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Hybrid energy storage system for microgrids applications: A review

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ABSTRACT

Energy storages introduce many advantages such as balancing generation and demand, power quality improvement, smoothing the renewable resource's intermittency, and enabling ancillary services like frequency and voltage regulation in microgrid (MG) operation. Hybrid energy storage systems (HESSs) characterized by coupling of two or more energy storage technologies are emerged as a solution to achieve the desired performance by combining the appropriate features of different technologies. A single ESS technology cannot fulfill the desired operation due to its limited capability and potency in terms of lifespan, cost, energy and power density, and dynamic response. Hence, different configurations of HESSs considering storage type, interface, control method, and the provided service have been proposed in the literature. This paper comprehensively reviews the state of the art of HESSs system for MG applications and presents a general outlook of developing HESS industry. Important aspects of HESS utilization in MGs including capacity sizing methods, power converter topologies for HESS interface, architecture, controlling, and energy management of HESS in MGs are reviewed and classified. An economic analysis along with design methodology is also included to point out the HESS from investor and distribution systems engineers view. Regarding literature review and available shortcomings, future trends of HESS in MGs are proposed.

1. Introduction

If there is no change in energy policy, the international energy agency predicts a 130% increase in CO_2 emissions and a 70% increase in oil consumption by 2050, increasing the global average temperature by 6 °C [1]. Renewable energy sources (RESs) are the best solution to deal with these problems. Solar and wind energies are widely used for electric power generation. The world's cumulative wind and photovoltaic (PV) installed capacity are shown in Fig. 1. The global cumulative wind and PV installed capacity in 2017 were 539 GW and 401 GW respectively [2].

RESs have been extensively used to supply the electrical energy demands and reduce greenhouse gas emission with an increasing trend. The intermittency nature of the clean energy sources influences the power generation adversely, becoming a challenge for the uninterrupted and regular supply of power to the consumer and endangering grids operation in terms of different operational and technical aspects. Microgrid (MG) as a cluster of loads and distributed generations (DGs) is proposed to take maximum benefits of RES which can be operated in both islanded and grid-connected modes. An ESS could contribute to integration of RESs into the MG by flattening the RESs fluctuations, power quality improvement, contributing in frequency and other ancillary services [3].

Various storages technologies are used in ESS structure to store electrical energy [4–6]. Fig.2 depicts the most important storage technologies in power systems and MGs. The classification of various electrical energy storages and their energy conversion process and also their efficiency have been studied in [7]. Batteries are accepted as one of the most important and efficient ways of stabilizing electricity networks [8]. They are attractive because they are economical, compact, and easy to deploy. A battery composed of multiple cells connected in parallel or in series, which uses a chemical reaction to convert the stored chemical energy into electrical energy and vice versa. Various battery technologies can be used for MG applications. Fig. 2 shows power density and energy density capabilities for different battery technologies. Among the different ESSs, pumped hydro energy storages and compressed air enable to support large-scale energy storage applications [9]. However, the pumped hydro energy storage dependence on specific geographic and environmental conditions, making its development quite difficult challenging [10]. Flywheel energy storage system is electromechanical energy storage [11–13] that consists of a back-to-back converter, an electrical machine, a massive disk, and a dc bus capacitor. However, this type of storage system has mechanical components that can affect efficiency and stability. In order to

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Nomenclature

AM	Analytical method	MG	Microgrid
ANN	Artificial neural network	MOM	Mathematical optimization method
DBC	Droop based controller	MPC	Model predictive control
DG	Distribution generation	PAM	Pinch analysis method
FLC	Fuzzy logic control	PSO	Particle swarm optimization
FBC	Filtration based control	PV	Photovoltaic
FC	Fuel cell	RBC	Rule based control
HES	High-energy storage	RESs	Renewable energy sources
HESS	Hybrid energy storage system	RPM	Ragone plot method
HM	Heuristic method	SBM	Search-based method
HPS	High-power storage	SC	Supercapacitor
ID	Integral droop	SM	Statistical method
		SMES	Superconducting magnetic energy storage
		SoC	State of charge

overcome some problems with the flywheel, a superconducting thrust bearing system for flywheel energy storage with low loss and maintenance cost is proposed in [14], which has low loss and maintenance cost. In this structure two bearings are used. The one composed entirely of permanent magnets provides the levitation force and the other, which consists of a permanent magnet and a superconductor, provides the stabilization. Supercapacitors (SCs) are the electrostatic storages, and the high degree of recyclability and high power density are their main advantages [15]. Superconducting magnetic energy storage (SMES) is one of the few direct electric energy storage systems. The SMES is based on a cooling system, a superconducting coil and an electrical and control system for the adaptation of currents, and the optimization of the process [16].

Power density and energy density are two main characteristics of energy storages technologies. The power and energy density of different energy storages are shown and compared in Fig. 2. An ESS technology featured with low power density but high energy density like batteries and fuel cells (FCs), creates power control challenges as the dynamic response of these technologies is slow. In contrast, technologies like SCs and flywheels can supply a high power demand that decreases the lifespan of the storage system [17]. None of the existing storage technologies can meet both power and energy density at the same time. Due to storage technological limitations, it is often necessary to enrich the transient and steady state performance of storage system called as hybrid energy storage system (HESS) [18,19]. Appropriate technologies with required control schemes should be combined for secure and optimum operation of MG. The overall design of a HESS in MG depends on four coupled factors: the choice of storage technology and rated capacity, power converter topology, energy management and the control strategy where should be dealt carefully.

Various review papers have been presented with the HESS. From the literature, most of the review papers focus on the HESSs in electrical vehicle [6,19–22] and some of them focus on HESS in renewable energy [3,23,24] and MGs [17,25]. The converter topologies, control methods, and applications are investigated in most of the review papers. However, none of them addresses the comprehensive review of hybrid

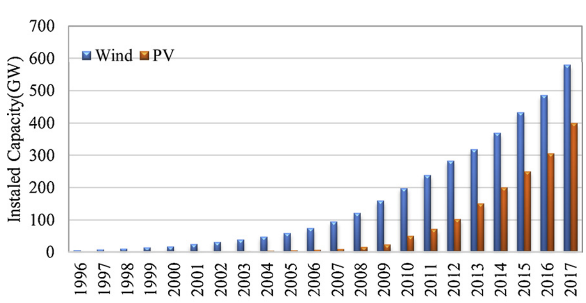

Fig. 1. PV and wind installed capacities.

storages in MGs and RESs in detail. In addition, new control methods are proposed for HESS control in recent research. Classification and analysis of the HESS capacity sizing methods have not been carried out in the previous researches, which is fully addressed and categorized in this paper. The main contributions of the paper are listed below:

- Studies different operational and technical aspects of hybrid storages in MGs field and presents general outlook and complete outlook of state of art developments.
- Comprehensive study of HESS for MGs application from the different point of view including HESS sizing, HESS applications in MGs, HESS configurations and connection, and HESS control methods.
- Comparison of control methods, capacity sizing methods and power converter topologies.
- A conceptual flowchart for correlation of different sections of HESS for implementation in MGs.
- Regarding literature review and available shortcomings, future trends of HESS and the research gaps technology are proposed.

The remaining of this paper is organized as follows: In Section 2, hybridization concept and applications are presented. The HESS sizing methods are summarized in Section 3. HESS topologies classifications are given in Section 4. HESSs control methods are studied and reviewed in Section 5. Finally, this paper conclusion is presented in Section 6.

2. Hybridization benefits and applications

As mentioned before, MGs and RESs suffer from problems like the intermittency nature, poor power quality, stability issues, frequency control, and unbalanced load. In a typical MGs, the ESS usually experiences irregular and frequent discharging/charging pattern which truncates the ESS lifespan, therefore the replacement cost of the ESS increase significantly [26]. HESS is an appropriate solution to overcome MGs and RESs challenges. Many studies have been done in recent years with the common goal of demonstrating the positive effects of HESS on the RESs [27–29]. Depending on the purpose of the hybridization, different energy storages can be used as a HESS. Generally, the HESS consists of high-power storage (HPS) and high-energy storage (HES) where the HPS absorbs or delivers the transient and peak power while the HES meets the long-term energy demand [30,31]. HESSs provide many benefits for MGs and RES including improving the total system efficiency, reducing the system cost, and prolonging the lifespan of the ESS [32]. Due to the various types of energy storages technologies with different characteristics, a wide range of energy storage hybridization can be formed. Fig. 3 shows the combination of different storage technologies which can be used for various applications [6]. It can be seen that the SC/battery, SMES/battery, FC/battery, FC/SC, battery/flywheel, battery/CAES, and FC/flywheel HESS are commonly

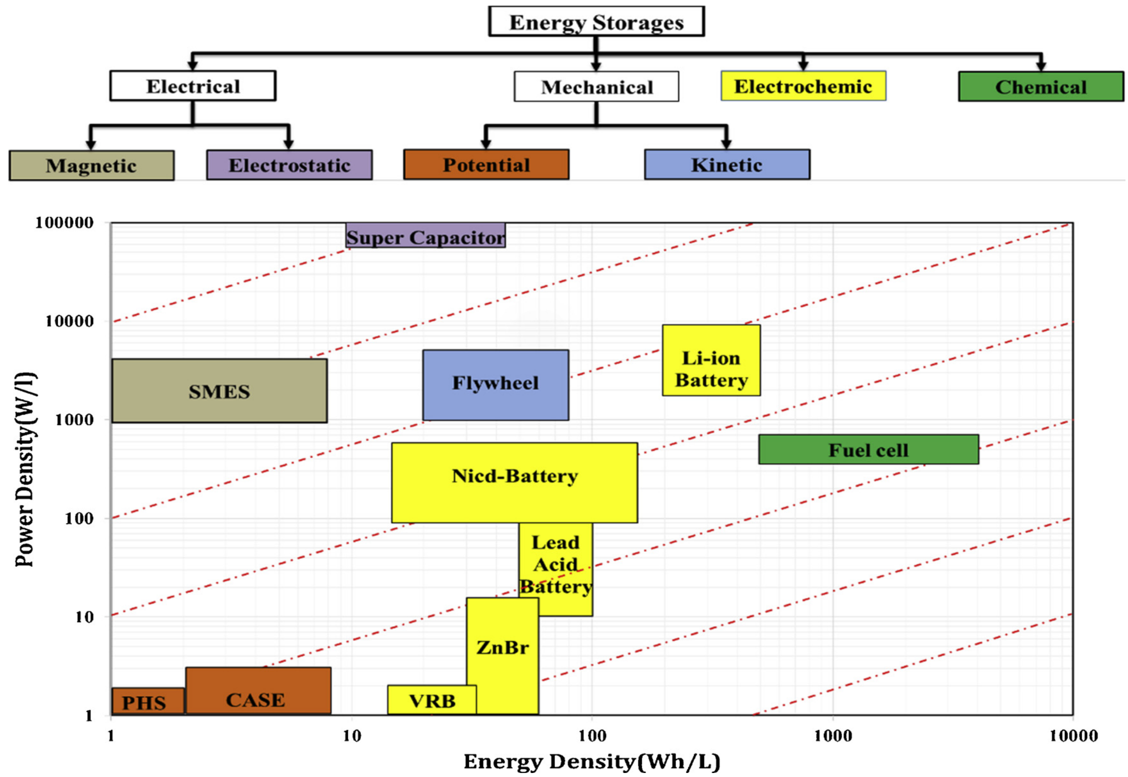

Fig. 2. Energy storages classification.

implemented in RESs application [4,9,11,33]. Selection of appropriate HESS combinations depends on the variety of items, including storages hybridization targets, storage costs, geo-location, and storage space availability.

