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A Review of Recent Advances on Hybrid Energy Storage System for Solar Photovoltaics Power Generation

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ABSTRACT The use of hybrid energy storage systems (HESS) in renewable energy sources (RES) of photovoltaic (PV) power generation provides many advantages. These include increased balance between generation and demand, improvement in power quality, flattening PV intermittence, frequency, and voltage regulation in Microgrid (MG) operation. Ideally, HESS has one storage is dedicated for high energy storage (HES) and another storage for high power storage (HPS) purpose. HES is used to fulfill long-term energy demand, while HPS is used to handle power transients and fast load fluctuations. This paper examines HESS comprehensively for PV power generation and focuses on its ability to combine two storage technologies. The two storage technologies include high energy and high power. This paper also analyzes the important aspects of advance HESS in PV power generation in the context of capacity sizing, power converter topology and strategies management energy. Several capacity sizing methods were critically reviewed and tabulated. Power converter (PC) topologies are classified and briefly discussed regarding their advantages and disadvantages. Furthermore, energy management strategies with various control techniques are critically classified and evaluated for better future direction. In addition, the implementation of HESS on PV power generation in current real projects is presented and evaluated. Finally, this paper can be considered as useful guide for the use of HESS in PV power generation including features, limitations, and real applications.

INDEX TERMS Energy storage, hybrid energy storage system, photovoltaic, capacity sizing, power converter, energy management system, microgrid.

I. INTRODUCTION

Renewable energy source (RES) is an alternative means of generating energy to reduce greenhouse gas emissions [1]. Preliminary studies on RES-based power generation such as solar photovoltaic (PV), wind, hydro, biomass, geothermal have been extensively conducted. However, in the last few decades, PV power generation has become one of the most prominent RES technologies because it is easy to install, has low operating costs, and comprises mature technology [2]. PV and Microgrid (MG) power generation as a batch of load are proposed to be operated in grid-connected mode.

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A PV power generation connected to the MG needs an energy storage system (ESS), which contributes to its integration by flattening PV fluctuations, power quality and system stability improvements, dc bus voltage regulation, contributing in frequency, *etc.* [3].

EES has been used for centuries and its experience continuous improvement. In the ESS structure, several energy storage technologies (ES) are used to store electrical energy [4]–[6]. Figure 1 shows ES technologies that is typically used for PV power generation in grid-connected mode. The classification of various electrical ES as well as their energy conversion processes and efficiencies are studied in [7]. In addition, its battery technology is considered competent storage that is economical, adequate for power balancing, and able to

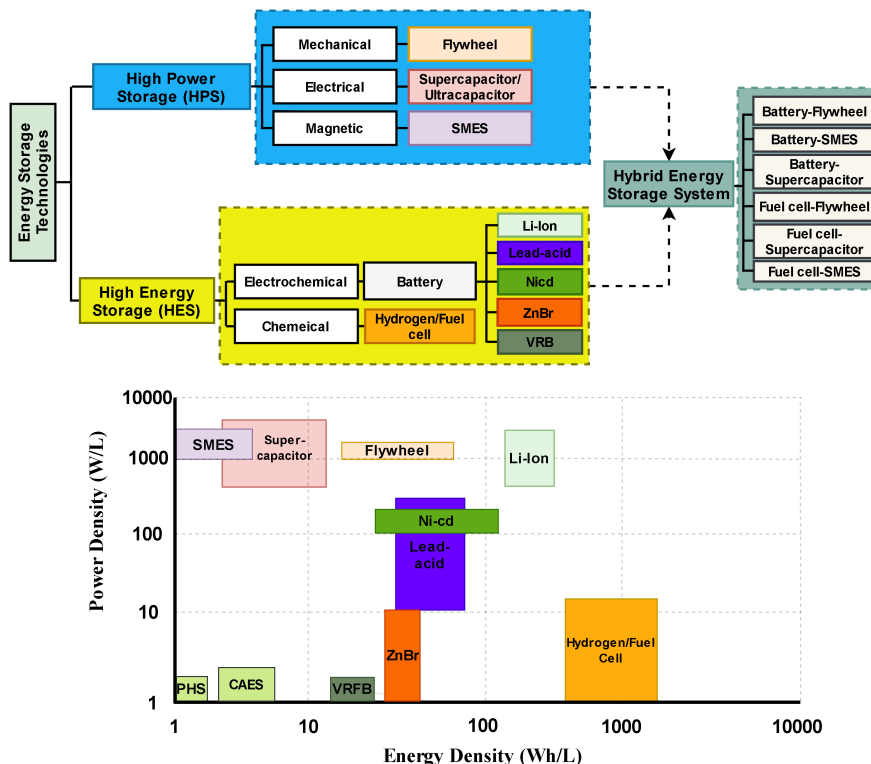


FIGURE 1. Classification of energy storage systems.

maintain the power grid [8]. In supporting large-scale energy storage applications, there are storage technologies such as compressed air energy storage (CAES) and pumped hydro energy storage (PHES) [9]. However, both these energy storages rely on environmental and geographic situations, which make their development challenging [10]. Furthermore, ESS Flywheel is based on electromechanical technology [11]–[13], with its stability and efficiency affected by mechanical parts. The ESS Supercapacitor (SC) technology is an example of electrostatic storage, with high recyclability and density [14]. Superconducting Magnetic energy storage (SMES) is an example of ESS that produces storage of electrical energy directly in a magnetic field obtained by current flow [15].

In this type of ES technology there is energy density and power density. Energy density is the accumulated energy per unit volume or mass, while power density is the rate of energy transfer per unit volume or mass. The energy and power densities of various ES technologies are shown and compared in Figure 1. ES technology such as batteries and fuel cells (FC) have high energy and low power densities, thereby creating power control challenges due to the slow dynamic response. Conversely, ES technology such as SC and flywheel have a high power density, hence it can supply high power demand but a decrease in the lifetime of the storage system [16]. However, of the several ES technologies, none has the ability to fulfill the power and energy densities simultaneously. Due to this limitation, it is necessary to enhance the performance of an advanced storage system known as

a hybrid energy storage system (HESS). HESS is a two or more energy storage technology combined into one device to improve ESS performance [17], [18]. The HESS can be incorporated with PV power generation for optimal and safe MG operation. HESS modeling in MG depends on several interrelated factors, such as energy storage capacity sizing, energy management, power converter topology, and control strategies that need to be handled with care.

Various papers have investigated HESS related to PV power generation. From various literature, HESS is used for PV power generation RES applications [19], [20], and Off-MG [21]–[24]. Capacity sizing, power converter topology, control strategies, and utilizations are examined in several papers. However, neither did discuss the on-grid HESS review in detail. In this paper, analyzes the important aspects of advance HESS in PV power generation in the context of capacity sizing, power converter topology and strategies management energy. Several capacity sizing methods were critically reviewed and tabulated. Power converter (PC) topologies are classified and briefly discussed regarding their advantages and disadvantages. Furthermore, energy management strategies with various control techniques are critically classified and evaluated for better future direction. In addition, the implementation of HESS on PV power generation in current real projects is presented and evaluated. Finally, the main contributions of this paper help scientists and practitioners to have a complete idea of maximize the utilization of HESS in PV power generation on-grid or off-grid. The remaining sections are organized as follows:

TABLE 1. The characteristics of types of technology ESS based on HES and HPS.

