energy is required, the water flows to a lower height reservoir and the potential energy is converted to kinetic and then to electrical energy.

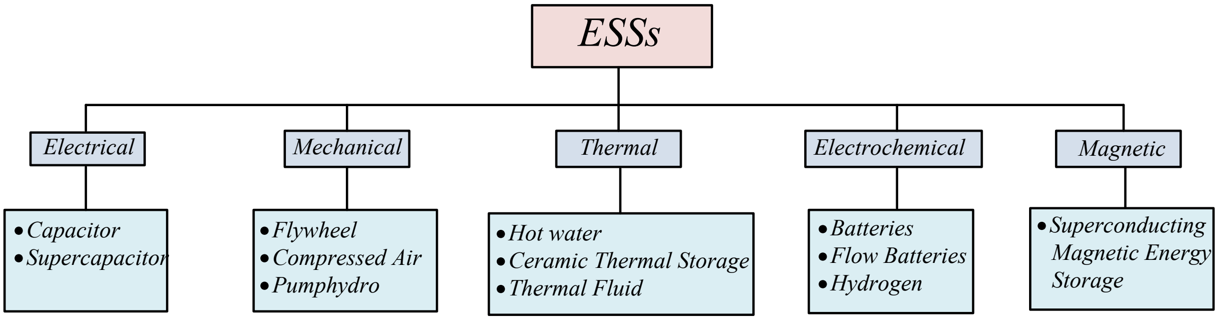

Fig. 3. Different energy storage system categories [80].

The stored water is transferred between the two reservoirs and the height difference between them determines the amount of stored energy. In the peak load period, the water flows down and the generators produce electrical power while in low demand periods, the water is pumped to the upper reservoir [95–97]. This action in 24 h, helps to flat the load curve in the power system.

The FESS is an electromechanical ESS, which stores the electrical power in mechanical form. A low friction round moving disk stores electrical energy in kinetic form. There are two types of FESS; low-speed and high-speed [38,39,98,99] with high and low inertia disk, respectively. The disk is connected to an electrical machine, which can operate in generator or motor mode. In the charge mode, the electrical energy flows, from network to the FESS and the disk speed increases (motor mode), while in discharge mode, the disk speed decreases and the motor operates in the generator mode. The applied machines in the FESS structure are usually induction machine, doubly fed induction machine or permanent magnet synchronous machine [100,101].

Compressed Air ESS (CAESS) is an ESS with large capacity, used in the power system [102,103]. This ESS stores air in low power demand hours in large tanks. In this situation, it absorbs electrical energy from the grid and compresses the air in large ground tanks. There are two types of CAESS with underground and aboveground tank. In the peak load hours, the compressed air energy is used in the combustion process or expansion work and using turbine and synchronous generator the electrical power is generated [104].

The ESS that stores heat in an insulated tank is called the Thermal Energy Storage System (TESS) [89,105,106]. The stored heat can be used in the power generation process. There are two types of TESS; low temperature and high temperature. The low temperature TESS uses water as energy carrier to store heat and is usually applied for heat peak demand while the high temperature one uses some materials such as ceramics as energy carrier. In general the efficiency is about 30–60% [89].

Another solution for electrical energy storage is its storage in the magnetic field. The Superconducting Magnetic Energy Storage (SMES) stores electric energy in the magnetic field generated by the DC current. The DC current flows in a coil which is maintained in low temperature (under critical temperature of superconductivity phenomenon). Generally, SMES are categorized in two main types; low temperature (about 5 Kelvin degree) and high temperature (about 70 Kelvin degree) [107–109].

3. MG control strategies

3.1. General methods

A MG should be controlled to ensure the stable operation of all its components. Voltage in DC MG and the frequency and voltage of AC MG should be controlled. In addition, some operational goals such as economic considerations should be followed via the control system. For example, in a MG, with heating loads, the optimization of heating management should be performed [110]. If sensitive loads exist in a MG, the uninterruptible operation should be guaranteed for them [111]. In this situation, ESSs as fast and reliable power supplies play an effective and important role. Therefore, in many researches, the control of MG power quality means the ESSs control [112–116].

In a MG, some controllers are near loads, and some others are near DGs location or microsources, which are called the Load Controller (LC) and Microsource Controller (MC) respectively. A controller that is usually located at PCC and sends the control signals throughout MG is called the MG Central Controller (MGCC). Fig. 4 shows the MG structure and controllers locations.

Two main general control strategies can be applied to ESSs; centralized and decentralized [117,118].