2.1. Renewable system intermittence improvement

Most researchers have used HESS to improve the fluctuation of wind and solar power [34–36]. ESS can be integrated to alleviate some of the challenges associated with a fluctuation power production source such as solar and wind energy. Wind power has composed from various frequency components with different amplitudes and since the HESS includes both low and high speed responses, improved smoothing can be obtained in comparison to single ESS [37]. In [38] a capacity configuration of HESS based on the wavelet transform algorithm is presented to flatten short and long-term fluctuations of wind power. A combination of batteries and SCs is used and dispatched considering the frequency distribution of RES output power. A similar HESS (containing battery and SC) is also proposed in [39] for managing the fluctuations of wind energy in a remote area power supply. Superconducting flywheel energy storages are proposed in [40] to improve the power fluctuations of the large-scale wind farms. Simulation results show that instead of only using the battery energy storage system, adequately mixing of SFES with battery energy storage is a more efficient and effective solution to stabilize the output regime of wind farms. In [31] SMES and battery are used for wind power generation connection to the

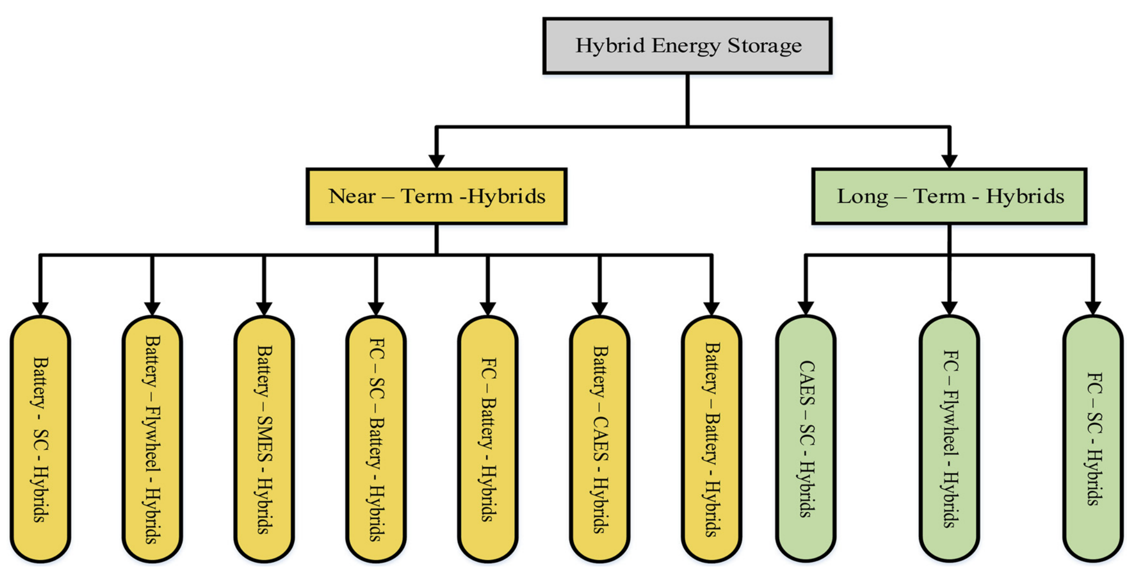

Fig. 3. Various methods of storages combination.

grid, where a double level control method is implemented. The system-level control performs power allocation between battery and SMES considering grid power demand. Meanwhile, the device-level control for converters aims at responding to the power-sharing of the system-level control and dc bus voltage regulation. A fuzzy logic controller optimized with the genetic algorithm is used to smooth the wind power fluctuations to satisfy the grid demand in [31]. The output fluctuations of a solar power plant are appropriately compensated by the use of SMES and electrolyzer in [41]. Fig. 4 shows an example of HESS application for power smoothing in a grid-integrated wind and PV system. The HESS includes HPS and HES that compensates both low and high frequency power fluctuations respectively.

2.2. Storage lifespan improvement

One of the disadvantages of electrochemical energy storages such as battery and FC is their low lifespan. Avoiding frequent cyclic charging and discharging of battery, prevents the degradation and improves its lifespan [42]. Battery lifespan in HESS structure can be increased by smoothing the battery power profile and preventing fluctuation supplied by battery, i.e. reducing the number of battery involved charge and discharge actions [43,44]. Authors in [45,46] proposed a power management strategy that utilizes both lithium battery and SC for battery life extension where SC provides the high frequency demand. The results show the battery lifespan is increased by 19%. A control strategy is proposed in [47] to contribute the instantaneous power between the battery and SMES. In this control method, the battery discharges and charges as a function of the SMES current rather than directly providing the power fluctuations.

FC lifespan is dependent on the fuel consumption of the FC and power fluctuations [48]. FC lifespan can be improved by combining FC with high power density storage [49,50]. Most researchers have used SC/FC hybridization to improve the FC lifespan. The use of SC and FC with appropriate energy management is presented in [49]. In this method, instantaneous power is supplied by the SC trying to improve FC power leveling and consequently its lifespan. Another study used hybridization of FC with SC to prevent the oxygen starvation and pressure oscillation of FC, caused by cyclic and frequent charging/discharging of FC [50].

2.3. Power quality improvement

HESSs are used for various power quality purposes, such as frequency regulation, stability improvement, harmonic compensation of unbalanced loads, supply of pulse loads, and dc bus voltage regulation in MGs. In this section, power quality benefits of HESSs are investigated.

2.3.1. Frequency regulation

The use of HESS for frequency control can be divided into two main parts: frequency control in off-grid systems [51–53] and on-grid systems [54–56].The high penetration of RESs in power system reduces system inertia, which could jeopardize the power system frequency and it may cause blackouts and equipment damage. A new design framework to system frequency regulation using HESS (coupled battery and SC) is presented in [57]. Moreover, an efficient coordinated operation strategy in electricity markets is proposed for frequency regulation. In [58] battery and SC are used to achieve the power management of the virtual synchronous generator. Particularly, the SC is employed to emulate the inertia of a virtual synchronous generator, and cope with high-frequency power fluctuations.

The battery energy storages have good features for regulating frequency in the off-grid MG systems. However, for frequency regulation, the battery charges and discharges at a high rate, which reduces its lifespan. Moreover, the battery needs to deal with the sudden power changes in the primary frequency control, which will also accelerate the battery degradation process. To solve the mentioned problems, authors in [51,52] proposed a novel concept of primary frequency control by combination the SMES with the battery that achieving both the frequency regulating function and the battery life-service extending.

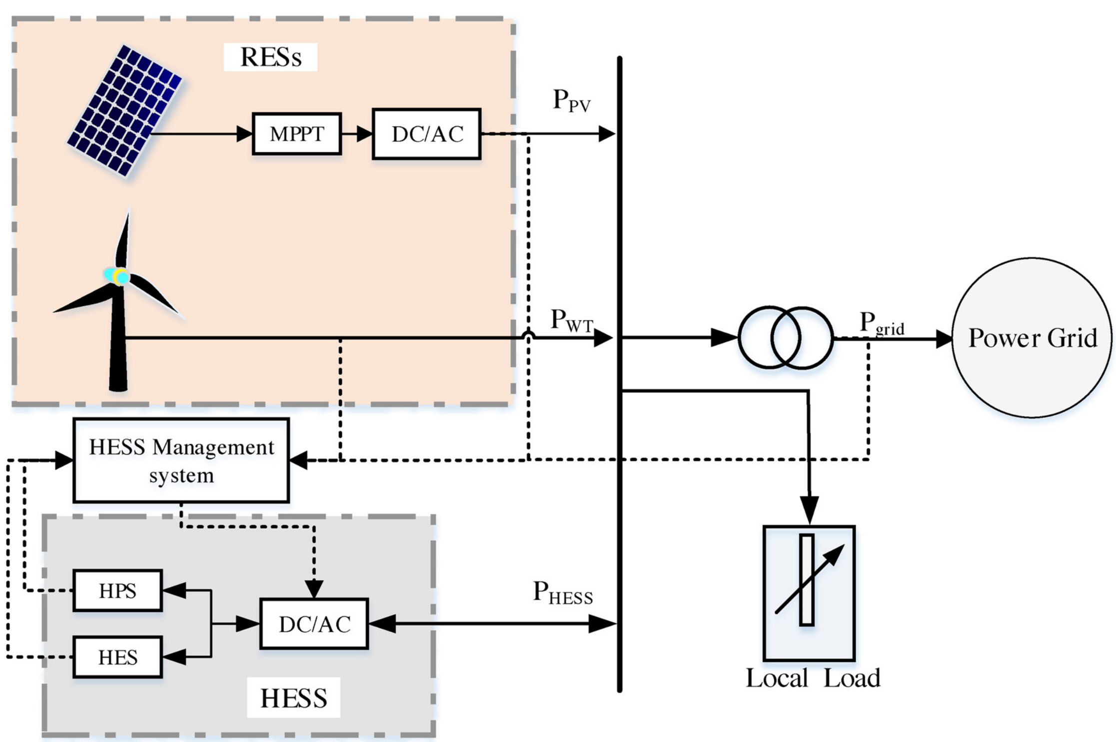

Fig. 4. HESS for RES intermittence improvement.

2.3.2. Pulse loads

Pulse loads require a high instantaneous power with low average power [59–61]. Once a single energy source is used to supply pulsed loads, thermal and power disturbance problems can be created. If a high power density storage is integrated to the system, various benefits such as the elimination of thermal issues, less volume and weight of the system, and reducing voltage deviation and frequency fluctuation can be achieved [62–64]. Authors in [65] proposed a real-time control strategy for a standalone dc MG with heavy pulse load and high redundancy. Battery and SC are used as HESS. The SC bank is used to supplies the pulsed load and supports the grid during transient periods. The results show that using this control method prevents the frequency fluctuation of the generator and improves system performance. Pulsed loads have significantly negative impacts on battery service life. The impact of pulsed load on battery lifespan is investigated in [66]. Two scenarios are considered to evaluate battery lifespan. In the first scenario, the pulsed load power is only supplied with battery where in the latter, battery and SC as a hybrid system supplied the pulsed load. Finally, a substantial gain of 17.6% in the lifespan cost of the hybrid system was concluded.

2.3.3. DC bus voltage regulation

For standalone MG, common dc bus is the preferred choice due to various reasons. DC bus voltage regulation as fast and accurate as possible is one of the important issues in MGs. In [67,68] battery-SC storages are used for rapid dc bus voltage restoration and effective power allocation between the SC and the battery in an isolated system. In some researches, battery-SC are used for dc bus regulation improvement in grid-connected mode [69,70].

2.3.4. Unbalanced load and harmonics

High power quality supply for consumers is one of the important issues for MGs. Nonlinear and unbalanced load conditions can be dealt with HESS. Using the negative-sequence voltage control method, the MG voltage quality can be enhanced. Nevertheless, the unbalanced current challenges remains unsolved for the majority of converters [71]. The use of battery/SC combination for MG performance improvement under unbalanced load in proposed in [71]. The results show that HESS utilization leads to fast and accurate voltage regulation under unbalanced load conditions. Authors in [72] proposed a coordination control strategy that uses HESS to improve the power quality for MG under unbalanced load conditions. In [73], the power management of a HESS composed of a lithium battery and a vanadium redox battery is presented. The four leg three-level neutral point clamped inverter is used to interface the HESS with the MG, due to its low total harmonic distortion, its ability to manage unbalanced ac loads through the fourth leg and high efficiency.

2.4. Stability

The MG stability is generally divided into three categories: stability of the rotor angle, voltage stability, and frequency stability. The stability of the rotor angle is due to the stability that generators can keep their synchronization in the face of turbulence. It's the stability between the electromagnetic torque and the mechanical torque of the generator and rotor. Frequency stability refers to the stability that the power grid can maintain constant frequency under different conditions. This kind of stability is an equilibrium between the production and the power dissipation and loss of loads. Voltage stability rests on the stability that maintains a constant voltage in all buses after confronting turbulence. This type of stability is the balance between load demand and power supply per bus. Stability in the MG can be divided into the stability of the MG in the grid-connected mode as well as islanded from the grid [74].

Energy storages can be used for transient stability issues in MG applications [75–78]. In [79], a new method based on active damping is proposed to overcome instability problems in dc MG, which is created by constant power loads. This method is based on existing energy storages in dc MG. These storage units also have an additional duty, such as setting the system's damping rate to deal with the problem of instability caused by constant power loads. Using the proposed method, known as the energy storage method by the SC, the constant power loads in the system are reduced virtually and the resistive loads are increased virtually. Therefore, the undesirable effects of constant power loads on the stability of the grid are virtually eliminated and MG stability is improved. In [77], a battery/SMES HESS is employed to improve the transient performance of a PV-based MG under various faults. The results of this study have shown that the HESS presents a better performance in comparison HES to the timely handling of transient fault issues of the MG. The HESS is capable of offering a rapid power injection for the MG at the initial stage of the fault feeding. About the articles reviewed, it can be concluded that the use of energy storage devices increases MGs stability margin, and with the use of HESS, this improvement is further than conventional storage.

3. HESS capacity sizing

One of the most important issues in HESS applications is to determine the appropriate storages capacity. Various methods have been proposed for storages capacity sizing. Some methods are developed to determine the HESS capacity of a particular technology, and some other, regardless of technology, can be used for sizing all types of storages. Authors in [80] reviewed battery sizing methods and its applications in various RESs. In HESS sizing procedure total cost and the reliability of the system should be considered [81]. The HESS sizing methods based on the purpose of HESS application may be different. Storages capacity sizing techniques can be classified into the analytical methods (AM), statistical methods (SM), search-based methods (SBM), Pinch analysis method (PAM) and Ragone plot method (RPM) that are illustrated in Fig. 5. Table 1 shows the various capacity sizing studies for HESS.

3.1. Analytical method

Analytical methods are most commonly used for HESS sizing. Analytical methods are based on analyzing a series of power system configurations with the system elements varied being those that need to be optimized against performance criteria. Various analytical methods have been proposed to determine the HESS capacity, but the overall trend of these methods is similar and in some cases, such as HESS technology, objective function, constraints, and solution method are different. The general process of determining the sizing of HESS is

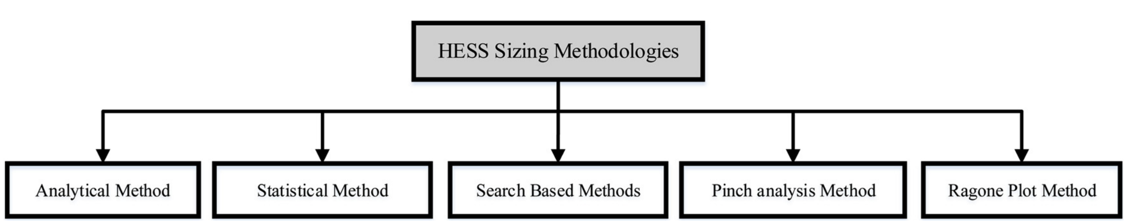

Fig. 5. HESS capacity sizing determining methodologies.