Technology ESS	Power capacity (MW)	Density		Response time	Efficiency			Life time [year]	Maturity	Note /info
		Energy (Wh/L)	Power (W/L)		Discharge [%]	Round-trip [%]	Daily self-discharge [%]			
Batteries:										
Ni-Cd	0-40	60-150	150-300	sec	60-70	65-80	0.03-0.6	3-20	fully commercializing	-
Li-Ion	0-100	200-480	500-2000	20 ms-sec	85	75-97	0.1-5	5-16	fully commercializing	HE
Lead-acid	0-40	50-80	10-400	sec	85	63-90	<0.1-0.3	5-15	fully commercializing	HP
NiMH	-	-	-	-	-	-	-	-	-	-
ZnBr	0.05-10	30-65	<25	ms	60-70	65-75	small	5-10	early commercializing	-
VRFB	0.3-3	16-33	0.5-2	sec	75-82	65-85	small	5-20	commercializing	-
Super-capacitor	0-0.3	2.5-15	500-5000	8 ms	95-98	95-98	5-40	10-30	fully commercializing	HP
SMES	0.1-10	0.5-15	1000-4000	<100 ms	-	95-98	10-15 %	20	proven/commercializing	HP
Fuel cell/hydrogen	0-50	750 /250bar	0.2-20	<1 sec	-	34-40	0.003-0.03 %	20	developing	HE
Flywheel	0-0.25	20-80	1000-2000	ms-sec	90-93	90-95	>20 % hr	>15	Early commercializing	HP
PHS	10-5000	0.5-1.5	0.5-1.5	sec-min	~ 87	65-85	very small	40	very mature	-
CAES	5-1000	3-6	0.5-2	1-15 min	70-79	70-89	small	20-40	proven	-

*Note: HE=High-Energy; HP =High-Power

Section II. Hybrid energy storage system. Section III. HESS capacity sizing. Section IV. HESS power converter (PC) topologies. Section V. HESS for on-grid PV power generation. Section VI. Energy management strategy (EMS) used in the HESS architecture of PV power generation. Section VII. Implementation HESS on PV power generation in recent project. Section VIII. Conclusion and future trends.

II. HYBRID ENERGY STORAGE SYSTEM

In MG, discharging/charging irregularities of the ESS can shorten the storage lifetime [25]. HESS is the right solution to solve PV and MG power generation challenges. Various studies have addressed the positive impact of HESS on PV and MG power generation [26]–[28]. Due to the existence of various ESSs with different characteristics, many possible HESS combinations are created depending on the hybridization process’s purpose.

In HESS ideally, one storage is high-energy (HE) storage. High energy storage (HES) as ESS1 is used to meet energy demand in the long term [29]–[31]. Another storage is storage that is dedicated to covering high-power (HP) applications. High power storage (HPS) as the ESS2 is used to handle power transients and fast load fluctuations. Therefore, HPS needs to have a fast response time, high efficiency, and high life cycle [31]. Several ES technologies with HPS and HES are shown in Figure 1. The ideal technical characteristics of HESS include density energy, density power, response time, energy efficiency, ease of implementation, and durability. In short, HESS leverages HES and HPS to achieve the desired performance.

Density energy (Wh/L) and power (W/L) refer to the maximum energy and power available per unit volume. While response time is the length of time, the storage device releases power. Furthermore, energy efficiency refers to the level of utilizing chemical and electrical energy [32]. Ease of implementation describes the difficulty of installing and maintaining a new system to ensure it operates properly under optimal conditions. Furthermore, while durability is the expected life of the ESS [33]. The characteristics of the types of technology ESS based on HES and HPS are shown in Table 1 [31], [34]–[40].

HESS is determined by analyzing the HPS and HES characteristics of different ES technologies. The possible variations in the combination of HESS created are shown in Figure 1. The combination of the storage system FC-Battery, Battery-Flywheel, Battery-SC, Battery-SMES, and SC-Fuel cell is frequently used for RES [41]–[45]. Several other factors need to be considered in choosing the appropriate HESS combination, such as storage hybridization targets, space for HESS, and costs. There are various technical problems associated with the use of PV and MG power generation, such as intermittent properties, poor power quality, stability problems, unbalanced loads, frequency instability, and DC bus voltage [27], [46]–[51]. In this section, various techniques from previously studies to solve the about problems are presented and evaluated.

A. RES INTERMITTENCE IMPROVEMENT

Many studies have used the HESS (SC-battery) to flattening the RES fluctuations in PV and wind power [52]. ESS can be

integrated to solve fluctuation in the power production source in PV and wind power generation, which comprises several frequency components with varying amplitudes. In this regard, HESS with a low and high-speed response has the ability to smoothen the process better than a single ESS [52]. Literature [53], presents flattening the fluctuation wind power short-term and long-term by using wavelet transformation algorithm in HESS capacity configuration. Battery-SC combination is used to consider the frequency distribution of wind power generation's output. Meanwhile, in [27], optimal fuzzy logic control with genetic algorithms was used in the SMES-Battery HESS to flattening PV and wind power generation fluctuations and fulfill grid demand. In [54], the HESS of the SMES-Fuel cell is precisely compensated for the fluctuation of PV power generation's output. HESS has two technologies, namely HPS and HES, with each compensating for low and high-frequency power fluctuations.

B. POWER QUALITY ENHANCEMENT

HESS is not only for managing power from RES rather it is also for sundry power quality purposes, such as for management frequency regulation, increased system stability, unbalanced load, and increased dc bus voltage regulation in MG by fast charging/discharging the battery to cope with the abrupt power changes [46], [47]. Furthermore, the benefits of HESS are investigated and presented.

1) FREQUENCY REGULATION

Frequency management controls in the use of HESS are divided into two types, namely the off-grid system [55]–[57] and on-grid [58]–[60] systems. Furthermore, the high penetration of the RES power generation in the electric system has a negative impact on the inertia of the system [60], [48]. Therefore, it has the endanger to compromise the system frequency, which leads to power outages and equipment damage [46], [47]. In ref [48] carried out research on the design of a new working structure for the Battery-Ultracapacitor HESS operation to keep the system frequency within allowable limits. Furthermore, frequency regulation in the electricity market proposed a strategy of efficient and coordinated operation. Battery storage technology plays a significant effect in regulating the frequency in off-grid MG systems. However, for frequency regulation, the battery experiences fast charging/discharging, reducing its life. Furthermore, the battery also needs to cope with sudden power changes in the main frequency control. This condition also accelerates the battery degradation process, therefore, to solve this problem, [55], [56] proposed the SMES-Battery HESS. This process was carried out by combining SMES and Battery, thereby enabling the successful regulation of the frequency and extending battery lifetime.

2) UNBALANCED LOAD REGULATION

The supply of high-quality power to consumers is an essential issue for MG, which enables the handling of unbalanced and nonlinear conditions using HESS. Furthermore, the

MG voltage quality is improved by applying the negative-sequence voltage control method. In ref [49] researched on the use of the Battery-SC HESS to improve MG performance under unbalanced loads. Utilization of HESS for MG demonstrates quick and appropriate voltage regulation unbalanced load conditions. Furthermore, Literature [61] proposes a coordination control strategy using HESS (Battery-SC) for increasing power quality in MG unbalanced load situations.

3) DC BUS VOLTAGE REGULATION

Problems associated with increasing the DC link voltage in MG. However, despite these problems, for a variety of reasons many prefer Standalone MG common bus DC. Besides that, Fast and accurate DC bus voltage regulation is one of the important problems in standalone MG [62]. HESS technology (Battery-SC) is used for DC link voltage restoration and is proposed in isolated systems with effective power-sharing between storage technology the battery and SC [63], [64]. In other studies, grid-connected mode the HESS (Battery-SC) was used for improved regulation of DC link [50], [65].

4) PULSE LOAD REGULATION

While the average power is low, the pulse load requires high instantaneous force [66]–[68]. Distributional disturbances in power and thermal are created when one energy source is used supplying pulsed loads. In addition, various advantage can be achieved while energy and power density ES technology is integrated into the system. Such an advantage as deficient volume and weight on the system, the elimination of the problem of thermal, voltage deviation is reduced and frequency fluctuations [69], [70]. Literature [71] a control strategy in real-time proposed on HESS (Battery-SC) to the DC MG independently with high redundancy and load pulse. The ES Supercapacitor technology is used to supply pulse loads and support the grid during transient periods. Therefore, to prevent frequency fluctuation in the generator and improve system performance, this control method is used. Pulse loads have a significant negative impact on battery lifetime. This impact was analyzed in research carried out by [72], and two scenarios were applied to rate the battery lifetime. The first scenario, uses only battery storage technology to supply load power pulses. The next scenario, uses HESS (battery-SC) to supply the load pulse power. There is a substantial profit of 17.6% in the cost of the HESS (battery-SC) lifetime.