In the centralized control strategy, the MGCC has a unique role. It sends and receives all the control signals of the MG. These signals are transferred to LCs and MCs to control the voltage in DC MG (or voltage and frequency in AC MG) and optimize power flow in feeders, etc. The centralized controller is relied on communication architectures. This reduces the system reliability [119]. In this control method, usually all the DGs have one owner which wants to optimize operational and economic criteria for all of them [120]. In contrast to the centralized strategy, the decentralized one does not rely on MGCC and communication architecture. In this method, LCs and MCs play an important role in MG stable operation. Another control method is the distributed control strategy. In distributed control strategy, there are controllers that are geographically distributed and functionally integrated. Indeed, in this strategy, some controllers are the interface between MGCCs and the local controllers [121,122]. Distributed control strategy has a concept between two-mentioned strategies. In this strategy, MG components exchange control signals. Fig. 5 shows the control strategies graphically.

A compromise between centralized and distributed control concepts. Results in another control method in MGs, named the hierarchical control strategy, which is very close to the distributed control strategy [123]. The hierarchical control strategy has three control levels, which are in different time domains known as: 1-primary, 2-secondary and 3-tertiary control. The first control level is activated immediately after a change in MG parameters such as frequency, voltage or load changes and tries to keep the frequency and voltage in stable ranges. The operation time of this level is about several seconds. The primary control is the fastest level in the hierarchical control system [124]. After performance of this level, a steady-state error may exist for voltage and frequency. Moreover, other parameters such as active and reactive power may be influenced by this error. To overcome the mentioned problems, the secondary control is activated. It tries to reduce errors between desired and real parameters. Finally, the tertiary control, which is the slowest control level is activated. Usually, the main goal of this level is the economical or market issues [125–127].

Table 1
Comparison of some ESSs [40,89–94].

Technology	Energy density (Wh/kg)	Power density	Capital cost (€/kW)	Response time	Self-discharge (per day)	Lifetime (year)	Overall efficiency	Advantages	Disadvantages
SC	0.1–5	800–23,500	200–1000	ms-10 min	20–40%	5–8	0.85–0.98	Suitable for power quality application, long lifetime, high power density, high efficiency	Low energy density, toxic compound
Nickel BESS	100–140	50–1000	200–750	4 h	0.2–0.6%	10–20	0.6–0.73	good power and energy density	Toxic, require maintenance, low efficiency
Lead acid BESS	30–50	75–300	50–150	2 h	0.1–0.3%	5–10	0.70–0.90	Low capital cost, mature technology	low efficiency, require maintenance
Vanadium redox flow	10–30	150–160	150–1000	2–12 h	Small	5–10	0.85	Non-flammable	Low energy density
Lithium-Ion	160–200	150–315	350–700	15 min. to hours	0.1–0.3%	5–15	Up to 0.97	High efficiency, Low maintenance	Ageing
CAESS	–	–	400	1–24 h	Small	20–40	0.70–0.90	High capacity ESS, suitable for generation and peak shaving	Require special site, negative influence on environment
FESS	5–100	1000	3000–10,000	ms-15 min.	Small	15–20	0.93–0.95	High lifetime, high power density, low maintenance cost	Low energy density, high capital cost
SMES	0.5–5	500–2000	350	ms-8 s	10–15%	15–20	0.95–0.98	high power density	Low energy density, strong magnetic field.
PHES	–	–	140–680 m for 1000 MW	1–24 h	Negligible	50–60	0.70–0.82	High capacity ESS	Environmental aspects

3.2. Droop control method

The conventional droop control method is a method that can be applied to ESSs of a MG using centralized and decentralized control strategies. This method is a mimic of synchronous generators, when frequency and voltage drop proportionally with generated active and reactive power, respectively [128,129]. To determine the reference frequency and voltage, local voltages and currents are measured and processed and as a result, it does not require communication infrastructure, so it has also been called the wireless method. Fig. 6 shows the one-line diagram of an ESS (or DG) connected to an infinite bus. E and φ are the voltage amplitude and angle of the ESS. Z and θ are the amplitude and angle of the line impedance. The active and reactive power ($P + \text{j}\,Q$) can be calculated as follows [130–132]:

$$I = \frac{E\angle\varphi - V\angle 0}{Z\angle\theta} \tag{1}$$

$$S = V \times I^* = P + jQ \tag{2}$$

$$P = \frac{V}{Z}\,[(E\cos\varphi - V)\cos\theta + E\sin\varphi\sin\theta] \tag{3}$$

$$Q = \frac{V}{Z}\,[(E\cos\varphi - V)\sin\theta - E\sin\varphi\cos\theta] \tag{4}$$