Table 1
HESS sizing methods.

Reference	MG configuration					Sizing Method	Objective Function	Considered Factors					Summary & Advantages
	MG Type	Grid-connected Mode	Islanded Mode	Energy Sources	Storage Technology			Installation cost	Operation & Maintenance	Lifetime	Replacement	Others	
[37]	ac	✓	✗	✓WT ✓hydro & thermal plant	HP & HE	AM	wind power Smoothing	In this method, the storage capacity is obtained using a level below the net power curve					In this study, Using DFT unbalanced power is decomposed to four components named very short-term, short-term, intra-day, and outer-day components, and the fast power frequencies are assigned to HP storages. A considerable capital saving is the main advantage of this method.
[83]	ac	✗	✓	✓WT ✓PV ✓ Diesel	FC/ SC	AM	Max (FC lifespan)	The difference in supply and demand is used to determine HESS capacity.					In this method, the experimental consumption and generation data is used and the difference storage sizing was made of the demand and supply data using a high pass filter. The main result of this method is the increased lifespan of FC. Moreover, the hybrid system efficiency increased by 5.8% compared to the conventional system.
[84]	ac	✓	✗	✓PV	Bat /SC	AM	Min (life-cycle cost)	✓	✓	✗	✗	Market price	Determining the HESS capacity for a 30 MW PV power plant in the Australian electricity market is done. The objective function of this study is the life-cycle cost, which considers the O&M cost, the capital cost, the lifetime of 20 years, and the efficiency. Leonardi has been used to PV power plan simulation under various operation modes. The optimum range of HESS capacity that provides positive profit improvement has been concluded. Moreover, it is concluded that HESS loses affect-sizing procedure.
[90]	ac/dc	✗	✓	✓PV ✓Diesel	Bat / Bat	SBM	Min(total cost of the whole ship)	✓	✗	✗	✓	Replacement	In this study, DFT has been used to decompose the unbalanced power into various time-varying components, which are used to HESS power calculation. Moreover, the PSO algorithm has been used to optimize HESS capacity. The optimum HESS capacity with cut-off frequency optimization is obtained. The simulation results show that the system cost with HESS is less than with a single conventional storage.

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Table 1 (*continued*)

Reference	MG configuration					Sizing Method	Objective Function	Considered Factors					Summary & Advantages
	MG Type	Grid-connected Mode	Islanded Mode	Energy Sources	Storage Technology			Installation cost	Operation & Maintenance	Lifetime	Replacement	Others	
[86]	ac	✗	✓	✓PV ✓WT	Bat /SC	SM	Max(economic benefits)	HESS capacity is determined based on maximum power delivering energy quantity storing.					A statistical method has been used to HESS capacity sizing. Moreover, a hysteresis control and a frequency management strategy have been proposed to control the output power of storages. HESS has been used to improve wind and solar power variations. The results show that the use of HESS has a significant effect on the performance improvement of the system indices than alone batteries.
[87]	ac	✗	✓	✓PV ✓MT ✓FC ✓WT	Bat / SC	SM	Extend the battery lifespan	The net power profile is used to HESS capacity sizing.					A novel frequency control method based on the hysteretic loop is proposed for a battery. A capacity statistical model that is composed of time-domain simulation, statistical analysis, and a capacity determination algorithm is presented. In this strategy, HESS capacity at various cumulative probability levels can be determined. Hysteretic loop control by preventing the battery from small charging and discharging prolongs battery lifespan. Compared with classical hybrid control, the hysteresis control loop method can save the battery energy capacity by 7.7%
[91]	–	✗	✓	–	Generic method	SBM	Min (operating cost)	✓	✗	✗	✗	✗	This method returns a Pareto-optimal frontier of the sizes of the underlying storage technologies. This frontier can be used to find the optimal operating point of any application with a linear objective function that is non-decreasing in the vector of storage sizes. The main feature of this method is that it can be used to determine the capacity of the various HESS.
[88]	–	–	–	–	Bat / SC	SBM	Min(investment costs)	✓	✓	✓	✓	✗	In this study, a new optimization algorithm, titled simulated annealing particle swarm optimization, is proposed to determine the capacity of HESS. The system operation cost based on renewable energy maximization is greatly reduced.

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Table 1 (*continued*)

Reference	MG configuration					Sizing Method	Objective Function	Considered Factors					Summary & Advantages
	MG Type	Grid-connected Mode	Islanded Mode	Energy Sources	Storage Technology			Installation cost	Operation & Maintenance	Lifetime	Replacement	Others	
[89]	Hybrid Electric Vehicles				Bat /SC	SBM	Max (battery life)	✓	✗	✓	✓	✗	In this paper, genetic algorithm is used to determine HESS capacity sizing. The objective function includes 10-years battery replacement and initial cost. The results are indicated that adding SC to the system will significantly improve the battery lifespan and reduce the total cost of the system.
[85]	Pulsed load and driving cycle				Generic method	AM	Min (installation costs)	✓	✗	✗	✗	✗	In this strategy total capacity of HESS is determined and then decompose between the storages based on operational constraints. This method is independent of topology, technology, application, and control strategy. The main drawback to this approach is its theoretical nature that requires an omniscient control strategy and reduces the problem to an energy balance
[94]	ac/dc	✗	✓		Bat /SC /FC	PAM	Min(annualized life cycle cost)	✓	✓	✓	✓	✗	This method is based on variation in the production and load and discharges time of energy storages. By applying PAM on the resource and load information, sizing curves for various time scales are derived. Obtained curve describes a set of feasible capacities of the storage for the respective time scale. The main advantage of this study is to analysis the demand and supply variability in various timescales (seconds to minutes, hours to days, and weeks to months)and selects appropriate storage options (short, medium, and long-term) respectively, based on the nominal discharge time.
[95]	ac	✓	✗	✓WT	Bat /SC	RPM	Min(life cycle cost)	✓	✓	✓	✗	✗	Using this method, mutual restrictions between the rate capability and storage capacity of the energy storage is considered
[98]	ac	✓	✗	✓PV	Bat /SC	AM	Min(total cost)	Only the SC capacity is determined according to net power profile and the maximum gradient of the battery power profile.					In this research, the supercapacitor energy controller is used for SC capacity sizing instead of its voltage, which allows precise selection of the filter parameters and capacity of the SC for a given application.

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Table 1 (*continued*)

Reference	MG configuration					Sizing Method	Objective Function	Considered Factors					Summary & Advantages
	MG Type	Grid-connected Mode	Islanded Mode	Energy Sources	Storage Technology			Installation cost	Operation & Maintenance	Lifetime	Replacement	Others	
[97]	ac	✓	✗	✓WT	Bat /SC	AM	Min (system cost)	✓	✓	✗	✗	Frequency deviation	In this study, a differential evolution method is used, which determines the HESS capacity based on the grid frequency deviation. The simulation results show that the optimal control strategies and capacity sizing could improve the lifespan of the HESS and help minimize the size of HESS.
[99]	ac	✓	✗	✓WT ✓PV	Bat/SC/ flywheel/ CASE	SBM	Min (operation and investment cost)	✓	✓	✓	✗	Reliability	In this study, multi attribute combination optimization and capacity sizing for HESSs are conducted. various indices such as the annual cost, environmental impact and fluctuation smoothing ability as well as safety are considered in the objective function. The main feature of this method is an evaluation strategy which can offer an aggregate utility of each HESS combination.
[100]	ac	✓	✗	✓WT ✓PV	Bat /SC	SBM	Min (overall cost)	✓	✓	✓	✓	Greenhouse Gases Emissions	In this method, the capacity of the hybrid renewable power generation system and HESS are determined simultaneously. This strategy is based upon a few important factors related to MG systems such as greenhouse gases emissions reduction, cost minimization, higher reliability, and higher emission reduction. The results of the optimal solution have lesser greenhouse gas emissions and higher reliability, and economical compared with other methods.
[101]	dc	✓	✗	✓PV	Bat/SMES	AM	Max(efficiency)	Optimal efficiency points is selected for HESS capacity sizing					The optimal efficiency points of the system are used for HESS optimal capacity sizing. The HESS capacity is selected so that minimize the charging and discharging losses.
[102]	dc	✗	✓	✓PV ✓WT ✓Diesel	FC/Bat	SBM	Min (total annual cost)	✓	✓	✓	✗	Fuel consumption	The Harmony search method is used to determine the optimal capacity of a MG. In first case battery and in other case FC is considered as a storage device. Simulation results prove that the battery storage system is more cost-effective than FC storage system.

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Table 1 (*continued*)

Reference	MG configuration					Sizing Method	Objective Function	Considered Factors					Summary & Advantages
	MG Type	Grid-connected Mode	Islanded Mode	Energy Sources	Storage Technology			Installation cost	Operation & Maintenance	Lifetime	Replacement	Others	
[103]	dc	✗	✓	PV ✓Diesel	SC/CAES	AM	Min(cost)	✓	✗	✗	✗	✗	This method is based on a numerical model which takes into account various constraints and assumptions. The results of this analysis indicate that, the proposed CAES can store the renewable electric energy with very high efficiency (> 50%). Moreover, It concluded that hybrid solutions capital cost is lower than the renewable energy resource.
[104]	dc	✗	✓	✓PV	FC/Bat	AM	Min(net present cost)	✓	✓	✓	✓	✗	This optimization strategy is based on the energy Hub concept which determines the optimum sizes of equipment with the lowest cost. This strategy for three scenarios was examined and compared including hydrogen storage technology only, the battery only, and hybrid storage. It is concluded that by HESS overall system complexity will be increased, but on the other hand it can overcome each storing choice's drawbacks and reduce the system's net power cost when optimum storage design technique is used.

presented in Fig. 6. The operation of HESS depends on the difference between the distribution generations (DGs) output power and load consumption based on (1). If the load power is greater than DGs generated power, the HESS provides the power to the load by discharging its energy. Once the DGs output power is greater than the load power, storages are charged.

$$P_{HESS} = P_{DG} - P_{Load} \tag{1}$$

where P_{HESS} is hybrid storages net power ($P_{HESS} > 0$ charging & $P_{HESS} < 0$ discharging), which consist of the first energy storage power (*Ps1*) and second energy storage power (*Ps2*). P_{DG} is DGs output power, P_{Load} is load power. The various parameters can be considered as the cost function in determining storage sizing. System reliability should be achieved by all methods. Because of renewable energy intermittency nature and load profile variation, HESS sizing process period can be considered 1 day, 1month or 1 year.

Generally, the allocation of power is carried out in such a way that high energy density storage provides low frequencies power and high power density storage provides high frequencies power. Hence, the sizing method can be done in time or frequency domain. In [82], a Fourier transformation-based method is proposed for sizing SC-battery HESS to maintain power balance of an isolated system. This strategy considers the expected lifespan cost of each kind of the ESS as an objective function. In this method, variations of net power caused by wind are divided into three components according to the frequency spectrum of variations, and HPS is used to compensate for fast frequencies of power variations. In [83] SC and FC are used as HESS where the SCs power is determined by a high pass filter with different cut-off frequencies. FC and grid power can be obtained by the subtracting the SC power from $P_{HESS.}$ The cut-off frequency of each filter indicates the operating interval of each energy storage technology and determines the required size of the SC. In [37] DFT method is used to decompose the net power into four components which are very short-term, short-term, intra-day, and outer-day components. The HESS capacity allocation is determined based on the spectral analysis method including DFT and spectral decomposition. Authors in [84] presented a method that uses the life-cycle cost which considers the operation and maintenance cost, the capital cost, the efficiency, and an estimated lifespan of 20 years.

A theoretical and analytical method to the minimal set of HESS capacity sizing is proposed in [85]. Firstly, total capacity of HESS is determined and in next phase, the net capacity is divided between the technologies based on operational constraints. This method is independent of topology, technology, application, and control strategy. The main drawback to this approach is its theoretical nature that requires an omniscient control strategy and reduces the problem to an energy balance.

3.2. Statistical method

Compared to analytical methods, statistical methods have more flexibility to determine the energy storages capacity in some applications. A statistical method for HESS capacity sizing is suggested in [86]. Moreover, a hysteresis controller and frequency management have been proposed to control the output power of each storage system. The storages combination aimed to ensure a more controllable output power and smooth the variations in solar-wind power generation. A statistical method using Monte Carlo simulation is proposed in [87] to determine the battery and SC capacity the in a hybrid system.