C. STABILITY

In MG stability is usually divided into types 3, namely rotor angle, voltage, and frequency. The rotor angle stability is associated with the static state of the generator while maintaining synchronization during turbulence. This represents the firmness among the electromagnetic and the mechanical torques of the prime mover and rotor. Furthermore, frequency stability refers to the power grid maintaining a constant frequency under varying conditions. This stability is based on a balance between production, power dissipation, and load loss. Meanwhile, voltage stability is dependent on the constant

voltage across all buses after the occurrence of turbulence. This stability equilibrates the load demand and the power supply per bus. It is divided into two in MG, namely in grid-connected and grid-islanded modes [47], [73]. HESS has the ability to overcome transient stability problems in MG applications [74], [75]. While the Battery-SMES HESS proposed in [51] is used to enhance the transient performance of PV power generation-based MG in several disturbances. The outcomes showed that HESS has an excellent performance in the timely management of transient MG disorders due to its ability to provide fast power injection in the early stages of full feeding. Based on the studies reviewed, it is concluded that ES technology's use increases the margin of MG stability. In addition, the increase is much better using HESS than a single ESS [76].

D. STORAGE LIFETIME IMPROVEMENT

Electrochemical energy storages such as batteries and fuel cells have one major drawback, which is its low lifetime. Therefore, by avoiding excessive and frequent energy supplying and receiving of the battery, degradation is prevented with an increase in its lifetime [76]. The control strategy proposed by [76] contributes to the development of instantaneous power between storage technology SMES and battery. In the proposed control method, the discharge and charge of the battery function as SMES storage technology currents rather than directly accepting power fluctuations. The use of HESS battery lifetime is increased by reducing the involvement of the battery in fast charge and discharge cycles as proposed by [77], [78]. In ref [77], [78] researched on a power management strategy using a (lithium) battery with SC. These studies showed that to extend battery life, SC storage technology provides high-frequency demand, with a 19% increase in (lithium) battery lifetime. In [79], [80] stated Supercapacitor-Fuel Cell hybridization utilizing the Supercapacitor for instantaneous charging and discharging to increase the lifetime of Fuel Cell.

III. HESS CAPACITY SIZING

In HESS, determining a suitable energy storage capacity is one of the most important attributes. Therefore, various methods have been proposed and developed to measure its capacity. Furthermore, several methods have been developed to determine the HESS capacity of particular storage technology. In [81] carried out a research to analyze the various methods for battery sizing and applications of RES. The strategy in the HESS capacity sizing method is based on the objective function. Capacity sizing strategies for energy storage are classified into analytical methods (AM), statistical methods (SM), search-based methods (SBM), pinch analysis methods (PAM), and Ragone plot methods (RPM). The comparison of advantages and disadvantages in capacity sizing methods is summarized as Table 2. The classification of the capacity sizing methods on HESS further will be evaluated in this section.

A. ANALYTICAL METHOD (AM)

Analytical method (AM) is the strategy often used in HESS capacity sizing. It is based on circuit analysis of power system configurations with various weather systems which need optimization against performance criteria. The basic principle of this method operation is as shown in the following equation.

$$P_{HESS} = P_{DG} - P_{load} \quad (1)$$

where,

$$\begin{aligned} P_{HESS} > 0 & \text{ charging} \\ P_{HESS} < 0 & \text{ discharging} \end{aligned}$$

This method shows that the HESS operation varies upon the change between the distribution generations (DG) output power and based on the load power rate. In (1), P_{HESS} is a clean power storage hybrid consisting of the first and second energy storage power. P_{DG} denotes the DG output power, and P_{Load} is the load power. P_{HESS} sends power to the load via the discharging process when $P_{Load} > P_{DG}$ and HESS charge when $P_{DG} > P_{Load}$. The topology mentioned above is given in [82]. Meanwhile, in ref [83], a fuel cell-SC HESS was proposed where a high pass filter determines the power of the SC with different cut-off frequencies. Meanwhile, the power from the fuel cell and grid are obtained by subtracting the power of SC from P_{HESS} . The cut-off frequencies of an individual filter designate the operating period of each ESS technology and determine the required SC capacity. Furthermore, ref [84] researched by proposing a Fourier transform-based method for measuring the Battery-SC HESS to maintain an isolated system's power balance. This strategy is for the lifetime cost object function from each type of ESS technology. In this method, the power grid variation generated from wind energy is divided into two components, namely frequency spectrum, and HPS, for rapid compensation.

B. STATISTICAL METHODS (SM)

Statistical methods (SM) provide more flexibility for determining energy storage capacity in several applications than analytical methods. In a research carried out by [82], a statistical method was proposed to measure the Battery-SC HESS capacity. Furthermore, output power controllers for each storage system with hysteresis-loop and frequency control are projected. Battery-SC HESS controller aims to maneuver the variety of solar-wind power for the smoothen output generation power. Statistical methods with Monte Carlo simulation were proposed in [85] to determine Battery-SC capacity in the HESS.

C. SEARCH-BASED METHODS (SBM)

Search-based methods (SBM) are further divided into heuristic methods (HM) and mathematical optimization methods (MOM). These methods are basically used because of the non-linearity function in the energy storage size problem. Several studies have been conducted for capacity sizing of HESS using the heuristic methods (HM). In ref [86] proposed

a strengthening process for the particle swarm optimization (PSO) algorithm to prevent the HESS optimization problem from achieving a minimum cost. Furthermore, in [87] used a genetic algorithm to calculate the battery and supercapacitor's hybrid storage capacity. The results showed that adding a Supercapacitor to the system meaningfully rises the battery lifetime while reduces the total system cost.

D. PINCH ANALYSIS METHOD (PAM)

The pinch analysis method is a modest and flexible methodology for considering the minimum energy point in a radiator network utility system. It is a low burden computing tool used for RES in MG implementation [47]. A research carried out by [88] indicated that the general HESS capacity calculating method for island microgrids is based on the PAM and design space approach. The method incorporates the production variations, load, and discharge time of energy storage, therefore, the capacity curves of the HESS along with any time scales can be obtained by applying this method with the RES and its loads of information. The curves represent a practical set of storage capacities accordingly the timescales. Some are also researching the use of PAM in HESS applications [89], [90].

E. RAGONE THEORY METHOD

The Ragone plot method (RPM) is deployed for performance categorizing of the energy storage technologies in which makes up an HESS as is shown in ref [91] and [92]. In [91] stated that the enhancing of the energy storage life cycle is considered as an objective function, and the Ragone plot of the energy storage is added as a constraint. Thus, the common constraint between capability and capacity of energy storage is measured. HESS capacity and real-time control strategy are investigated separately. However, the control method is affected by the sizing due to the objective function and charge/discharge schemes. A greater study of the problem and a more precise solution is to consider capacity sizing and real-time control strategies simultaneously as in [93], [94].

The use of the correct method is based on a variety of various parameters i.e., data availability from the generation, load, and linearity or non-linearity problems. Furthermore, it is necessary to consider the dynamics between generation and load, combine HESS technology's dynamic characteristics, and determine different goals. From the existing parameters, different capacity sizing methods can be utilized.

IV. HESS POWER CONVERTER (PC) TOPOLOGIES

The charging/discharging characteristics of devices from energy storage are significantly different and dependent on the energy storage technology to be utilized. HESS connected to the grid, or the load goes through different power converter topologies. Ideally, the power converter topology combines ESS1 and ESS2 [95]–[97]. In ref [17] carried out a research that completely reviewed the HESS power converter topology classified into three, namely passive, semi-active, and active,

as shown in Figure 2 [47]. In this section, HESS power converter topology types are discussed.

A. PASSIVE HESS TOPOLOGY

The passive power converter (PC) topology consists of two storages with the same voltage connected to MG. Passive topology advantages are efficiency, simplicity, and cost-efficient [98]–[100]. The simplicity and cost-saving are due to low implementation and the absence of power electronics and control circuits [101]. However, the power distribution between ESS 1 and ESS 2 cannot be controlled. Passive topology PC is shown in Figure 2 (a). In a passive topology, a greater part of the voltage is determined from the internal resistance and the current characteristics due to the terminals' irregular voltages. Therefore, the potential for HESS in a passive topology is limited.