Assuming that the output impedance of an inverter is inductive and the phase difference between E and V is very small, (3) and (4) can be written as follows [119]:

$$P = \frac{V}{X}E\varphi \tag{5}$$

$$Q = \frac{V}{X}(E - V) \tag{6}$$

Based on the mentioned terms, droop equations can be expressed as follows:

$$\omega = \omega^* - mP \tag{7}$$

$$E = E^* - nQ \tag{8}$$

This equations is based on inductive lines impedance, but in many cases the line is resistive or resistive-inductive, that are discussed in [133–136]. Similar to inductive case, for an MG with resistive line, the droop equations can be achieved as follows [134]:

$$\omega = \omega^* + mQ \tag{9}$$

$$E = E^* - nP \tag{10}$$

In case of having resistive and resistive-inductive lines, the application of the virtual impedance for droop behavior enhancement has been proposed [137,138]. For a DC MG, the new droop equation is defined as follows [139,140]:

$$V = V^* - RI \tag{11}$$

The droop method is suitable for microsources control and it stabilizes the MG under load changes. It can be used in centralized and decentralized control strategies. Since, it relies on the local measurement in each DGs, it can be applied for several independent ESSs in the MG. Many researches have reviewed droop application in MG [114,117,141–144]. The authors in [141], have reviewed different power sharing methods in the islanded MG. In [114], the decentralized strategy and hierarchical control have been reviewed and the primary, secondary and tertiary control levels have been described based on the droop control method,.

4. Control methods of ESSs

In islanded mode of MG, the ESSs are planned to be charged to a distinct level of SoC determined by local or central controllers. In addition, due to economic considerations, the ESSs might inject power to

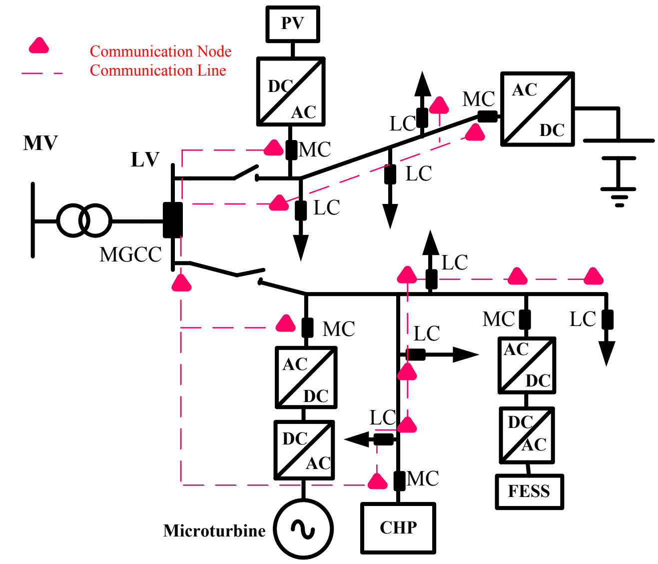

Fig. 4. MG artitecture and controllers locations.

the main grid. In this situation, an active and reactive power set point have been defined and using two Proportional–Integral (PI) controllers, the ESSs inject or absorb power. This control strategy is called the PQ control strategy. Usually, some DGs with a slow response such as FC, might be controlled by this control strategy. Fig. 7 shows this control strategy for inverter-based ESS, which is controlled in the *d-q* frame [145]. The detailed structure has been described in [53,146]. The authors in [147,148], have substituted the PI controller in Fig. 7 by fuzzy controllers. The fuzzy controller is suitable for nonlinear systems and is independent of system type. The reference currents determination structure for PQ control strategy is shown in Fig. 8. As can be seen, using i_d, i_q, v_d and v_q, active and reactive powers are calculated. Then their difference from ordered value passes though PI controller and the current reference values are calculated. More details can be found in [149,150].

In islanded mode, some of the ESSs must participate in voltage and frequency control of MG. These ESSs usually act as controllable voltage sources [149]. This control strategy is called the V/f control strategy. The reference set points of the voltage and frequency are received from higher control levels. The ESSs, after islanding or load switching, immediately compensate the lack or excess power in primary control and PQ controlled DGs might corporate in secondary control. In [30,98,151] three mentioned strategies (droop, PQ and V/f) have been applied on the aggregated BESS and FESS and the stability of MG has been studied. A summary of the control strategies applied to ESSs in the MG has been shown in Fig. 9.

The ESSs in a MG can be used in three main general configurations; 1-distributed, 2-aggregated and 3-hybrid. In distributed form, ESSs are located in several locations in MG, while in aggregated configuration, all of them are installed in one bus. Fig. 10 shows the schematic diagram of the MG with aggregated and distributed ESSs.

4.1. Aggregated ESS

In many research works, all the ESSs are supposed to be in one location to facilitate ESSs modeling. In [152], a BESS management based on State of Charge (SoC) of aggregated batteries, has been proposed, which enables the MG to operate in islanded and connected modes. An intelligent battery management based on artificial intelligent and fuzzy logic rules, has been presented in [153]. This management method minimizes the environmental (emission) and operational cost under uncertainty conditions of solar generations. In addition, the application of the fuzzy controller has increased the total lifetime of the BESS. The