3.3. Search-based methods

Search based methods are subdivided into heuristic methods (HM) and mathematical optimization methods (MOM). Due to the nonlinearity of the objective function in the sizing problem, some researchers have used the heuristic optimization methods. Improved simulated annealing particle swarm optimization algorithm is proposed in [88] to solve the HESS optimization problem to reach the minimum cost. Using genetic algorithm to determine hybrid storages capacity including battery and SC is proposed in [89]. The objective function includes 10-years battery replacement and initial cost. The results are indicated that adding SC to the system will significantly improve battery lifespan and reduce the total cost of the system. Authors in [90] presented a new strategy based on DFT analysis for optimizing the size of a HESS. Moreover, a cost analysis is done using particle swarm optimization (PSO) algorithm to optimize the size of various types of ESSs. The simulation results show that cost of the HESS is decreased. Authors in [91] proposed a method that returns a Pareto-optimal frontier of the sizes of the underlying storage technologies. This frontier can be used to find the optimal operating point of any application with a linear objective function that is non-decreasing in the vector of storage sizes.

3.4. Pinch analysis method

Pinch analysis is a simple and flexible methodology for the minimum energy points determination in a utility heat exchanger network. This method is the low burden computational tool which can be used in renewable MGs. Some researchers used the PAM in HESS applications [92,93]. A generic HESS sizing method for an islanded MG based on PAM and design space approach is proposed in [94]. This method is based on variation in the production and load and discharges time of energy storages. By applying PAM on the resource and load information, sizing curves for various time scales are derived. Obtained

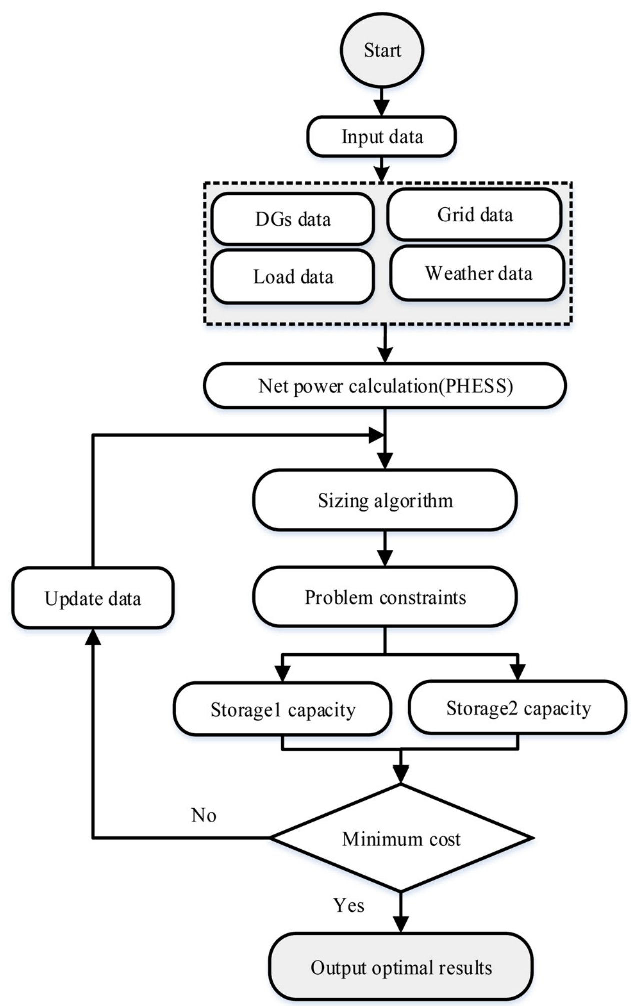

Fig. 6. Conventional HESS sizing flowchart.

curve describes a set of feasible capacities of the storage for the respective time scale.

3.5. Ragone theory method

Ragone plot is used to compare the performance characteristics of different energy storages. The use of Ragone theory to design HESS is proposed in [95,96]. In [95], the maximization of the storage life cycle is considered as the objective function, and the Ragone plots of energy storages are added to the problem as a constraint. Using this method, mutual restrictions between the rate capability and storage capacity of the energy storage is considered. HESS sizing and real-time operation strategy are different aspects that they have been investigated separately until now. However, the storage control method may affect the sizing results due to objective function and charge/discharge cycles. A deeper insight into the problem and more exact solution can be reached with simultaneous consideration of both capacity sizing and real time operation strategy. Sizing of storage in a wind/HESS system is studied in [97] considering the employed fuzzy-based control and state of charge (SoC), reflecting the real time operation of system.

3.6. Comparison of different capacity sizing methods

The advantages and limitations of various sizing methods are compared in Table 2. The use of appropriate methods depends on the different parameters such as available data of generation and load, the linearity or nonlinearity of the problem, taking into account the dynamics of generations and load, incorporating dynamic characteristics of HESS, and different constraints. Depending on the importance of mentioned factors, different capacity sizing method can be adopted. SBM methods due to capabilities such as considering different objective functions and solve nonlinear problems are mostly used.

4. Hybrid energy storages power converter topologies

HESS can be connected to MG through different topologies. Different topologies can be employed to combine HPS and HES [105–107]. A comprehensive review of HESS topologies is presented in [19]. Power converter topologies can be classified as active, semi-active, and passive that is shown in Fig. 7.

4.1. Passive topology

In passive topology, two storages with same voltage are simply connected together, that is efficient, simple, and cost-effective topology [66,108–110]. Since the terminal voltage of the storages is not regulated, the power distribution between HPS and the HES units is mainly determined by internal resistances and their voltage-current characteristics. As a result, the available energy from the HPS is very limited and it acts as a low pass filter for the HESS.

4.2. Semi-active topology

In the semi-active topology, a power converter is inserted at the terminals of one of storages, while the other storage is directly connected to the dc bus [111]. Although the use of a converter requires extra installation space and increases the cost, this class of topology offers more controllability and dispatch capability. There are different semi-active HESSs topologies that are reviewed in [111]. The use of the extra converters in this topology makes a better working range of the HESS [112].

4.3. Active topology

Active HESS topologies consist of two or more energy storages which each energy storage unit is connected to the system by the separate power converter. Although the complexity, losses, and cost of the system increase, this class of topology has the certain advantages. The advantage of this configuration is that all powers of storages can be controlled actively. Sophisticated control schemes can be implemented in a fully active HESS which is the most commonly used configuration [113]. The parallel active hybrid topology that is shown in Fig. 7(d) utilizes two converters for power control of the storage1 and the storage2. While in the traditional parallel topologies, the energy is exchanged via the common dc bus and the two cascaded converters that negatively affects the overall efficiency of the system. To solve the mentioned problem in a reconfigurable topology is proposed in [114]. Compared to conventional active topologies, the reconfigurable topology has advantages including reduction in the dc bus capacitor size, increased efficiency during the energy exchange modes, and the capability of reconfiguration. In some researches multilevel converters are used as hybrid storages power converters [115–120]. Using a multilevel structure, the system reliability, and power quality can also be enhanced. Meanwhile, connecting multiple energy storage in one converter reduces costs and coordination control complexity. However, the number of power electronics switches and capacitors in the multi-level converters are high and their control is more complicated. Isolated multiport converters for HESS have been used in [121–123]. Each structure has its own advantages and disadvantages, but in recent years the use of the active structure has been considered due to its high capabilities. For HESS connection to MG, the various class of power converter can be used [124–126]. To select a power converter, various

Table 2
Advantages and limitations of sizing methods.

Sizing methodology		Advantages	Limitations
AM		✓ This methods are very straight-forward. ✓ Simple and easy to understand.	✗ This method has a high computational volume. ✗ If data resolution is not sufficient, the optimal global solution may not be reached. ✗ Numerical approximation of system components is required.
SM		✓ More flexible for engineers to choose the optimum capacity according to the needs of the operation. ✓ Synthetic data can be generated when weather data is incomplete.	✗ The developed system will be less sensitive to the variation of the parameters.
SBM	MOM	✓ The solution can find in a limited number of steps. ✓ Professional software is available for solving optimization problems, such as GAMS and MATLAB.	✗ When the problem becomes more complex, especially for non-linear programming cases, these tools face difficulties in converging to an optimum solution.
	HM	✓These methods can avoid complicated derivatives, especially for nonlinear optimization problems. ✓Using reasonable computation time and memory.	✗Unable to represent the dynamic performance of the hybrid energy system. ✗ The optimum solution may not be achieved in some problems.
PAM		✓This method has a low burden computational tool. ✓Simple and flexible.	✗Not optimize the PV module slope angle, PV area, wind turbine swept parameter.
RPM		✓Rigorously defined for any kind of energy storages. ✓Readily display the two parameters with cost impact.	✗ Unable to represent the dynamic performance of the hybrid energy system.

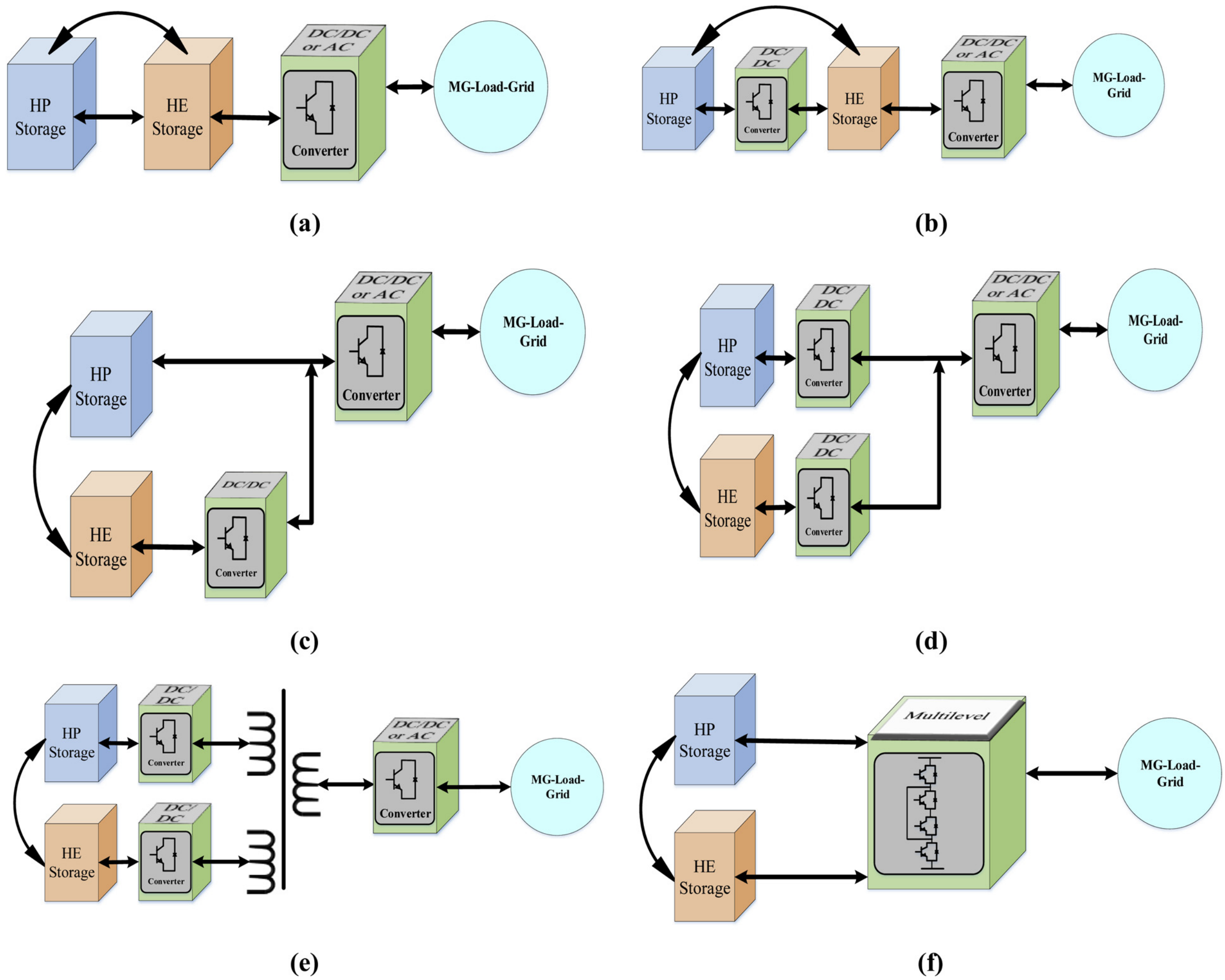

Fig. 7. HESS topologies classification. (a) passive topology (b) semi-active topology (c) series active topology (d) parallel active topology (e) isolated active topology (f) multilevel topology.

parameters such as efficiency, cost, reliability, and flexibility should be considered.

4.4. Comparison of different topologies

The HESS topology directly affects energy management strategy. In the passive topology, there is no direct control of storages power. In the semi active topology, the output power one of the storages is uncontrollable and the voltage of the other should be same as the dc bus. The active structure controls the output or input power of both storages by a rational control strategy, in cost of lower efficiency. Appropriate topology should be selected regarding different factors such as costs, efficiency, controllability, complexity, and flexibility. Fig. 8 compares the HESS topologies from different operational aspects. The passive topology is simple and cost-effective but non-controllable. In terms of controllability and flexibility and taking into account different constraints, such as SoC, the active topology exhibits the best performance, but its cost and complexity is high. The semi-active topology introduces limited controllability with lower cost.