B. SEMI-ACTIVE HESS TOPOLOGY

In semi-active topology, the PC is interfaced with one of the energy storages while the other is direct connection with the DC bus [102]. The application of the converter needs an extra space and costs incremental are inevitably. However, this topology class offers better control and delivery capabilities than the passive. Several semi-active HESS topologies have been reviewed in the study carried out by [102]. The use of an additional converters in semi-active topology allows a better control of energy of the HESS [103]. Figure 2 (b) shows the semi-active topology in PC.

C. ACTIVE HESS TOPOLOGY

In [47], the active PC topology has two or more ESSs, and each storage unit interfacing with the system has an individual control of the power converter. This topology has a higher complexity, cost, and system losses than the passive and semi-active ones. However, this topology class has certain advantages, such as controlling all energy storage forces [98]. Active parallel PC topology uses two converters to control the ESS1 and ESS2 power. Figure 2 (d) shows the topology of the parallel active power converter. Meanwhile, for the traditional parallel active topology, energy is converted through the main DC bus. However, the whole system is negatively affected by two multi-level converters.

In [104], the authors studied to solve the problem mentioned in the reconfigurable topology to decrease the DC bus capacitor in order to increase the efficiency during the energy exchange mode compared to basic active topologies. In several studies, multi-level converters were developed and used for power converters in HESS [105]–[108]. The use of multi-level converters tends to improve the system reliability and power quality. Furthermore, connecting many energy storages using a single power converter decreases the expenses and difficulty of control coordination. However, the capacitors and the switching power electronics switches used in the multi-level converter are large, and controls are more complex [47]. In [109]–[111] stated that various PC topology classes are used to connect HESS to MG.

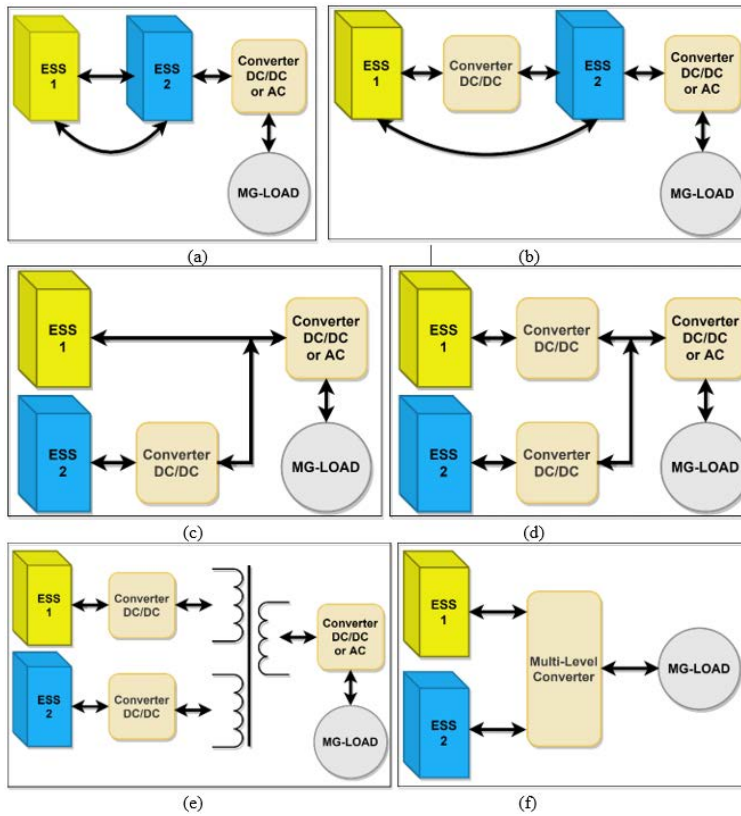


FIGURE 2. The classification of HESS power converter topologies (a) passive, (b) semi-active, (c) series active, (d) parallel active, (e) isolated active, and (f) multi-level active.

HESS PC topology directly influences energy management strategies with a comparison of various topologies shown in Table 3 [63], [72], [98], [102], [112]–[114]. Although the passive PC topology has no direct control over storage power, it comprises a simple configuration and economical. Furthermore, for semi-active PC topology, the output power of one ESS cannot be controlled, and the other voltages need to be similar to the DC bus. The semi-active topology provides limited controllability at a lower cost. Meanwhile, for the active PC topology, the input or output power is from the two ESSs with a rational control strategy and low-cost efficiency. The active topology has flexibility ability, performance, and controllability the best. Despite the fact that flexibility, complexity, controllability, efficiency, and cost are all factors that influence the selection of a suitable PC [47], making an active topology is complicated and expensive.

V. HESS FOR ON-GRID PV POWER GENERATION

Studies carried out by [18], [115], [116] stated that HESS has the ability to flattening the fluctuations of RES in the wind and solar PV power generation. Furthermore, HESS also controls the power output generated from the PV. In this section, the most popular of the HESS configurations for on-grid PV power generation are evaluated. Performance comparison of the different HESS configurations for on-grid

PV in term of power quality, lifetime, intermittence and stability is compared in Table 4.

A. BATTERY-SUPERCAPACITOR (SC) HESS FOR ON-GRID PV POWER GENERATION

Hajiaghahi *et al.* [49] proposed HESS to enhance power quality under unbalanced load conditions for microgrid applications. According to the study, one of the important issues in microgrids is providing high-quality power to consumers. When an unbalanced load is present in the microgrid system, the voltage loses its symmetry and reduces the power quality. Hajiaghahi *et al.* [49] used the AM capacity sizing method to determine Battery (ESS1) and SC (ESS2) capacity. In Hajiaghahi’s research, battery storage technology is used to support constant power changes due to its high energy density. Meanwhile, SC supports rapid transient power changes due to high power density with an active PC parallel topology. The Battery-SC HESS configuration is shown in Figure 3. Hajiaghahi *et al.* [49] added a proportional resonance (PR) and fuzzy control to adjust the AC load voltage and DC bus voltage control. Performance goals generated using this configuration are increased system performance, good response to its dynamics under unbalanced load conditions, and extended battery lifetime.

Tummuru *et al.* [60] carried out research on the Battery (ESS1) and SC (ESS2) HESS for grid integrated

TABLE 2. Comparison of advantages and disadvantages in capacity sizing methods.

Sizing method	Advantages	Disadvantages	
AM	<ul style="list-style-type: none"> • Easy to use • Simple and understandable 	<ul style="list-style-type: none"> • High computational volume 	
SM	<ul style="list-style-type: none"> • Flexible to choose optimum capacity as needed • Synthetic data can be utilized when the data is incomplete 	<ul style="list-style-type: none"> • The system is not sensitive for the variation of the parameters 	
SBM	MOM	<ul style="list-style-type: none"> • Solution can be obtained from limited data and several steps • Can be utilized in professional software i.e. MATLAB 	<ul style="list-style-type: none"> • Having problem to find optimum solution for complex problem especially non-linear programming problem
	HM	<ul style="list-style-type: none"> • Uses reasonable computing time and capacity 	<ul style="list-style-type: none"> • Cannot represent dynamic performance and avoid difficult derivatives
PAM	<ul style="list-style-type: none"> • Flexible, and low-load computation 	<ul style="list-style-type: none"> • Limited parameter to be optimized such as area and PV tilt angel 	
RPM	<ul style="list-style-type: none"> • Defined in detail by visualization for each type of energy storage. 	<ul style="list-style-type: none"> • Cannot represent dynamic performance of hybrid energy system 	

TABLE 3. Comparison of various HESS PC topologies.

Topology	advantages	Disadvantages	Recommendations
Passive	A simple approach to connecting ESS1 (HES) and ESS 2 (HPS) to the system. Low power complexity control due to direct connected ESS without additional power converters. Less space requirement, and low cost.	Low flexibility due to matching of the voltage level of the ESS with the DC bus voltage or load voltage is a prerequisite for direct connection.	Used in small capacity systems with low cost required.
Semi-active	Better flexibility control than passive PC because there is one power controller to connect ESS1 (HES) and ESS 2 (HPS) to the system. Capable to handle DC bus voltage fluctuations or loads faster when there is a power controller on the ESS2 (HPS)	The DC-DC converter must be designed to handle large power surges when connected to an HPS. More space requirements than passive PCs, and slightly more cost than passive PCs are high.	Used to extend battery life for slightly higher cost.
Active	Increased flexibility due to having separate control between ESS1 (HES) and ESS2 (HPS). Various control strategies can be used. The ESS voltage level is independent of the system voltage. The fault tolerance capacity inherent with each ESS converter is a separate system.	Larger space requirements and higher costs because more power converters are used. High power complexity control.	Suitable for system with larger-scale capacity as it requires a dynamic and higher response.