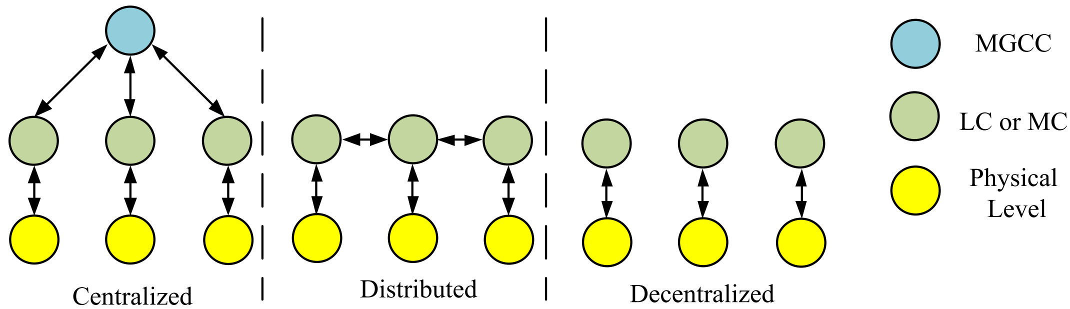

Fig. 5. Control strategies of MG.

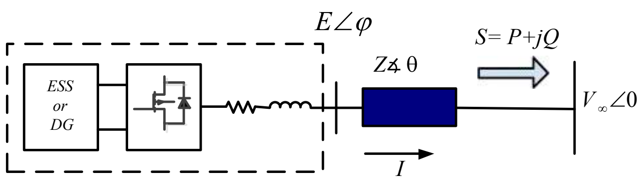

Fig. 6. Equivalent circuit of ESS connected to a bus [131].

aggregated model of the BESS has been presented and used for stability analysis of off-grid MG in [154]. In this work, the BESS has been introduced as a widespread solution for the MG stability problems specially for short term frequency stability. A similar work has been carried out in [155]. The authors in [156], have used the aggregated SC to compensate frequency fluctuations in MG including wind generations. The aggregation of SCs is necessary to provide a high power density ESS. Moreover, this application improves the MG voltage profile.

In previous studies on economic problems of MGs, the aggregated model has been used [157–160]. This consideration can be used, since the converter cost can be neglected in the time range of the study. In [161], the authors have considered ESS as an aggregated unit which has rating in the range of MW nominal power range. The main goal of the paper was the energy cost minimization.

In [162], the application of BESS, SMES and SC has been compared with FESS for wind farm application. Two mentioned applications have been assessed for distributed and aggregated configuration. The fluctuation of the harmonic content in output power is the main criterion for this comparison. It has been shown that two configurations have the same results while the aggregated configuration needs larger convertor capacity. In a similar research, the same authors have compared distributed and aggregated ESSs for different wind turbine peach angles [163]. The application of the BESS for power smoothing of the wind farm has been presented in [164] and three configurations have been simulated; these three were aggregated, distributed and a new method called semi-distributed. The main goal of the paper was minimization of BESS capacity, which results in cost reduction. The application of the aggregated FESS using fuzzy controller has fixed the DC link voltage of WTs in the desired range [165].

4.2. Distributed configuration of ESS

In distributed configuration, several ESSs are dispersed in MG. The application of distributed ESSs with the distributed photovoltaic system has been studied in [166]. The photovoltaic panels provide electrical energy for local consumption and ESSs increase system reliability [166]. Using distributed NaS batteries alongside PVs has increased the flexibility and improved peak shaving [167,168]. In [169], using coordinated control of distributed ESS, the voltage rise problem has been solved under high PV penetration. The presented solution has reduced depth of discharge of ESSs and has improved the peak shaving. The optimal place and size of distributed ESSs have been studied for voltage profile improvement in [170].

In [171], dispersed ESS has been used as ancillary service for an active distribution network. An optimization has been run out to achieve the best economic solution under technical considerations. A convex optimization has been presented for ac power flow to improve voltage profile and losses. The hierarchical control of distributed ESSs has been defined for several BESSs consisting of primary and secondary controls [172]. The proposed control strategy has been based on the droop equation with some additional conditional terms. Moreover reactive power dispatching has been offered in secondary control.

4.3. Hybrid ESS

As before mentioned, none of ESS can provide all the characteristics needed for a power system or MG. The BESSs have high energy density but have low power density and a short lifetime. In contrast, some ESSs such SCs and FESS have high power density, a long lifetime and low energy density. Due to mentioned reasons, combined application of ESSs with different types is a common solution called Hybrid ESS (HESS). In many researches, HESS has been used for MG control and operation [89,173–179].

In [173], SC and BESS have been used to improve power sharing in DC MG. The load changes in DC MG result in voltage changes. During transients, the BESS compensates low frequency changes and the SC compensates high frequency variations of the load power. In [180], a new power convertor has been proposed to use SC and BESS as hybrid ESS. The proposed method is decentralized. Like to SC, the SMES can compensate short-term fluctuations. Fig. 11 shows a typical 24-hour load profile [181]. As can be seen, it consists of two terms; low and high frequency terms. The BESS can provide power for MG loads during the peak period or supply the low frequency term. The SMES, SC, or FESS can respond to high frequency terms as mentioned above. By proposing a new droop for enhancing power sharing, this capability has been used in [174,175], and a HESS which consists of SMES and BESS, has been designed and tested. A SC along with BESS has been used for safe operation of MG and reduction of main grid dependency [179]. Application of the HESS of SMES and BESS for photovoltaic-based MG has been investigated in [176] and PQ and V/f control strategies have been applied on this system. The results of the paper verify that the MG consisting of with HESS has better transient response compared to the one with BESS. Moreover, in fault conditions, the power losses have been reduced in the MG.