5. HESS energy management and control

Designing and implementing a proper control system is the most important issue in HESS. The choice of the appropriate control method for HESS depends on different parameters: The purpose of the use of HESS (such as storage life extension, power quality, intermittency improvement and etc.), the type of system (dc MG, ac MG, grid-connected), the cost of the control method, the control method response time, the hybridization architecture and etc. To achieve the safe, stable, and efficient operation of HESS, a reasonable power-sharing strategy is essential.

Generally, the energy management and control system of HESS can be classified into two parts: (i) the underlying control unit that controls the current or power flowing of HESS elements based on the reference signal generated by energy management control unit (ii) the energy management unit which performs power allocation between the HESS storages to enhance system dynamics, reach high overall efficiency, monitor SoC, reduce the loss and cost of system, minimize operational

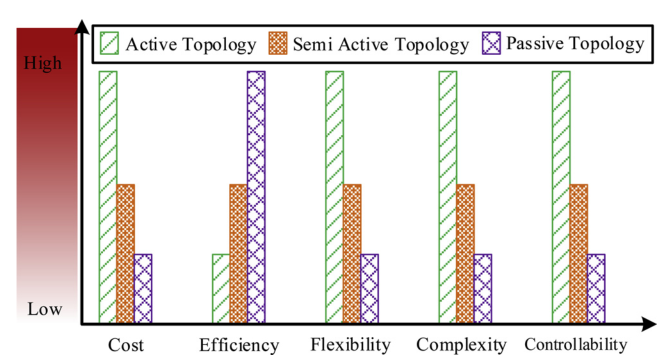

Fig. 8. Comparison of different hybrid storages topologies.

cost of the system, frequency regulation. Fig. 9 shows the classification of energy management and control methods developed for HESS.

5.1. HESS energy management system

Power allocation is a major concern in HESS. In literature, various methods have been proposed for allocating power in HESS. In general, the energy management methods can be categorized into intelligent control methods and classical control methods. Various HESS control methods are proposed in literatures, being investigated in Table 3.

5.1.1. Classical energy management control strategies

The classical control methods can be divided into the rules-based controller (RBC), droop based control (DBC), and filtration based controller (FBC). These control methods are sensitive to changes in parameters and the exact mathematical model of the system is required. In RBC, power allocation of HESS is performed according to the pre-defined rules. RBC can be divided into thermostat, state machine, and power follower control methods [23]. The RBC controller is simple and easy to implement and is an effective method for real-time energy management. Nevertheless, the sensitivity to parameters variation is the disadvantage of this method.

In FBC, a filter is used to decompose net power to the high and low frequency. In most MG applications power-sharing between hybrid storages is based on FBC control. In this method, the storages reference powers are determined based on the filter parameters. Scheduling the reference current among ESs is characterized by different ramp rates, low pass filters, and high pass filters are normally utilized to share power demand into low/high frequency components. Power-sharing in energy storages based on dc bus voltage regulation and filtration method is shown in Fig. 10. Implementing this method is easy and cost-effective. But in cases where the number of DGs or ESs increases, this method is not suitable because the power-sharing between the storage devices is less accurate.

When HESSs are used in MG, the hybrid storages power is determined by active coordination, and this power is divided by the energy management unit between different storages. Active coordination can further be classified as centralized, distributed, and decentralized ones. However, the both distributed and centralized controls are vulnerable to system communication failures. In this regard, the decentralized control methods are the most reliable one among the MGs control strategies. The DBC methods are one of the effective decentralized control methods.

The various types of droop control in MGs applications are reviewed and compared in [127]. However, the conventional droop control methods cannot be directly used to HESS control. In recent researches about HESS control, various types of DBC methods such as: high-pass filter-based droop control, extended droop control strategy [128], adaptive droop- based control [129], integral droop (ID) control [122], virtual capacitance droop [130], virtual resistance droop [131], virtual

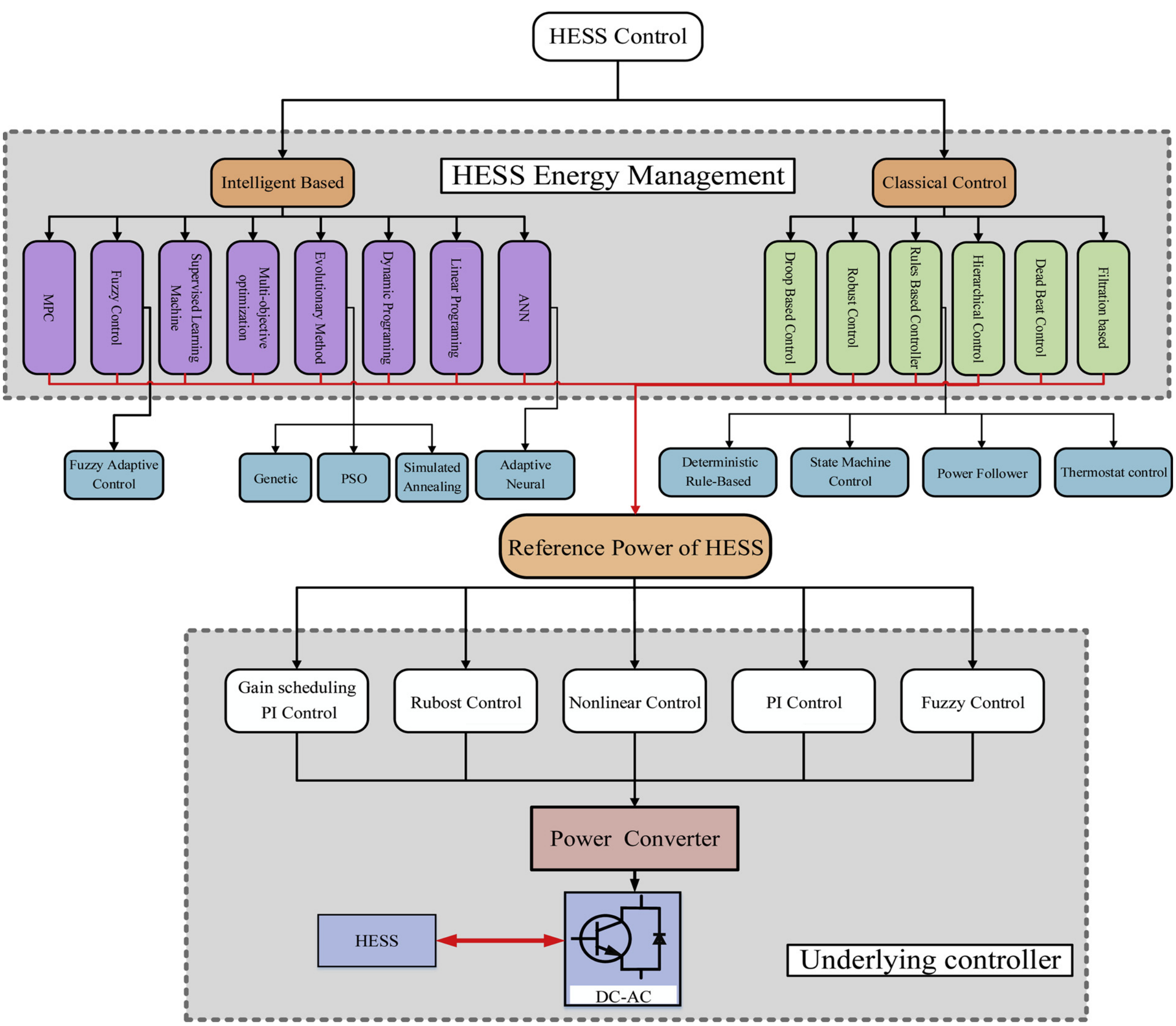

Fig. 9. HESS energy management and control classification.

Table 3
HESS energy management and control classification.

Refs	MG configuration				Control Strategy	Summary	The main advantages
	MG Type	Grid	RE source (s)	Storage Technology			
[46]	ac	Off-Grid	✔WT	Bat/SC	FBC	In this strategy, short-term charge and discharge cycles are supplied by SC. Accurate HESS modeling and battery life model are provided. The results show that with increasing the low pass filter time constant, battery cyclic wear is reduced.	Improving battery lifespan.
[69]	ac	On-Grid	✔PV	Bat/SC	FBC	This strategy changes the mode of renewable energy sources based on the amount of load variations and RES power change as well. Moreover, this presented EMS provides the real power transfer along with ancillary services such as reactive power support, power factor improvement, and current harmonic mitigation at the point of common coupling.	The voltage regulation is improved up to 25 times than the conventional system.
[67,68]	dc	Off-Grid	✔PV	Bat/SC	FBC	To increase the performance of HESS, the joint control method is presented that utilizes the uncompensated power from the battery. In this method, the high-frequency error component of the battery is supplied by the SC until the battery current is reached to the steady state.	Reducing stress in the battery.
[161]	dc	Off-Grid	✔PV ✔WT	Bat/SC	FBC	A Control strategy to power-sharing among HESS for match demand-generation mismatch is presented. In this method, SC supplies fast transient power demand and slow dynamics of the battery.	Improves the dc grid voltage regulation. Reduce the charge/discharge rates.
[162]	dc	On-Grid	✔PV	Bat/SC	FBC	An energy management strategy for HESS control is proposed. The advantages of this method in comparison with previous methods [67,68,69,161] are as follows: The voltage overshoot, the rate of change of the battery current, and settling time are reduced.	Better dc bus voltage regulation and power quality improvement in AC grid.
[163]	dc	Off-Grid	✔PV	Bat/SC	FBC	An energy management system combining energy management of storages and a control of bus voltage is proposed. The impact of the filter constant and the number of parallel SCs on the gain in battery RMS current under various operating state conditions are investigated and the optimal parameters have been achieved.	Reducing battery current stress.
[71,164]	ac/dc	Off-Grid	✔PV	Bat/SC	FBC	This paper presents an approach for power quality improvement by using HESS under unbalanced load conditions. The proportional resonance(PR) and fuzzy controllers are, respectively, used to regulate the AC load voltage and dc bus voltage controller.	Better dc bus voltage regulation.
[130]	dc	Off-Grid	–	Bat/SC	DBC	In this reference, virtual capacitance droop (VCD) strategy and high-pass filter-based droop proposed to SC and battery control respectively. The cooperation of VCD and high- pass filter droop enables simultaneous SC SoC recovery and bus voltage restoration.	Eliminates the output voltage deviation.
[128]	dc	Off-Grid	✔PV	Bat/SC	DBC	In this strategy Extended droop control that consists of a virtual capacitance droop and a virtual resistance droop is proposed for a dynamic power sharing among HESS under sudden resource variations and load change. For practical implementation, a precise design model including dynamic model and derived transfer functions is presented.	Stable operation, voltage regulation, and dynamic current sharing.
[129]	ac/dc	Off-Grid	✔PV	Bat/SC/FC	DBC	In this method, moving average filter is used to separate fluctuating and average power components. In this strategy energy management system is extended to multiple batteries and PV generation systems, with all the storages and sources geographically distributed and operating under multi time-scale adaptive droop control with supervisory control for mode transition	Better dc bus voltage regulation under dynamic changes.
[136,137]	dc	Off-Grid	–	Bat/SC	DBC	In this paper ID droop, for energy storages with fast response is proposed.The smooth change of load power components is supplied by the storages with V-P droop, whereas the storages with ID respond to high-frequency power demand.	Smoothing the load power changing. Dynamic power allocation of energy storages in decentralized level is achieved.
[165]	dc	Off-Grid	–	Bat/SC	DBC	For dc bus voltage regulation, Improved virtual capacitive droop is proposed in this reference. Under transient conditions, SoC of SC is automatically restored and SoC restoration loop is eliminated.	Redundant SoC restoration loop.
[143]	ac/dc	Off-Grid	✔PV	Bat/SC	FLC		

(*continued on next page*)

Table 3 (*continued*)