TABLE 4. Performance comparison of the different HESS types for on-grid PV.

HEES Technology	Sizing Technique	Power converter (PC) topologies	Goal of Hybridization			
			Power Quality Improvement	Lifetime Improvement	Intermittence Improvement	Stability Improvement
Battery-SC [49] [50] [65]	AM	Active (Parallel)	✓	✓	✓	✓
Battery-SC [117]	RPM	Active (Parallel)	✓	✗	✗	✓
Battery-Ultracapacitor [121]	SB-MOM	Active (Parallel)	✓	✗	✗	✓
Battery-Flywheel [42], [118]	AM	Active (Parallel)	✗	✓	✗	✓
SMES-Battery [51], [120]	AM	Active (Parallel)	✓	✓	✗	✓
Fuel cell-SC [119]	AM	Active (Parallel)	✓	✗	✓	✓

PV systems. The study stated that due to the intermittent properties of PV and irregular load changes, the system experienced issues of power quality and MG stability. To deal with these issues, Tummuru *et al.* [60] used ES with high energy (battery) and power (SC) densities, with the AM capacity sizing method used to determine each storage technology’s capacity. SC storage is used to handle sudden changes in power surges. Meanwhile, HESS interface with grid, active

parallel PC topology was used by Tummuru *et al.* [60]. Furthermore, Tummuru *et al.* [60]. also proposed an energy management system for HESS which achieved fast DC-link regulation, effective energy management, and increased battery lifetime.

Mohamed *et al.* [117] researched the Battery (ESS1) and SC (ESS2) HESS to minimize the effect of pulsed (short duration) loads. According to Mohamed *et al.* [117], the

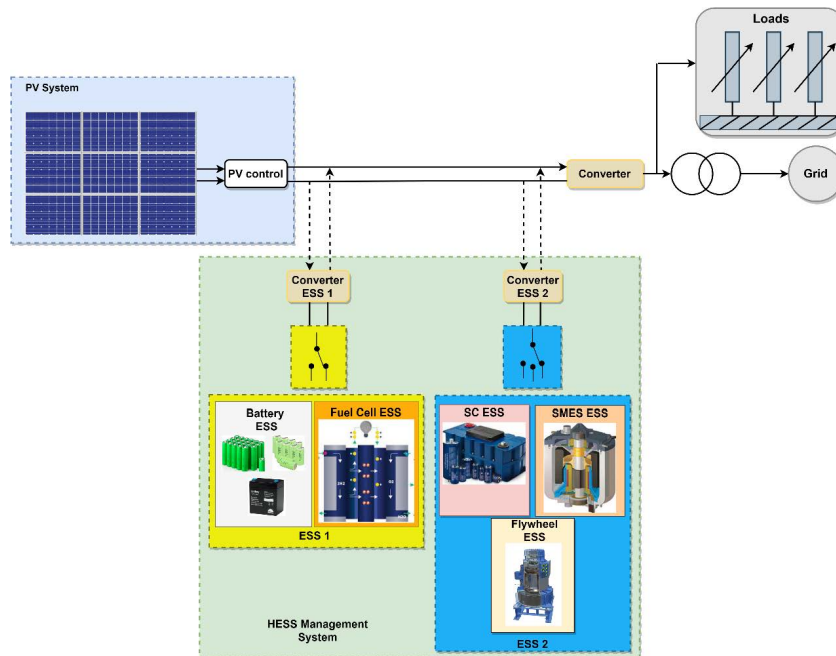


FIGURE 3. The configuration of active parallel HESS topology.

effect of pulsed (short duration) loads causes power quality and MG stability issues. Furthermore, this study used the Ragone plot capacity sizing method to determine the capacity of HESS. In SC storage is used to fulfill loads rapidly due to high power density. Meanwhile, the battery is used for relatively long-term buffer loads due to its high energy density. Active parallel PC topology is used by Mohamed *et al.* to determine the HESS interface to the grid. Furthermore, Mohamed *et al.* [117] developed a real-time energy management algorithm on HESS for AC/DC microgrids. The performance goal generated using this configuration is that pulsed loads show a better margin of stability. Furthermore, shifting the load to off-peak hours saves energy by 7% per year.

B. BATTERY-FLYWHEEL HESS FOR ON-GRID PV POWER GENERATION

Barelli *et al.* [42], [118] carried out an analysis on the impact of power fluctuation on battery current (ESS1) and power exchange to the grid. This research indicated the possibilities of lifetime issues on battery and MG stability. Barelli *et al.* [42], [118] used the AM capacity sizing method to determine the capacity of the HESS. Flywheel energy storage (ESS2) serves as peak-shaving due to its high-power density. Therefore, the battery tends to avoid fast charging/discharging loads due to high energy density, which tends to affect the lifespan. Barelli *et al.* [42], [118] applied the active parallel PC topology to determine the grid's interface. The Battery-Flywheel HESS configuration is shown in Figure 3. This configuration's performance goals are the more stable quality of power transferred to a grid and a significant battery increase for a longer lifetime.

C. FUEL CELL-SC HESS FOR ON-GRID PV POWER GENERATION

Kong *et al.* [119] proposed modeling for grid-connected HESS. According to the study, the intermittent properties of PV created inconsistencies in power quality and MG stability. However, in order to avoid existing issues, fuel cell (ESS1) and SC (ESS2) HESS were proposed. Kong *et al.* used the AM capacity sizing method to determine the capacity of the HESS. The study further chose Fuel cell storage technology and SC due to their high energy and power densities, respectively. Kong *et al.* [119] applied active parallel PC topology for interface to the grid and further proposed the formulation of a coordinated control strategy for HESS. Performance goals generated using this configuration increased power quality, improved intermittence, and MG stability. The Fuel cell-SC HESS configuration is shown in Figure 3.

D. SMES-BATTERY HESS FOR ON-GRID PV POWER GENERATION

Chen *et al.* [51] carried out a research on the Battery (ESS1) and SMES (ESS2) HESS technologies in on-grid PV power generation. According to several studies, energy transfer, transient stability, and voltage fluctuation are some of the issues in on-grid PV power generation. HESS is used to stabilize the Microgrid under different faults and used the AM capacity sizing method to determine the HESS's capacity. The SMES storage is used to handle transient microgrid faults in a timely manner due to their high-power density. Meanwhile, battery storage is used to control long-term power fluctuations when the Microgrid operates normally. For interfaces to the grid, Chen *et al.* applied active parallel PC topology to the HESS configuration, as shown in Figure 3.

The performance goals generated using this configuration increases in power quality, battery lifetime, and MG stability.

Bae *et al.* [120] carried out a research that examined the Battery (ESS1) and SMES (ESS2) HESS in on-grid PV power generation. The various inconsistencies associated with this study are related to eliminating fluctuations in power output, stability, and quality. Furthermore, Bae *et al.* applied the AM capacity sizing method to determine the capacity of the HESS with SMES storage used to handle large and fast output power and demand due to its high-power density. Meanwhile, battery storage is used to handle normal responses to baseload and power generation. For interfaces to the grid, Bae *et al.* apply active parallel PC topology. Furthermore, the study focuses on the optimization operation of HESS to achieve an effective energy management system. Performance goals generated using this configuration increased power quality, MG stability, and battery lifetime.

The combination of HESS supercapacitor (SC) technology with Battery is one of the most interesting solutions and also the most significantly developed [49], [50], [65], [117], [121]–[125]. Furthermore, the use of SC has high charge/discharge efficiency [126], [127] and increases battery lifetime.