Since, many some ESSs have a DC voltage terminal, they can be coupled to a DC link. Fig. 12 shows the connection with more details. In [183], a HESS including FESS and BESS has been used for frequency regulation in autonomous MG. As shown in this figure, there are three power electronic converters. “Conv.1” is a DC/AC converter, which can operate in inverter or rectifier operation mode. In rectifier mode, energy flows from MG to HESS and the ESSs are charged while in inverter mode, the HESS is discharged and energy is absorbed by MG. The BESS supports the DC link voltage of the FESS. In [184], the FESS and BESS do not have any connection to the DC link. Two ESSs are in DC MG and the FESS works as the main ESS while the BESS supplies the rest of the

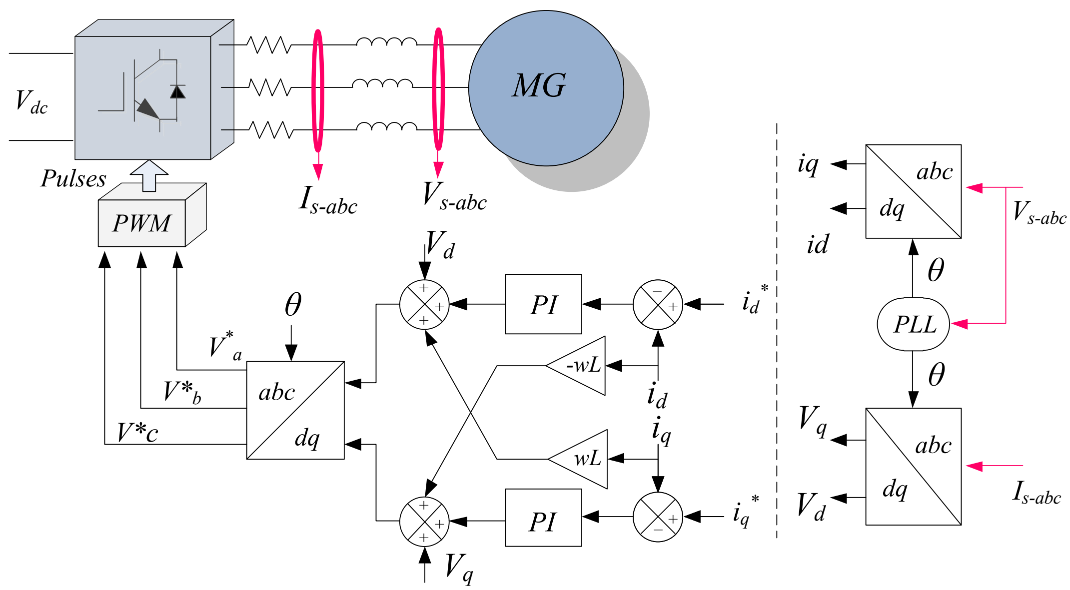

Fig. 7. Control of inverter-based ESS.

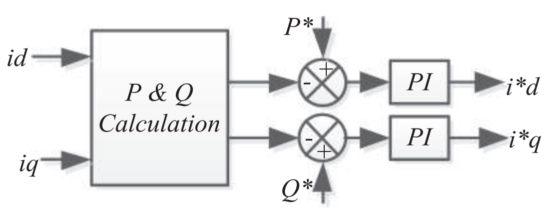

Fig. 8. Reference currents achievement in grid-side converter controller.

demanded power. As shown in [185], the combined application of the FESS and vanadium redox BESS using configuration of Fig. 12, causes improvement of frequency stability in the AC MG.

4.4. Control technique based on ESSs SoC

One of the most important aspects in controlling ESSs, especially in distributed and hybrid configurations, is SoC control. When two or more ESSs operate in a power system or MG, they should be simultaneously charged and discharged. This causes an increase in the average lifetime of ESSs and improving the response of voltage control. Therefore, many researches have tried to equalize the SoC of ESSs. On the other hand, as mentioned, the most important issue in the MG control is its stability. Therefore, in the system operation optimization process, the MG stability should be considered as an essential condition. In the next sections, some works that have been done in this realm are reviewed.

The research works in ESS SoC control can be classified in researches in DC and AC MGs. In DC MG, the voltage and power control are very important. However, in AC MG, the stability is more complex where the voltage, frequency, active and reactive powers should properly be controlled.