Refs	MG configuration				Control Strategy	Summary	The main advantages
	MG Type	Grid	RE source (s)	Storage Technology			
						In this reference an energy management strategy for is proposed, which minimizes the negative impact of pulse loads on power system stability. Also, by using the shifting load to off-peak hours, 7% energy saving per year is achieved.	Better stability margin of the system under pulsed load conditions is concluded.
[144]	dc	Off-Grid	–	Bat/SC	FLC	In this paper, a FLC strategy for HESS control under transient pulsed load conditions is proposed. Moreover, the HESS model validation under the effects of a pulsed load is validated using experimental test.	DC bus voltage is well controlled under pulsed load conditions.
[145]	dc	Off-Grid	✓PV	Bat/SC	FLC	A FLC strategy for power allocation of HESS with three modes is proposed. One mode is dedicated to exchanging power between SCs and batteries to prevent over charging and discharging the energy storages. The results of control implementation show that SoC values of storages maintain within the acceptable range and power compensation efficiency is improved.	Compared with[166] battery lifespan increased and power fluctuations decreased.
[147]	dc	Off-Grid	✓PV	Bat/SC/FC	FLC	For dc bus voltage regulation Nonlinear differential flatness-based Takagi-Sugeno fuzzy logic control is proposed. Fast variation current of battery and FC is removed, and their current stress is reduced.	The stress of FC and battery are reduced.
[148]	ac	Off-Grid	✓PV	SC/FC	FLC	This reference proposed a coordinated Fuzzy control method to achieve power management of HESS. Moreover, SoC of SC is considered to enhance the lifetime of UC.	FC lifespan is increased.
[149]	dc	Off-Grid	✓PV	Bat/SC	FLC & PSO	To minimize battery peak current, optimized the membership functions of FLC by PSO algorithm is presented. In comparison with RBC and FLC methods, the proposed strategy increases the level of SC utilization up to 687.122%.	The peak current and dynamic stress of battery are reduced,
[167]	dc	Off-Grid	✓PV ✓WT	Bat/FC	FLC	In this method, Water Cycle Algorithm is proposed to optimize fuzzy membership functions to simultaneously minimize the maintenance, loss of power supply and operation. In comparison with PSO and un-optimized FLC methods, the loss of power supply, maintenance and operation costs are reduced	The average battery SoC and the LPSP improved by 3.26% and 59.6% respectively.
[168]	ac	Off-Grid On-Grid	✓PV	Bat/SC	RBC	In this study, the MG control center power strategy refers to the SoC of the battery. Moreover, a load control method is presented to assist energy management. The results show a large capacity of HESS can make the normal operation of the planned load and ensure the whole system steadily, at the same time.	Internal power flow balance is improved,
[169]	dc	Off-Grid	–	Bat/SC	RBC	In this paper, three power control methods based on the amount of load demand are proposed to control the HESS. The SC and Battery, provide peak and transient power load requirement. The effect of controller parameters variations on the performance of the system has also been studied.	The dc link voltage overshoot is reduced and the response time is improved.
[170]	dc	Off-Grid	✓PV	SC/FC	RBC	The main goal of the presented EMS is the satisfaction of the load demands. In this method, all power generations and loads data are collected and based on the collected data and considering SoC of storages, the reference charging or discharging power of storage is determined.	Ensure the electricity production without interruption.
[171]	dc	Off-Grid	✓PV	Bat/FC	RBC	In this paper, an energy management method, which ensures that the load is supplied uninterruptedly and battery SoC keep in acceptable range, is proposed. This control strategy suppresses the short term variations load and PV power by the use of a battery bank. Moreover, by matching the power drawn from FC and PV to the load and electrolyzer demand the need for a dump load is eliminated.	Suppresses the short-term fluctuations in PV and load power.
[172]	dc	Off-Grid	✓PV	Bat/FC/SC	RBC	In this reference, two control systems are designed: a local energy management strategy at the customer side and a central power flow controller. The central power controller manages the energy and the power among the sources by gathering data through the producing and sensors control signals for the various converters which are used to control the power system. The local load strategy controls the various load, according to the energy balance	Increases the battery and FC lifespan, reduces the ON–OFF switch cycle of the FC, avoid deep discharge of the battery under bad weather condition.

(*continued on next page*)

Table 3 (*continued*)

Refs	MG configuration				Control Strategy	Summary	The main advantages
	MG Type	Grid	RE source (s)	Storage Technology			
						of the whole system, it can reduce a part of the home power demand when the system is under stress by disconnecting the offered controllable loads	
[173]	dc	Off-Grid	–	Bat/SMES	RBC	The combination of SMES and Battery, to handle both long-term and frequent power fluctuation caused by wave energy, is proposed. The classical controller is used to control the power of the battery and SMES, and the power fluctuations caused by the waves is compensated by the SMES.	Both the slow and fast power fluctuations, from direct drive linear wave energy, are compensated.
[174]	ac	On-Grid	✓PV	Bat/SMES	RBC	In this study, the SMES effect on the distribution system stability is analyzed with a PV system and a battery system. Voltage regulation and power reserve margin tests are done to evaluate the effect of SMES on system stability. The results show that SMES can provide effective stabilization and load regulation of distribution system with battery and PV system.	The battery SoC is limited at the acceptable range in the high power output event.
[175]	dc	Off-Grid	✓WT	Bat/FES	RBC	This control method is based on a two-level structure. The top level is the control unit and power regulation system. Depending on load and wind conditions, this control strategy generates reference dynamic operating points to low level individual subsystems. The overall coordination of the FC, WT, battery, electrolyze, and loads are archived.	Prevent the system from blackouts in the event of inadequate energy reserves or low wind conditions
[176]	dc	Off-Grid	✓PV	Bat/SC	RBC	In this study support vector machine load predictive EMS is proposed to control the energy among DGs. In the control algorithm, the battery depth of discharge is optimized to increase battery lifespan. The results show that the predictive method is capable of accurately predicting load demand.100% accuracy with the classification time of 0.004866 s is achieved.	Battery lifespan is improved. Power converter is reduced and system cost optimized.
[177]	dc	Off-Grid	✓PV✓WT	Battery/SC	FBC & ANN	In this reference, the neural network arithmetic and wavelet transform combination are used to control the system. A wavelet transform has been used to decompose net power into the fast and smooth component. The neural network calculates reference power of the battery. Moreover, SC is used to dc bus voltage regulation.	Battery SoC remains within the acceptable range.
[178]	dc	Off-Grid	–	FC/SC	MPC	The control method consists of two parts: 1) low-level control that split current between SC and FC and regulates dc bus voltage. 2) The supervisory level that controls rapid fluctuations in load while minimizing damaging variations.	The fluctuation of FC current is minimized and SC voltage maintains in an allowable range.
[152]	ac	On-Grid	✓PV✓WT	FC/SC/Bat	MPC	MPC controller is proposed to solve the optimization problem in a grid-connected MG that containing various energy storages. In the control design, various constraints including degradation issues, operational limitations, and operational cost associated with HESS is considered	Minimizing operational cost and reduce degradation issues.
[153]	ac	On-Grid	–	Bat/SC/FC	MPC	MPC control is used to power sharing in an MG The controller receives as a reference power scheduled by the economic dispatch of the MG for the batteries, the electrolyzer, and the FC, as well as the energy exchanging with the main grid.	The various degradation challenges of each energy storage concerning to shut-down/start-up cycle and load fluctuation are investigated and minimized.
[154]	dc	Off-Grid	–	Bat/SC	MPC	The purpose of the control system is to allocate the fast current changes to SC and slow current changes to the battery. MPC predicts the modulation indices for the SC and the battery dc/dc converter, so that the total power matches the required total power subjected to specified constraints.	The battery SoC, the SC current, the battery current and the SC voltage are maintained within the allowed range.
[73]	ac	On-Grid	–	Bat/SC	SM	The power management of a HESS composed of a lithium battery and a vanadium redox battery is presented. The four leg three-level neutral point clamped inverter is used to interface the HESS with the MG, due to its low total harmonic distortion, its ability to manage unbalanced ac loads through the fourth leg and high efficiency.	Power quality is improvement.
[160]	ac	On-Grid	✓PV	Bat/SC	SM	To solving variable frequency problem a fixed frequency sliding mode control method is proposed for HESS control. In comparison with the traditional method[73], the SM controller was able to achieve better output capacitor reference tracking. Classical control methods are most common to the power or current reference tracking in HESS.	DC current injection to the grid is eliminated. Better output capacitor reference tracking, and is achieved.
[179]	ac	On-Grid	✓PV	Bat/SC	SM		

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Table 3 (*continued*)

Refs	MG configuration				Control Strategy	Summary	The main advantages
	MG Type	Grid	RE source (s)	Storage Technology			
						In this research, to HESS operation improvement, phase-shifted interleaved of the boost converter is proposed. This phase shifter interleaved operation reduces the switching frequency current ripple component in both the SC and battery current. Both the double line frequency ripple current and fast current variations due to the HESS output power supplied by SC.	The current ripple in SC and battery is reduced. Battery lifetime is increased due to reduction in its internal heating.
[180]	dc	On-Grid	✓PV	Bat/FC	FLC & SM	In this reference, a combination of FLC and sliding mode control for HESS control is presented. The aim of this control method is to split the active power flow between hybrid power sources while taking into account component and system constraints.	System performance is improved and grid to operation at near unity power factor is achieved.
[181]	dc	On-Grid	–	FC/SC	Flatness	The flatness-based control strategy is used for SC and FC. The results show that the flatness control strategy provides better performance than the PI controller [182]. However, in this strategy for load power estimation measure, the load current is required.	Improved dc bus stabilization.
[183]	ac	On-Grid	✓WT	Bat/SMES	Coordinated Control	A hierarchical control strategy for HESS control is proposed. There are two levels of control in this strategy: device level and system level. A HESS control strategy based on the port-controlled Hamiltonian models is used to improve its output performance. At the system level, a multilevel power management strategy based on Fuzzy control, empirical mode decomposition, and advanced control is presented to achieve an efficient grid connection for a wind farm.	Smooth the output of wind farms.
[157]	ac/dc	On-Grid	✓PV ✓WT	Bat/FC	ANN	A feed-forward ANN is used for the dc-bus voltage regulation. Two Elman neural networks based controllers are designed to ensure the control of the bidirectional flow of the active power as well as the compensation of the ac load reactive power. Moreover, a FLC based power management system is adopted to minimize the energy purchased from the electrical grid.	Power purchased from the electric grid is minimized.
[184]	ac	On-Grid	✓PV	Bat/FC	ANN	In this study, a central power supervisor strategy is proposed to efficiently manage the power sharing between DGs. An online-trained ANN based controller is designed to perform the tracking of the optimal operating point of the PV source. In addition, a Takagi-Sugeno-Kang based fuzzy gain tuner is designed for the adjustment of the PI parameters of the battery and FC controllers.	The system mathematical model is not required and the system is robustness versus perturbation.
[185]	ac/dc	On-Grid	✓PV ✓WT	Bat/FC	ANFIS	In this reference, an ANFIS-based supervisory control strategy is proposed to determine the reference power of energy storages. In this method, different items, including SoC of the battery, the hydrogen tank level, the available power, and power demanded by the grid are considered. Moreover, an ANFIS-based control is designed for the three-phase inverter, which connects the system to the grid. it is concluded that the ANFIS control achieves higher system and battery efficiencies than the classical control.	Battery obtained and capable of injecting more power into grid than the classical EMS.

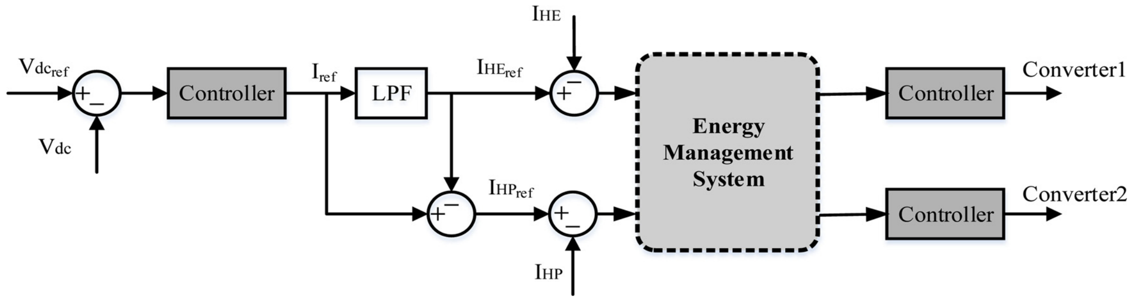


Fig. 10. HESS filtration based control.

capacitance droop with SoC recovery [132], adaptive droop [133], secondary voltage recovery droop [134], and virtual impedance droop [135] are proposed. The Various droop control methods are shown in Fig. 11. In [136,137], an ID is used for a group of energy storages with high ramp rates. Conventional V-P droop control method is shown in Fig. 11(a). The power split between the hybrid storages with ID is shown in Fig.11(b). The smooth change of load power components is supplied by the storages with V-P droop, whereas the storages with ID respond to high-frequency power demand. Additionally, the coefficient of ID can be designed based on the nominal ramp rate of the energy storages with slow response, which leads an improved lifespan of HESS. Each of the droop control methods has some advantages and disadvantages. All droop methods have plug "n" play capability. However, droop control methods with SoC recovery loop provide better storage performance. Extended droop can realize SoC of SC automatic recovery only when the line impedance can be ignored. Virtual capacitance droop is not suitable for dc MGs with multiple HESSs. If the SC leakage current is considered, the performance of virtual capacitance droop with SoC recovery strategy will deteriorate. To solve the problems associated with droop control, authors in [134] proposed an advanced secondary voltage recovery strategy using consensus algorithm based on the primary virtual impedance droop for multiple HESSs. In this strategy, secondary voltage recovery control for battery restore voltage deviation which caused by virtual impedance droop control, and secondary voltage recovery for SC recover the SoC of the SC after discharging and charging in spite of the existence of SC leakage current.