VI. ENERGY MANAGEMENT STRATEGY (EMS) USED IN THE HESS ARCHITECTURE OF PV POWER GENERATION

The implementation and design of the optimal controller is the most significant concern in HESS [128]. The selection of the appropriate control technique for HESS depends on a series of parameters. The application of appropriate realistic control techniques is critical to achieve consistent, effective and safe HESS operation. There are two levels of architecture in the energy management system. First, a system that controls the DC bus voltage and maintains current flow. Second, high-level control that focuses on power allocation, monitoring the State of Charge (SoC), and other purposes of the system. The control strategy is classified into classical and intelligent control strategies. The detailed classification of the HESS-PV control strategy is shown in Figure 4.

A. CLASSICAL STRATEGIES CONTROL HESS PV POWER GENERATION

1) FILTRATION BASED CONTROL (FBC) FOR HESS ON PV POWER GENERATION

The power transfer between ESS1 and ESS2 can be classified in the high frequency (HF) and low frequency (LF) sections. The HF section is the result of irregularities in the PV systems or sudden load variations. HF is usually found in ESS with the characteristics of fast response time and high power. While LF is the result of regular power action. The LF part is usually present in the EES with the characteristic high energy density. Filter based control (FBC) separates the power requirements with the help of a filter circuit which leads to the flattening of the storage current variations. In the literature [64] developed a low pass filter (LPF) based FBC to control the

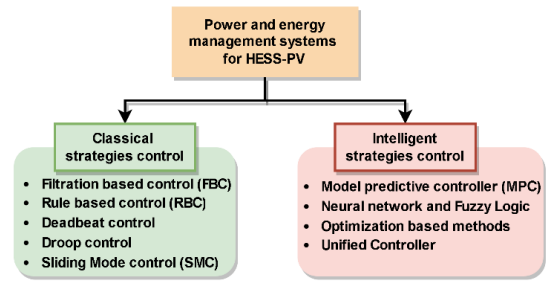


FIGURE 4. Classification of the HESS-PV control strategy.

battery charge level. Improved battery lifetime and faster dynamic response are obtained with the proposed controller. The scheme of HESS with FBC in the literature [64] is shown in Figure 5.

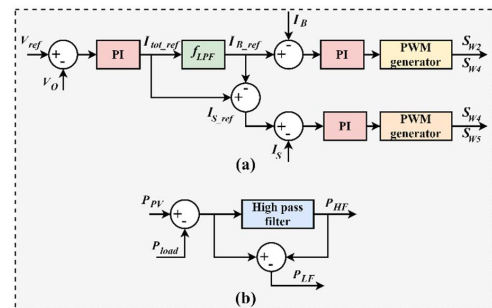


FIGURE 5. Various types of FBC. (a) With low pass filter [64]. (b) With high pass filter.

2) RULE BASED CONTROL (RBC) FOR HESS ON PV POWER GENERATION

Generally, rule-based control is based on a sequential decision-making process from both current and previous values. Rules are defined by mathematical models or system capabilities. In this approach, the high energy ESS is constrained by the State of Charge (SoC). Rule-based techniques have been widely used because of their less computational load, ease of implementation and simple attributes [129]. The literature [129] presented a comparison between the implementation of the SC-battery HESS combination in PV systems and battery storage only. The HESS-PV system with RBC demonstrates the ability to reduce peak battery current (up to 8.607%) and increase the average SoC of the battery (up to 0.34%) compared to a battery-only system. Thus, this affects the battery lifetime to be longer. RBC is shown as in Figure 6.

3) DEADBEAT CONTROL FOR HESS ON PV POWER GENERATION

Deadbeat control works based on the model of the system that produces the ratio of duty cycles. This is to minimize fault regulation in one control cycle. Thus, it can overcome the status variable fault effectively maintaining the power sharing between ESS1 and ESS2. Dead bead control has

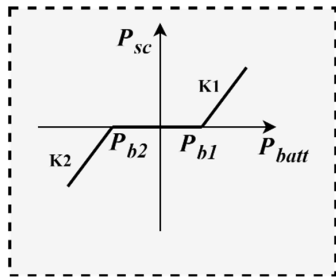


FIGURE 6. RBC control strategy with HESS [129].

additional capabilities such as fast dynamic response and high control accuracy [130]. In the literature [130], [131] deadbeat control is proposed for HESS-PV systems. Battery storage responds to average power demands, while SC storage handles transient power fluctuations. This extends cycle life and effectively improves HESS dynamic response. The developed deadbeat controller is shown in Figure 7.

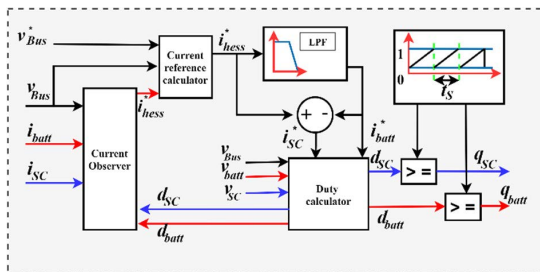


FIGURE 7. Deadbeat control strategy.

4) DROOP CONTROL FOR PV POWER GENERATION

This type of virtual impedance drop (VID) controller is widely used for HESS power management. In the literature [132] developed a combination of virtual capacitor drop (VCD) and virtual resistance drop (VRD) controllers. The development of this type of controller can regulate the distribution of high and low frequency power on the SC and battery. Also added secondary voltage recovery (SVR) to set the average bus voltage to the reference value. The performance of the developed controller has a stable dynamic system performance. The control scheme is shown in Figure 8.

Furthermore, a type of extended drop control (EDC) is presented in the literature [133]. It was developed with a combination of virtual capacitor drop (VCD) and virtual resistance drop (VRD). This is to control the HESS power flow on the DC microgrid. This method focuses on battery storage providing consistent power and the SC only compensates for high frequency fluctuations. The performance of this method, stable operation in bus voltage regulation, and dynamic current sharing. The control scheme is shown in Figure 9.

In the literature [134] a new droop technique with integral droop (ID) control is proposed to improve virtual impedance drop (VID) performance. The proposed control between voltage droop (V-P) and ID based on HPS/LPF development.

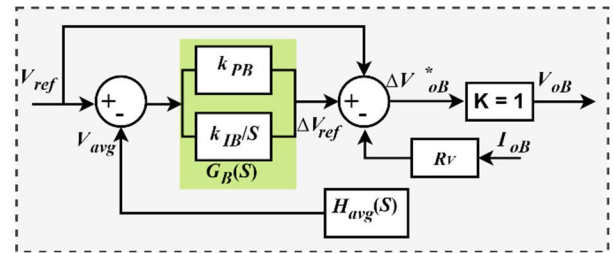


FIGURE 8. Secondary voltage controller scheme.

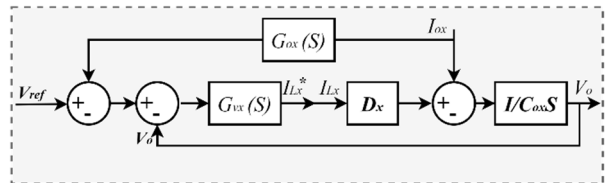


FIGURE 9. Extended droop control scheme.

This is for optimal dynamic power allocation between ESS1 and ESS2. The performance of this control is dynamic power sharing and the response rate is good. The proposed control scheme for ID and V-P is shown in Figure 10.

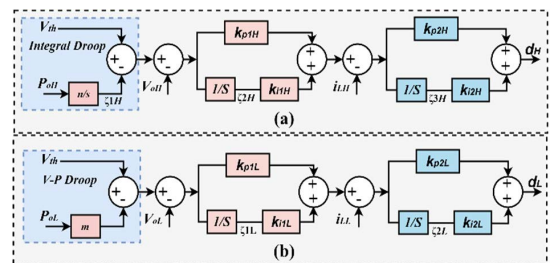


FIGURE 10. Control scheme: (a) integral droop dan double PI controller, (b) traditional V-P droop dan double PI controller.

5) SLIDING MODE CONTROL (SMC) FOR HESS ON PV POWER GENERATION

Sliding mode control (SM) is a type of control that is widely used in power converter design because of its non-linearity, robustness, and dynamics [135]. In the literature [136] proposed sliding mode control (SM) for HESS-PV systems based on a boost inverter. SM control is implemented using an amplitude pulse width modulation (PWM) carrier signal. The performance of the developed control, able to achieve better tracking of output reference. In addition, it minimizes the complexity of the design on the system. The proposed sliding mode (SM) control scheme with HESS is shown in Figure 11.