Although the droop method is a useful method in MG control, some papers have proposed methods that are not based on droop [186–188]. The SoC balancing control has been presented in [186], which is based on cascade converters and the centralized control strategy. In [187,189], a virtual resistance has been added to the control structure of ESSs. Since, the virtual resistance value has been computed based on the value of all ESSs SoC, these methods can be classified in the centralized control methods category.

Many researches have used the droop equations to balance the SoC of ESSs. In [190], a multi-agent-based control procedure has been presented for distributed ESSs, which balances ESSs SoC. In [191], new droop equations based on SoC have been proposed. In this method, the ESS with more SoC injects more active power compared to others and in the charging mode, the ESS with less SoC absorbs more power. In [192], Eq. (10) has been presented. For charging and discharging modes, different functions have been defined. The results of the proposed method clearly improve the SoC balancing.

$$\begin{aligned} f &= f_0 - M_P \cdot P = f_0 - \frac{M_0}{SOC^n} \cdot P, \quad P > 0 \\ f &= f_0 - M_P \cdot P = f_0 - M_0 \cdot SOC^n \cdot P, \quad P < 0 \end{aligned} \tag{12}$$

A new droop equation for *f-P* has been proposed in [193] as follows:

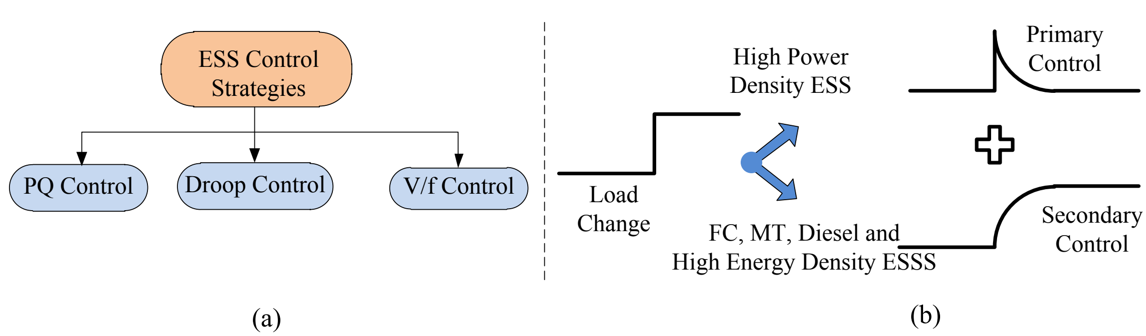

Fig. 9. (a) ESS control strategies and (b) primary and secondary frequency control.

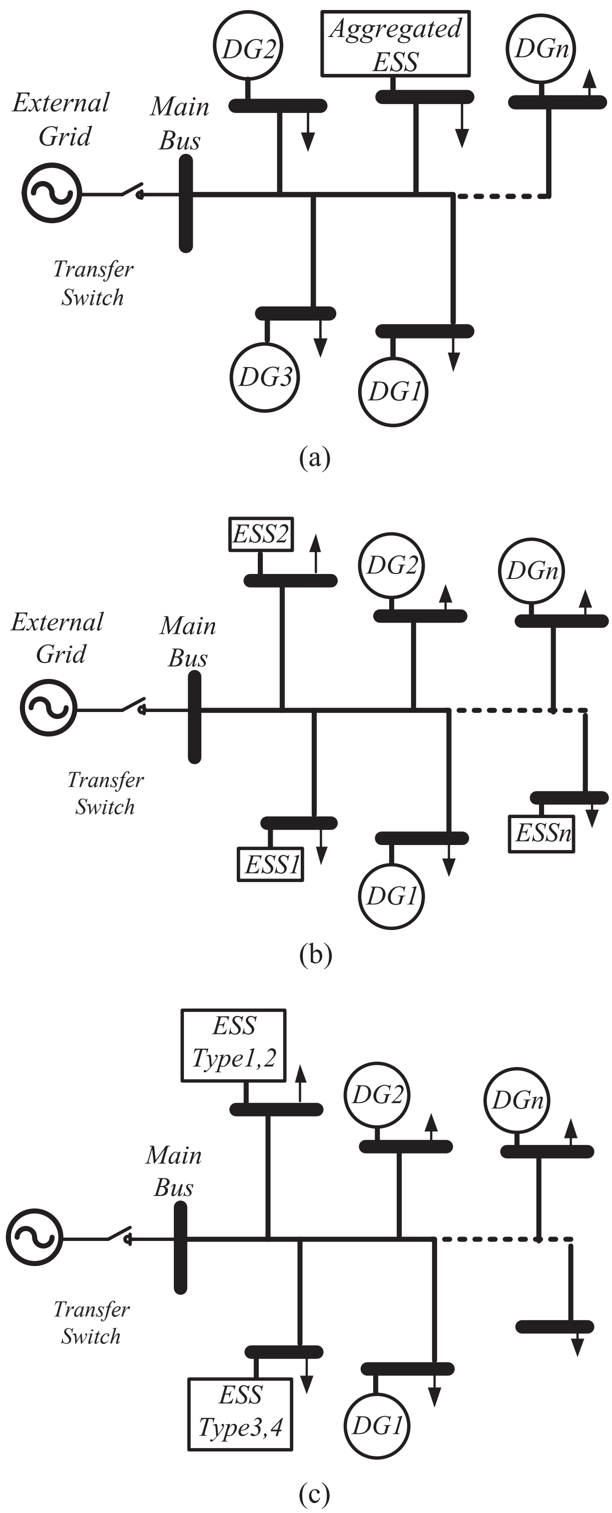

Fig. 10. MG with (a) aggregated, (b) distributed and (c) hybrid ESSs.