To improve the dynamic response of HESSs, the deadbeat control method (DCM) is presented in [138]. This strategy generates the optimal duty ratio in one control cycle, so that it can respond faster to the disturbance than various PI-based methods. The fast dynamic response of SC relieves the stress on the battery to extend its lifetime and the bus voltage can be maintained around its reference tightly. In addition, it is implemented with a reduced hardware cost by eliminating extra current sensors compared to the other model-based control approaches. However, this method is dependent on the system model, and in cases where the exact model of the system does not exist and the system parameters change, it does not respond appropriately.

Hierarchical control is another control method used to HESS control [139–142]. In comparison with other energy management strategy, the hierarchical method not only handle the uncertainty of loads and RESs by embedding the robust /stochastic energy management, but also reduce such uncertainty through using the intraday forecast data with higher precision. To secure and economic operation of MG with HESS under load and RESs uncertainty a hierarchical energy management strategy is presented in [139], which consists of real-time scheduling and hour-ahead scheduling. The results confirm that the control strategy is effective to provide a safe generation and economic plan. The calculation speed is sufficiently fast to satisfy online operation requirements. Moreover, the proposed control method of HESSs increases the lifespan of battery by 10.48%. To enhance dc MG reliability, hierarchical strategy witch composed of both distributed and centralized control is proposed in [140]. In this strategy, the traditional HESS control has been refined with implementations of secondary voltage regulation, autonomous SoC recovery, and online iteration. Using autonomous SoC recovery the SoC violation of storage is reduced, moreover, dc link voltage deviation is minimized and power quality improved. However, the accuracy of the system has decreased compared to the central control methods. A hierarchical control method to management and control a shipboard power system is presented in [141], which composed of the diesel generator, HEESs, and loads. To overcome the limitation controllability of HESS a new inverse droop control method is presented, which the power sharing is according to DG characteristic, rather their power rating. The results show that compared with conventional control strategy the method has advancement in bus voltage regulation and real-time fuel efficiency.

5.1.2. *Intelligent energy management control strategies*

To control nonlinear and complex systems, optimization based methods have become more popular. These methods can be categorized as the artificial neural network (ANN), Fuzzy logic control (FLC), evolutionary algorithms such as genetic algorithm, dynamic programming, linear programming (if the system is convex and could be mathematically represented via a set of linear functions), and model predictive control (MPC). FLC method is one of the effective methods for controlling complex systems. This control method is simple and not requires the exact mathematical model of the system. In some references such as [97,143–148], FLC has been used for HESS control. A FLC strategy for power allocation of HESS with three modes is proposed in [145]. One mode is dedicated to exchange power between SCs and batteries to prevent over charging and discharging the energy storages. The results of control implementation show that SoC values of storages maintain within the acceptable range and power compensation efficiency is improved. To minimize battery peak current, authors in [149] optimized the membership functions of FLC by PSO algorithm. A HESS and relevant control strategy for dc bus voltage regulation are proposed in [150]. The dc bus voltage is controlled according to the principle described in Fig. 12. FLC and FBC are used for energy storage management. A low pass filter is applied to the dc bus current to divert sudden power variation into the SCs. A PI controller is used to calculate the energy storages reference currents so that the bus voltage maintained at the reference value. The main purpose of using the FLC is to control the power of storage devices considering the limits of battery and SC charging within acceptable limits. An adaptive fuzzy logic based energy management strategy to split the power requirement between the battery and the SC is proposed in [151]. The key issues of this strategy are to improve the system efficiency, to reduce the battery current variation, and to minimize SC state of charge difference.

The MPCs provide another alternative to control the HESSs. The MPC in HESS control can be used either for power allocation in HESS and reference determination of storages with consideration of different constraints [152,153] or for direct control of power converter by controlling modulation index [154–156]. Moreover, the combination of the both mentioned approaches can be incorporated.

In [153], the MPC control is used to power sharing in an MG

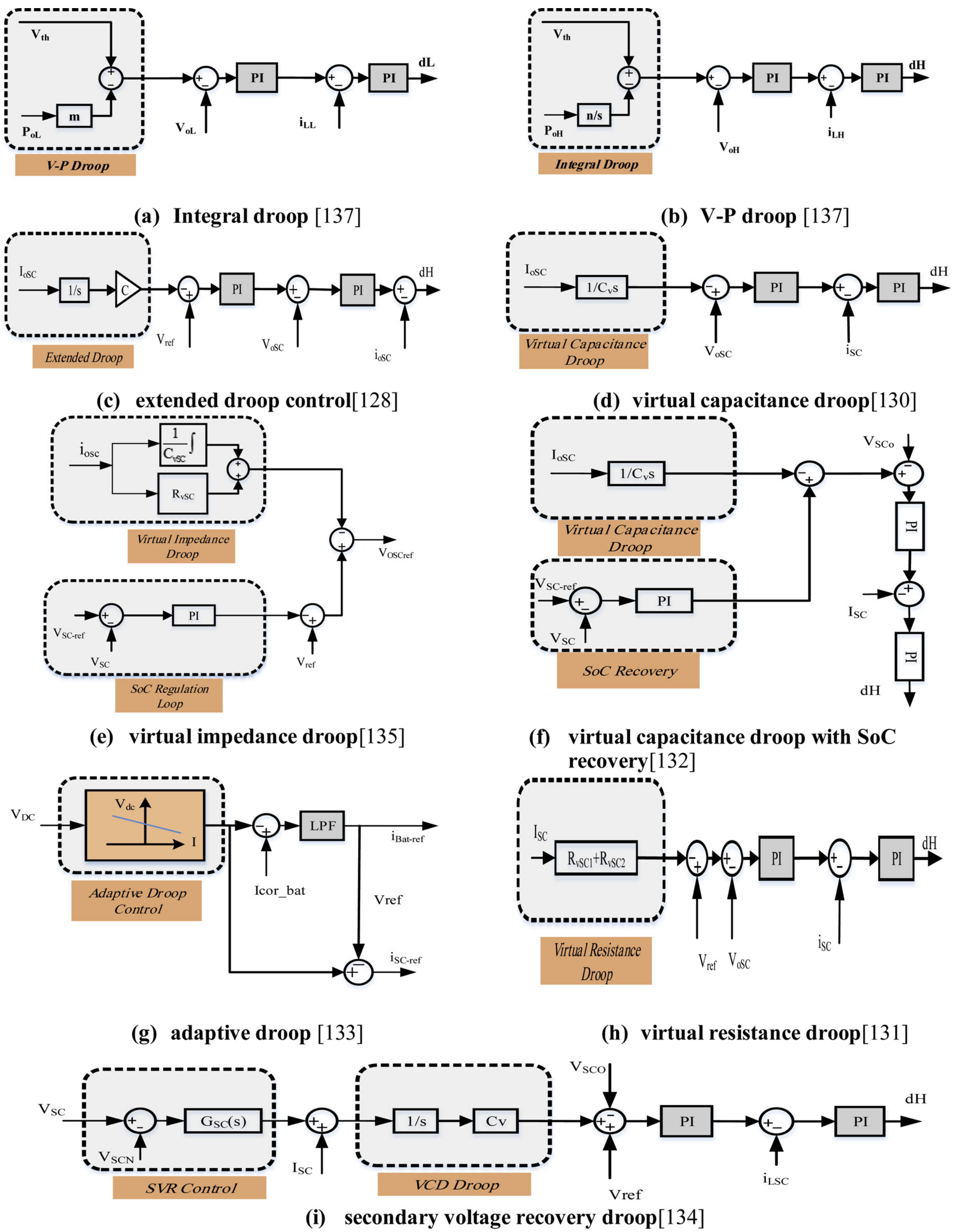


Fig. 11. Various droop control methods for HESS control in MG.

containing FC/batteries/SC. The different degradation challenges of energy storages related to start-up cycles, shut-down cycles and load fluctuation are investigated and minimized. The block diagram for the MPC controller is shown in Fig. 13(a). The controller receives as a reference power scheduled by the economic dispatch of the MG for the batteries, the electrolyzer, and the FC, as well as the energy exchange with the main grid. In [152], the MPC controller is proposed to solve the optimization problem in a grid-connected MG that containing various energy storages. In the control design, various constraints including degradation issues, operational limitations, and operational cost associated with HESS is considered. An example of the power converter modulation index control by MPC is shown in Fig. 13(b). MPC predicts the modulation indices m_{cap} and m_{batt} for the SC and the battery dc/dc converter, respectively, so that the total power matches the required total power subjected to specified constraints. The purpose of the control system is to allocate the fast current changes to SC and slow current changes to the battery [154].

ANN approaches do not require an exact system model and pattern

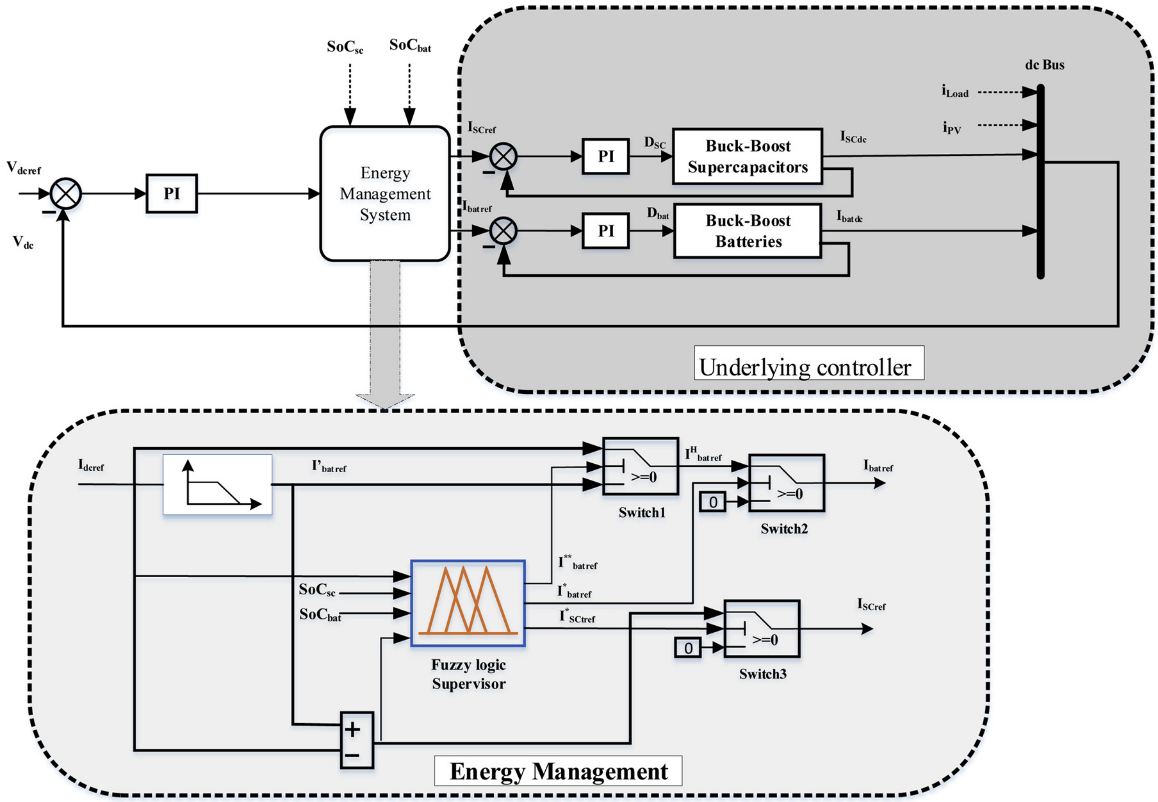
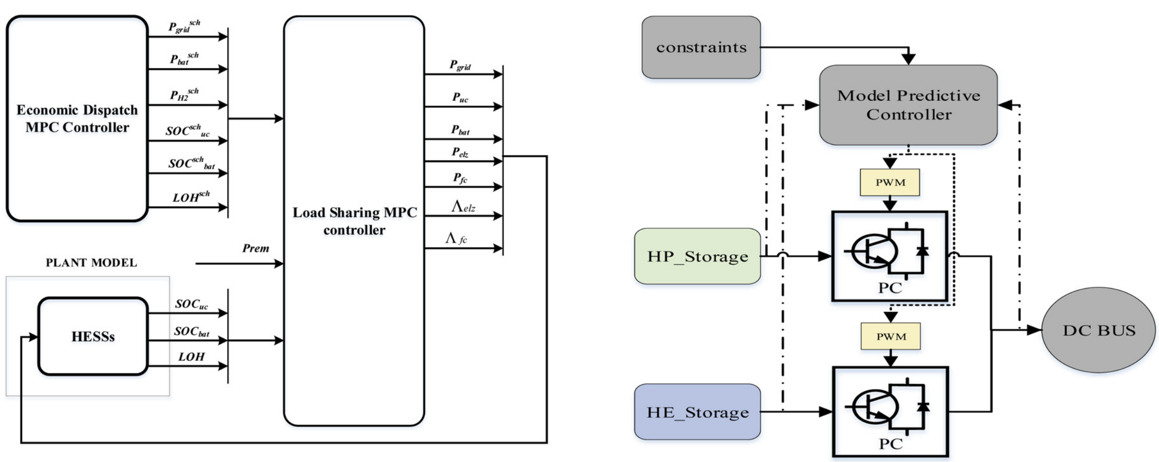


Fig. 12. Fuzzy energy management for battery- SC [150].



a) Optimal load-sharing MPC controller block diagram[153].

b) The MPC for direct control of power converter

Fig. 13. MPC control for HESS.

recognition capabilities of these methods make them attractive for renewable energy and MG applications. In literatures, ANNs have been used to predict the wind velocity and solar radiation, and few articles have used the ANN to energy management in HESS. Nevertheless, the ANN -based control methods require historical data for the tuning and learning process which makes it difficult to implement.