The analysis of the classical control strategies for HESS-PV power generation is summarized as shown in Table 5.

B. INTELLIGENT STRATEGIES CONTROL HESS PV POWER GENERATION

Since classical control strategies have limitations, intelligent control techniques were developed for implementing energy management in HESS-PV. The system implemented with

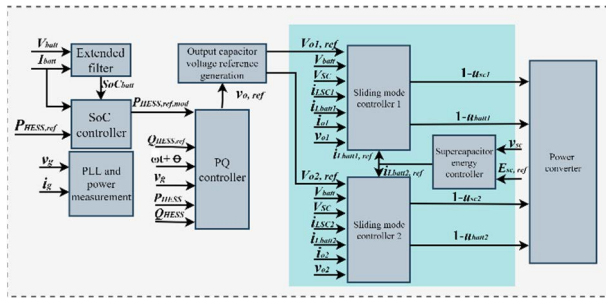


FIGURE 11. Control scheme of the sliding mode (SM).

intelligent control techniques is proven to improve control performance. The system implemented with intelligent control techniques is proven to improve control performance. However, the time required for calculations in each cycle is high and the cost of the system is also high [128]. A discussion of the intelligent control techniques developed for the HESS-PV system is discussed in the following subsection.

1) MODEL PREDICTIVE CONTROLLER (MPC) HESS PV POWER GENERATION

Predictive control model is an optimization technique in the power generation process that predicts the effect of future control decisions on changes in the state of the generation. It is a systematic and efficient technique as it allows optimization of the current time frame while preserving the future timeframe [128]. An MPC strategy is proposed in [137] or HESS-PV systems. The main capability of this method is that the SC responds to rapid changes in current while the battery responds to slow changes in current while maintaining the SOC limit. However, the method used uses two space models for the converter, so it is computationally ineffective in classical MPC. In addition, this method is not capable of regulating the DC bus voltage. On the same concept, the literature [138] proposed an MPC technique with less complicated controls for effective management of the HESS-PV system. The advantage of this method is that it is easier to design and implement. In addition, a high sampling frequency can be achieved when the control system is discretized for practical implementation.

Furthermore, the literature [139] proposed a single-inductor dual-input single (SI-DISO) converter for HESS with a model predictive control (MPC) based controller. The work ability and effectiveness of this method distributes the demand for variable load power and PV power generation efficiently and optimally to HESS. MPC is able to control many control variables in the system. In addition, future control inputs and future system responses can also be predicted with optimal control. The schema of the predictive control model is shown in Figure 12.

2) NEURAL NETWORK AND FUZZY LOGIC FOR HESS PV POWER GENERATION

Artificial neural network (ANN) is a highly dynamic adaptive computing system, capable of parallel processing

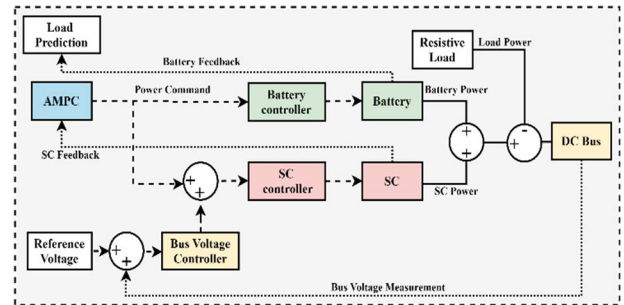


FIGURE 12. Real-time model predictive control scheme.

of information. The ANN architecture consists of three layers, namely input, hidden and output [140]. In the literature [141], [140] proposed an ANN power management strategy for HESS-PV systems. This strategy analyzes the SOC of each EES in real-time and provides charging/discharging orders for the safety and lifetime of the ESS. The implemented architecture uses a Multi-Layer Feed-Forward Neural Network (FFNN) as shown in Figure 13 [140]. The proposed power management strategy is capable of managing the power flow of all HESS elements. This strategy is able to increase battery lifetime by reducing peak demand and dynamic voltage while continuing to provide power at the required load.

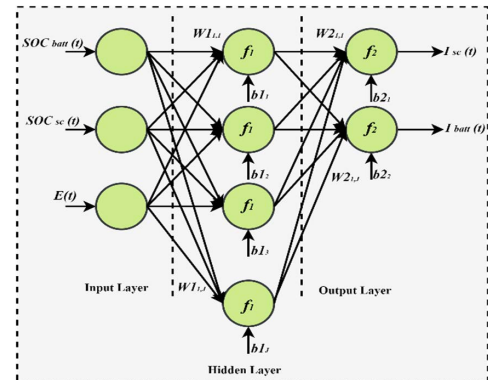


FIGURE 13. Multi-layer feed-forward neural network architecture.

In contrast to the ANN strategy, fuzzy logic control (FLC) is more understandable and not sensitive to parameter variations. The FLC strategy requires appropriate models and methods. The FLC algorithm is based on membership function rules [142], [143].

In the literature [142] proposed the use of the FLC strategy for HESS in PV systems. In addition, a hysteresis current control mode is introduced to control the current flowing into and out of the HESS. The FLC energy management system delivers battery and SC reference currents. This reference current is compared with the corresponding inductor and converter currents. Performance afforded better dynamic control of hysteresis currents. Meanwhile, the FLC provides a decision regarding the charging/discharging of HESS.

Thus, preventing overfilling and over-discharging. In the literature [143] proposed the use of FLC for HESS batteries and hydrogen/fuel cells in PV systems. The proposed FLC strategy with type-Mamdani/Mamdani for multi-purpose. The FLC approach was chosen because it simplifies its management and control, given its complexity [143]. The FLC-based EMS (as shown in Figure 14) performance for microgrids ensures an appropriate power balance between PV power generation and load demand. It also considers improving the performance of the microgrid from a technical and economic point of view.

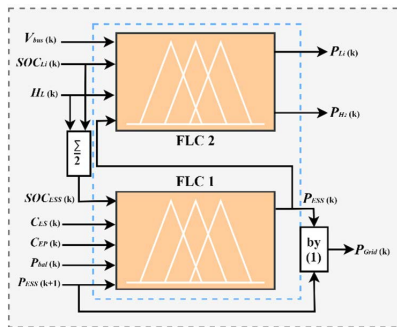


FIGURE 14. FLC-based EMS control scheme.

3) OPTIMIZATION BASED METHODS FOR HESS PV POWER GENERATION

Several other optimization-based control techniques are also applied for effective management of HESS-PV systems. As in the literature [24] proposed a combination management strategy using FLC and LPF for SC-battery HESS in PV systems. This strategy is to reduce dynamic stress and peak power demand on the battery. Furthermore, the Particle Swarm Optimization (PSO) Algorithm was implemented to adjust the MFs of the FLC in optimizing the reduction of the battery peak current. This energy management scheme is shown in Figure 15. The performance of the system shows that the dynamic stress and peak power demand from the battery have improved greatly, resulting in a longer lifetime. In addition, the SC operates within the recommended SOC range and makes effective use of the limited SC energy in the system.

4) UNIFIED CONTROLLER FOR HESS PV POWER GENERATION

The unified energy management system for hess in pv systems was developed in the literature [65]. the proposed strategy provides for the extended life time of the sc and battery under various operating conditions. the developed unified control is presented in the flow chart in figure 16. the performance achieved in the system provides better charging and discharging rates of the battery. a similar type of unified controller is applied by manandhar et al [50]. in [50], it has several features such as faster voltage regulation, effective power sharing across all disturbances, reduced dynamic charging/discharging state of the battery and improved power

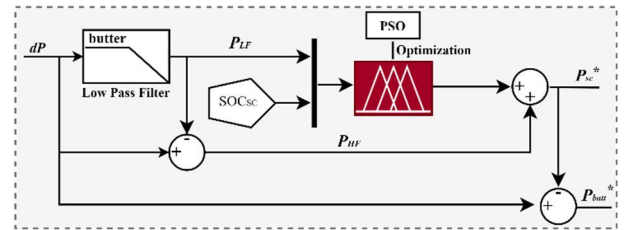


FIGURE 15. Optimized FLC controller scheme with PSO.