$$f = f_0 - \frac{m}{C_i}\cdot(P - P_{ref})(1 - k_{soc}SoC_i) \tag{13}$$

In addition, a root-locus analysis has been presented in [192,193] and it has been shown that the method has an effective role in SoCs balancing while frequency has been controlled very well.

In [194], a centralized method has been proposed which is based on SoCs averaging and transient virtual resistance for distributed BESS. The multi-agent based control of two ESSs in the AC MG has been described in [190] and hardware in the loop results have been presented as well. In [195], an adaptive droop based on SoC has been proposed to improve SoC balancing; however the proposed method in [195] has lead to frequency deviation.

A decentralized method has been presented for voltage and frequency control of the MG based on ESS SoC as follows [196]:

$$\omega = \omega_0 - k_P.\ P - k_{soc}(1 - SoC_i) \tag{14}$$

$$E = E^* - k_Q\int_0^{t-} Q\ dt + k_{PV}\int_0^{t-} P\ dt \tag{15}$$

In DC MG, the resistance droop has been used. The authors in [197] have promoted this droop for secondary control and equalizing the ESSs SoC. In [173], for HESS including SC and BESS, a high-passed filter droop has been proposed for SC. Using this method, the communication infrastructure requirement has been removed and the MG has been controlled decentralized. The *P-E* droop coefficient has been set to be proportional to the *n-th* order of SoC in [198], as follows:

$$V = V^* - m_0 SoC_i^n I \tag{16}$$

The authors in [199], have proposed a new decentralized droop-based equation for DC MG with distributed ESS. In this method, the no-load voltage has been changed as a function of ESS SoCs.

5. Discussion and future works

The energy systems are developing all over the world. Therefore, a new concept has been appeared called microgrid. Microgrids are the low or medium voltage distribution systems, which have many smart meters, conventional and renewable energy resources, smart appliances, etc.. All or most of the generators and loads can be monitored and controlled. The MGs can help the power system to be smarter. A MG should be able to operate in both connected and islanded mode. The MG operation in off-grid mode is challenging. In this situation, reliable energy producers such as ESSs play an important role.

The ESSs have been used for different applications in power systems and MGs. Todays, there are several types of them that have diverse applications. Some ESSs such as CAESS and PHESS are large ESSs that are usually used for power systems [200]. The BESSs, as a mature technology, are used in different applications. However, in the MGs, it is better to use BESSs for power supply applications due to their high energy density. Some ESSs such as the SC, SMES, and FESS that have a high lifetime and high power density are usually used for power quality applications. It should be noted that the ESS application to maintain stability in the MGs is inevitable. Considering the required power, energy density and economic issues, the MG operators should select the best choice from different ESSs.

In the islanded mode, three main configurations of ESSs are used; aggregated, distributed and hybrid. In aggregated configuration, all the ESS units have been installed in one location or only a large ESS has been used in the MG, while in the distributed one, they have been dispersed in the MG area. The ESSs can be controlled locally or decentralized or they can be controlled by the MGCC (centralized). Two mentioned strategies might be executed in the hierarchical structure. This means that similar to power system operation, the primary, secondary and tertiary control levels should be applied to the ESSs. The droop control method has been applied to the ESSs that provide good response in stability aspects of the MG. It is concluded from research works that the distributed and hybrid applications are more preferable compared to the aggregated one. Moreover the hybrid application of the ESS is useful for the MG with high and low frequency changing the load power profile.

One of the important issues in ESSs control, operation and maintenance, is SoC balancing among different ESS units. The lifetime of the ESS is influenced by charge/discharge times. Since the stability of the MG is the most important issue, after that, the maintenance issues are important.