ANN based control system for investigating the behavior of a grid-connected hybrid ac/dc MG including PVs modules, a wind turbine generator, solid oxide FC and a battery energy storage system is proposed in [151]. This strategy tracks the maximum power point of renewable energy generators and controls the power exchanged between the front-end converter and the electrical grid.

A grid connected hybrid MG which consists of a PV system, a battery energy storage, a wind turbine generator, a FC and the ac and dc loads is presented in [157]. A feed-forward ANN is used for the dc-bus voltage regulation. Two Elman neural networks based controllers are designed to ensure the control of the bidirectional flow of the active power as well as the compensation of the ac load reactive power. Moreover, a FLC based power management system is adopted to minimize the energy purchased from the electrical grid. The performance of the mentioned control system has been evaluated for different situations: variable load demands, perturbed grid, and variable climate conditions. The results show that it is possible to control complicated nonlinear systems without the need for a precise model. Furthermore, the mentioned methods are adaptable, flexible, and easy to implement in real-time applications with low computational costs.

Table 4
Advantages and limitations of HESS control strategies.

HESS control strategy		Advantages		limitations	
Classical	FBC	✓ These methods are easy to understand and cost-effective.	✓These classes are suitable for real-time applications.	✗Determining the filter parameters is complicated and system performance is dependent on the cutoff frequency.	✗Exact mathematical model of the system is required.
	RBC	✓These methods are simple and have a low computational burden.		✗sensitivity to parameters variation. ✗In cases where the number of DGs or ESs increases, this method is not suitable because the power-sharing between the storage devices is less accurate.	
	DBC	✓ These methods are decentralized and easy to implement. ✓Have plug "n" play capability. ✓High reliability		✗The accuracy of power sharing is low among DGs.	
	Hierarchical control	✓Power sharing and control of various device of the system are done with high accuracy. ✓handle the uncertainty of loads and RESs.		✗Vulnerable to system communication failures.	
	DCM	✓This method has a faster dynamic response and requires fewer hardware sensors Compared to controller PI controller.		✗ The exact model of the system is required. ✗sensitivity to parameters variation.	
	Robust control	✓These methods are less sensitive to changing parameters. ✓Better response than conventional controllers.		✗Due to the high amount of calculus in each switching period, implementation of these controllers is difficult.	
Intelligent	ANN	✓ Has the ability of learning and parallel data processing.	✓ The exact model of the system is not required. ✓ Efficient and robust as compared to classical control methods.	✗ ANN-based control strategies require historical data for tuning and learning process. ✗ANN is lacking rules for defining the structure due to their "black box" nature.	✗ The computational burden in these methods is high.
	FLC	✓This technique is easy to understand and does not have much sensitivity to parameters changing.		✗Fuzzy membership functions are usually determined by trial and error, which may not be optimized.	
	Evolutionary methods	✓ Different cost functions for control can be considered and optimized compared to classical control.		✗These methods are not systematic and may not achieve optimal results.	
	Multi objective methods	✓The possibility of considering several objective functions is possible.		✗These methods are not systematic and may not achieve optimal results.	
	MPC	✓Various optimization parameters can be considered. ✓The ability to predict future system events.		✗The exact model of the system is required.	

5.2. Underlying controller

The task of underlying control is to tracking HESS references power generated by energy management control system. Concerning to the HESS control, existing control methods can be classified into the modern control method and the classical control method [158]. This classification is shown in Fig. 9. In classical control strategies, the controller based on the linearized system is designed in the frequency domain. The main problem of the classical methods is that the system nonlinearities are not considered. Moreover, in some applications controller performance may not be acceptable. In this regards, some researchers have used nonlinear control methods to control HESS. There are various types of nonlinear control methods. In some of the references, sliding mode control is used to control energy storages [159,160]. The comparison between the classical PI controller and the sliding mode controller for a HESS is investigated in [159]. The simulation results of the show that the sliding mode controller has higher stability and robustness compared to the PI controller. However, the conventional sliding mode controller has some drawback for ESS converters such as variable and high switching frequency that increases system complexity and power losses. To solving the mentioned problem a fixed frequency sliding mode control method is proposed in [160] for HESS control. In comparison with the traditional method, the SM controller was able to achieve better output capacitor reference tracking. Classical control methods are most common to the power or current reference tracking in HESS. However, due to the nonlinear properties of HESSs, the use of nonlinear controllers will lead to better results.

5.3. The comparison of various control methods

Choosing an energy management approach and control strategy do not have a specific flowchart or a predetermined process. Different items such as the purpose of the control system, response time, control system cost, energy storages characteristics and reliability can be considered. Advantages and limitations of different control methods of HESS are presented in Table 4. Due to less computational, classical control methods are more suitable for real-time applications. However, they need mathematical model of the system makes it difficult to use in some cases. One of the main disadvantages of intelligent control methods is the high computational burden of these strategies where in real-time applications may affect the performance of the system and requires hardware systems with high computational capabilities. Theses method are flexible where different cost functions or power quality parameters can be adopted.

The flowchart of the implementation of HESS in MGs applications is shown in Fig. 14. The Fig. 14 shows the trend and dependence of the different sections for the implementation of HESS in MGs. In general, the use of HESS in MGs and RESs can be divided into four main sections: 1) HESS technologies selection based on application and target 2) HESS capacity sizing 3) HESS topology and configuration 4) HESS energy management and control system. Different steps in the use of HESS in MGs were investigated in detail in different sections of this paper. The challenges of different sectors and their advantages and disadvantages have been analyzed.

6. Conclusion and future trends

In this paper, recent researches of HESS implementation in MGs and RESs are reviewed. HESS accommodates the MGs operation in presence of different uncertainties and they can beneficiary to satisfy the power balance and the required dynamic energy. Main format of HESS is the coupled utilization of limited energy and power resources to cope with the requirements. Since the battery and SC technologies are reached

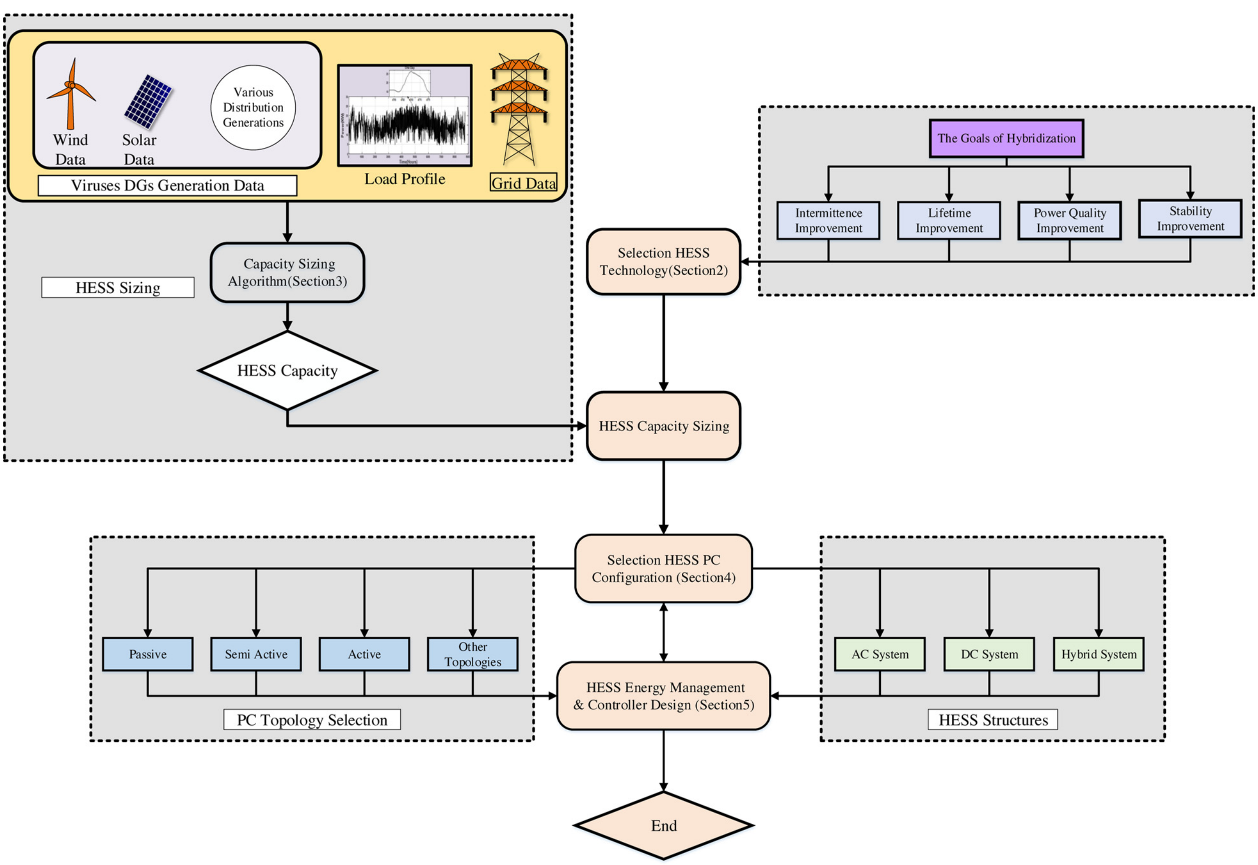


Fig. 14. The flowchart of the implementation of HESS in MGs applications.

relative maturity, prices are quite low and they are commercially available in a variety sizes. Battery-SC are the mostly used HESS where the FC-SC, battery-flywheel and battery-SMC are less common and more work should be done to develop detailed modeling of these combinations.

The important advantages of HESS in MGs can be summarized as follows: storage system cost reduction, increasing storage lifespan, response time reduction of MG dynamics, increasing MG reliability, power quality improvement and pulse loads supply. Appropriate design is an essential to reach out the benefits of HESS.

HESS design procedure is pretty complicated and a specific trend is not available. The design procedure is highly dependent on the operator target and it varies according to required ancillary service. The studies show the sustainability compensation and lifespan improvement of the storage is received much more attention and the design procedure is approximately clear. However, HESS design for system stabilization and power quality improvement is not fully addressed. There is a gap for multi-objective design method that sizes the HESS considering different factors. HESS design can be categorized into four main fields: HESS sizing, power converter topology selection, control method and the energy management.

Various HESS capacity sizing methods have been presented in literature. Different objective functions have been used to determine the energy storage capacity. An important factor in determining the chemical and electrochemical storages sizing is the storages lifespan. Determining HESS capacity in islanded MG, taking into account the model of the length of the concrete and various parameters such as SoC, DoD (depth of discharge), reducing generation pollution such as diesel generator, greenhouse gases, fuel consumption, and costs can be simultaneously solved by multi-objective methods. Determining the capacity of the HESS, considering the mentioned objective functions is proposed for the future researches.

Various topologies have been used for HESS connection to MGs. Impedance source converters can be recommended for HESS connection considering the converter cost and efficiency. The use of Impedance source converter for HESS connection to MGs has not been reported yet, although Impedance source converter has been used to connect HESS in electric vehicles [186,187]. Impedance source converter is capable of working as a dc/ac or dc/dc converter which is significant advantage in hybrid dc/ac MGs. Particularly in dc/ac converters, the use of z source inverters reduces the number of converters, cost, weight, and offers more controllability.

The hierarchical control is widely used for the coordination of HESSs in MGs. As the hierarchical control contains the decentralized and the centralized control levels, the time delays during signal transfer processes between two control levels may significantly affect HESS operation and may lead to instability. Effect of control scheme on HESS operation and its stability regarding realistic circumstances should be performed as an important future work. In this regard, the authors investigated the effect of the hierarchical control on the dc MG [188]. This research demonstrated that the time-delay stability of HESS is more sensitive to energy storage with high response speed than energy storage with low response speed. Various parameters such as SoC, DoD, accurate power sharing should be considered in developing an appropriate control scheme. However, integrated design of distributed HESS and local controllers have not done which can be considered as future work.

For a MG, it is important to provide high quality power to consumers. In practice, various types of loads such as unbalanced, nonlinear loads, pulse loads are supplied by a MG system. If the only HES is used in MG with the mentioned loads, there will be no suitable dynamic response to the loads, and the lifespan of the storage devices will be reduced. The use of HESS in such conditions can provide the proper dynamic response and increase the lifespan of the storage devices, which can be studied as one of the future trends.

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