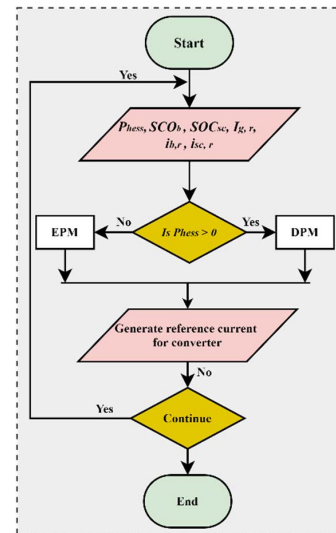


FIGURE 16. Flowchart of the unified HESS controller.

quality. furthermore, in the literature [63] a faster joint control (fjc) control strategy was proposed to control the hess-pv system. in the proposed system, the efficiency of the system is increased by the use of sc to meet the unmet load of the battery.

The analysis of the intelligent control strategy for hess-pv power generation is summarized as shown in Table 6.

VII. IMPLEMENTATIONS HESS ON PV POWER GENERATIONS IN RECENT PROJECTS

Various combinations Of HESS in PV power generation are widely used in simulation software such as MATLAB/Simulink, HOMER And P-graph studio[141], [144]–[149]. Many studies and demonstration projects as listed in Table 7 are currently underway in different parts of the world. there is limited information available about these projects because the companies and governments involved did not provide detailed information. Most Of the HESS applications in real-life PV power generation are for the integration of frequency control, and backup power. HESS is thought to improve grid operations and save money for clients by lowering energy wastage and increasing efficiency [128] Some examples of HESS implementation in real PV power generation are:

- Scientists in Thailand built a 53 kWh HESS (Fuel cell-Battery lead-acid) for storage energy PV power

TABLE 5. Comparison of classic control strategies of HESS on PV power generation.

Types strategies	Features	Limitations
Filtration based control	<ul style="list-style-type: none"> Control strategy is straightforward, can be implemented in real-time. 	<ul style="list-style-type: none"> The design of the filter components is complex. Requires an accurate mathematical model of the system under consideration.
Rule based control	<ul style="list-style-type: none"> Control of this type of strategy is easy, uses less calculations and is easy to implement. 	<ul style="list-style-type: none"> It has a rigid nature because it involves thresholds, rules and operations that have been previously determined. Very sensitive to parameter changes.
Deadbeat control	<ul style="list-style-type: none"> This control strategy has high control accuracy and fast dynamic response. Easy implementation process. 	<ul style="list-style-type: none"> Requires a precision system model because it is very sensitive to changes in controller parameters.
Drop based control	<ul style="list-style-type: none"> Control of this strategy is decentralized and can be implemented easily. 	<ul style="list-style-type: none"> Low accuracy in power sharing between each storage system. Slow response.
Integral droop control	<ul style="list-style-type: none"> This control strategy overcomes the limitations of the low pass filter/high pass filter. Fully autonomous and decentralized control system. 	<ul style="list-style-type: none"> It has a slower response when compared to traditional droop controls.
Sliding mode control	<ul style="list-style-type: none"> It is a high robust controller. Insensitive to parameter changes. 	<ul style="list-style-type: none"> Involves very complex design procedures.

TABLE 6. Comparison of intelligent control strategies of HESS on PV power generation.

Types strategies	Features	Limitations
ANN	<ul style="list-style-type: none"> This strategy has very dynamic adaptive computing capabilities. Able to process parallel information. 	<ul style="list-style-type: none"> Very complex design. Requires proper network structure and uses a lot of calculations.
FLC	<ul style="list-style-type: none"> Insensitive to parameter changes and easy-to-implement controllers. Fast response 	<ul style="list-style-type: none"> Using an approach trial-error to improve accuracy. It takes a high and long computational time because membership functions are set by trial and error.
MPC	<ul style="list-style-type: none"> These controllers can predict the behavior of the system and its future performance. It can also be optimized at regular intervals. Provides a uniform approach to control system design. Can also control high scale systems with many control variables. 	<ul style="list-style-type: none"> Without an accurate system model, the controller will not work. High computational load. Computationally intensive
Optimization based method	<ul style="list-style-type: none"> This method can handle multiple objectives functions to optimize at once and provide better response. 	<ul style="list-style-type: none"> It takes time to provide an optimal solution because it is necessary to select parameters at random values and sometimes the results may not be as accurate as expected.
Unified controller	<ul style="list-style-type: none"> Provides a uniform approach in designing control systems. Dynamic voltage regulation. 	<ul style="list-style-type: none"> Very complex design. Requires a lot of calculations in each switching period.

TABLE 7. Implementations HESS on PV power generations in recent projects.

HESS	Location	Capacity	Company	Type	Year
fuel cell-battery (lead-acid) [150]	Thailand	53 kWh	A group of scientists from the Chiang Mai University	On-Grid	2021
battery (Lithium)-battery (Lead-acid) [151]	India	1 MWh	Indian manufacturer Vision Mechatronics	On-Gid	2021
fuel cell-battery (Li-Ion) [152]	Germany	458,9 kWh,	German scientists	Off-Grid	2021
Flywheel-battery [153]	Ireland	1 MWh	European Union’s Horizon 2020	On-Grid	2020
battery (Li-Ion)-battery (Lead-acid) [154]	Spain	44,7 kWh	European Union’s Horizon 2020	On-grid	2019

generation microgrid. It aims to identify the best DC coupling voltage. Furthermore, the voltage was evaluated first and it was found that the difference of

2V indicates the optimal operating conditions with the longest operating time in the transition period without system failure

- Scientists in Thailand built a 53 kWh HESS (Fuel cell-Battery lead-acid) for storage energy PV power generation microgrid. It aims to identify the best DC coupling voltage. Furthermore, the voltage was evaluated first and it was found that the difference of 2V indicates the optimal operating conditions with the longest operating time in the transition period without system failure [150].
- A company in India is building a hybrid batteries storage system between lithium and lead-acid battery with PV power generation. The system is located at Om Shanti Retreat Center (ORC) in Haryana State. This 1MWh HESS battery is intended for use during power outages and at night. This system has a fast response of less than ten seconds, which makes the electronics connected to the system unaffected by power outages and fluctuations [151].
- Scientists from the German research center Forschungszentrum Jülich GmbH have proposed a storage hybrid Fuel cell/battery Li-Ion with stand-alone PV power generation. This HESS configuration enables cost-effective, self-contained residential buildings with rooftop PV power generation rather than Li-Ion battery storage only [152].
- A research project in Ireland is building a Flywheel-battery adaptive hybrid storage system for PV power generation. The HESS is connected to the Irish and UK transmission grid. This system aims for dynamic grid stability. The HESS Flywheel-battery shows a faster-than-expected reaction and an accurate system behavior following the power commands of the energy management system [153].
- A research project in Spain is building a 44.7 kWh hybrid battery storage system (Li-Ion and lead-acid) in a PV power generation. The purpose of this research project is to maximize the security of supply voltage requirements for customers in the event of a grid-connected power failure. This HESS is able to provide sufficient voltage supply to the entire customer environment in the event of a power failure [154].

VIII. CONCLUSION AND FUTURE TRENDS

In conclusion, this paper analyzed the implementation of HESS for PV power generation to fulfill a dynamic balance of power and energy. It focused on HESS by combining two storage technologies based on the characteristics of HPS and HES. In this paper also provided a brief overview of the capacity sizing and power converter topology for HESS in PV power generation. Furthermore, various energy and power management systems implemented for HESS on PV power generations are reviewed. Various different control strategies have been described. Next, the related literature on HESS in PV power generation is critically reviewed and summarized. In addition, a related discussion of the features and limitations of classical and intelligent control techniques is also presented. As an added value, HESS implementations on PV power generations in recent projects are analyzed and

discussed. Finally, a structured path for future research to conduct related to the use of HESS in PV power generation is presented. Thus, this paper helps scientists and practitioners to have a complete idea of maximize the utilization of HESS in PV power generation on-grid or off-grid.

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