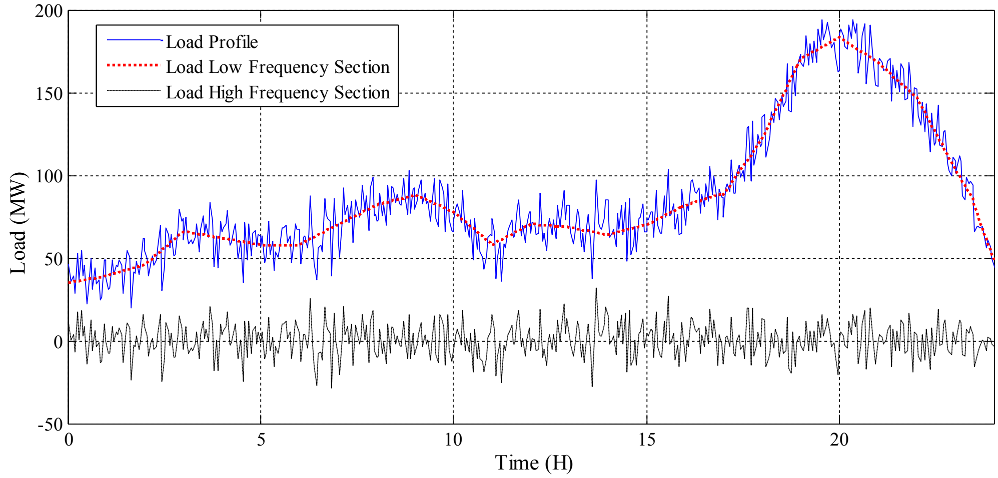

Fig. 11. Typical 24-hour load profile of MG [158,181,182].

In the future, by developing of electrical vehicles such as plug-in hybrid electric vehicles (PHEVs) in the microgrids, they can participate in voltage and frequency of MG. on the other side by reducing renewable energy costs in the future they can compete by common energy producers but they need ESSs to provide acceptable reliability. Some ESSs such as Lithium batteries are developing to charge and discharge thousands times which, this faciliate its application in the future [201].

6. Conclusion

In this study, a review on previous works on ESSs in the MG has been carried out and different studies have been presented. Firstly, a brief introduction about different ESSs types and their comparison have been explained. It is described that different ESSs with different characteristics can be used in various applications.

Two main configurations for ESSs locations in the MG have been used in MGs. In the aggregated ESS, all the ESS units are located in one location and in the distributed configuration, several units are placed in different locations.

There are three main control strategies for ESSs control. In the grid-connected MG, the ESSs are usually controlled by the PQ control strategy, which causes a distinct level of SoCs to adjust for ESSs. In the islanded MG with aggregated ESS, the V/f control strategy might be applied. The droop control strategy has been used for cooperation of different ESSs.

Some ESSs, such as BESS have high energy density and other ones such as FESS and SMES have high power density. In the practice, these characteristics are important. The SoC of ESSs should be controlled to ensure the suitable operation of the MG. Finally a discussion on the control strategies and future trends in this subject has been presented.

In the future, by developing ESSs technology such as FESS, SC, SMES, hydrogen ESS, etc., their widespread application is expectable. Moreover, the BESSs technology has dramatically progressed recently. Todays, BESSs with high density of power and energy are available, which can be used for different applications in MGs. Many experimental and test MGs including ESSs, have been and are being developed in the world. Effective and efficient control of these MGs is one of the most important aspects of their operation. This can be obtained by proper combination and allocation of EESs in MG, and also selection of effective control strategies for ESSs and DGs. Considering the current ESSs technology progresses, it is expected that more efficient control strategies will be designed for ESSs and the islanded operation of the MG will be facilitated.

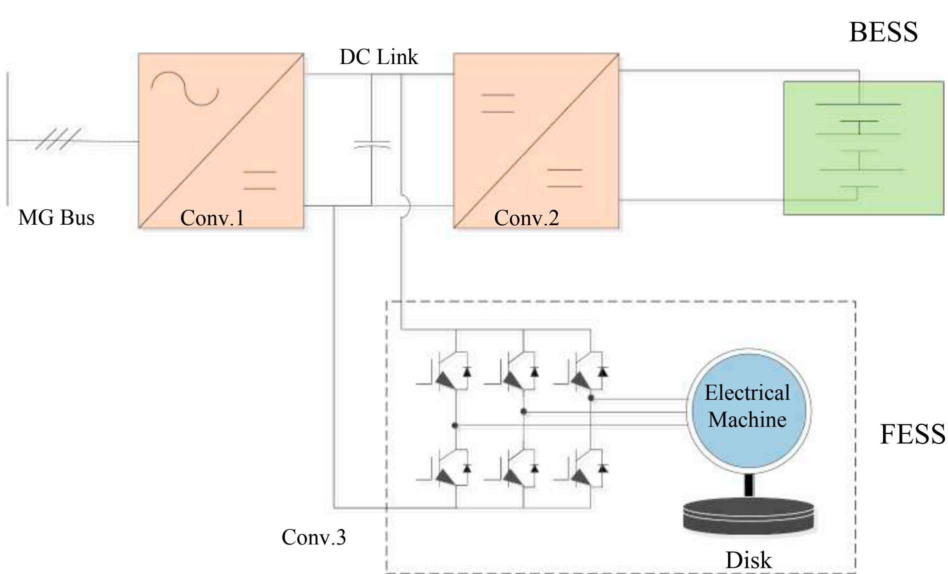

Fig. 12. HESS structure including FESS and BESS [183].

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