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A Comprehensive Review of Hybrid Energy Storage Systems: Converter Topologies, Control Strategies and Future Prospects

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ABSTRACT The ever increasing trend of renewable energy sources (RES) into the power system has increased the uncertainty in the operation and control of power system. The vulnerability of RES towards the unforeseeable variation of meteorological conditions demands additional resources to support. In such instance, energy storage systems (ESS) are inevitable as they are one among the various resources to support RES penetration. However, ESS has limited ability to fulfil all the requirements of a certain application. So, hybridization of multiple ESS to form a composite ESS is a potential solution. While integrating these different ESS, their power sharing control plays a crucial role to exploit the complementary characteristics of each other. Therefore, this article attempts to bring the numerous control strategies proposed in the literature at one place. Various control techniques implemented for HESS are critically reviewed and the notable observations are tabulated for better insights. Furthermore, the control techniques are classified into broad categories and they are briefly discussed with their limitations. From the carried-out analysis, the challenges faced towards the implementation of HESS for standalone and grid connected microgrid systems are presented. Finally, the future directions are laid out for the researchers to carry out the research and implementation of HESS technologies. Overall, this article would serve as a thorough guide on various control techniques implemented for HESS including their features, limitations and real-time applications.

INDEX TERMS Hybrid energy storage system, microgrid, intelligent control, renewable energy, energy management, power electronics.

NOMENCLATURE

ACRONYMS

AC	alternating current
ANFIS	adaptive neuro-fuzzy inference system
ANN	artificial neural network
BESS	battery energy storage system
BEV	battery electric vehicle
CAES	compressed air energy storage
CVT	continuous variable transmission

DC	direct current
DG	distributed generation
DP	dynamic programming
EDC	extended droop control
EDLC	electrical double layer capacitor
EGP	Enel Green Power
EMS	energy management system
ESS	energy storage system
FBC	filtration based control
FC	fuel cell
FFSVM	feed-forward-space-vector-modulation
FJC	faster joint control

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FLC	fuzzy logic control
FR	frequency control or regulation
FR	frequency regulation
HSS	high energy storage
HESS	hybrid energy storage system
HF	high frequency
HPF	high-pass filter
HPS	high power storage
HSS	hydrogen storage system
ID	integral droop
ISO	independent system operator
LF	low-frequency
Li-ion	lithium-ion
LPF	low pass filter
LPSP	loss of power supply probability
LR	load regulation
MF	membership function
MIAD	multiplicative-increase- additive-decrease
MLD	mixed logic dynamic
MMC	modular multilevel converter
MPC	model predictive control
NaS	sodium-sulfur
NFC	neuro-fuzzy controller
PCH	port-controlled hamiltonian
PMP	pontryagin's minimum principle
PQ	power quality
PSO	particle swarm optimization
RBC	rule based control
RES	renewable energy resource
RL	reinforcement learning
SC	supercapacitor
SFL	shuffled frog leap
SMC	sliding mode control
SMES	superconducting magnetic energy storage
SOC	state of charge
SVM	support vector machine
SVR	secondary voltage regulation
V-P	voltage-power
VCD	virtual capacitance droop
VF	Vanadium flow
VFB	vanadium flow battery
VID	virtual impedance droop
VR	voltage regulation
VRD	virtual resistance droop
WCA	water cycle algorithm
WES	wind energy system

I. INTRODUCTION

From the past few years, the growing concerns on environmental effects due depletion of fossil fuels has resulted in transition towards RES to satisfy the global energy demand. Eco-friendliness, scalability and other extensive features of RES has attracted its deployment in commercial, industrial, and residential sectors. This is further supported by the quick progression in power electronics [1], which aids the complete

control of RES limited by stochastic natural conditions [2]. Moreover, RES have various limitations like poor load following, intermittent power generation and non-dispatchable nature. Due to these factors, their coordination in the grid system is a challenging task for efficient operation, particularly for high capacity systems [3]. The notable challenges faced during the integration of RES are voltage instability, load discrepancy, frequency fluctuation, poor power quality and load-following [4].

The integration of ESS is a promising solution to overcome these limitations and to facilitate stable operation of grid. The integration of ESS with RES into the microgrid can avoid power fluctuations, improve power quality, frequency regulation and enable additional ancillary services [5]. Therefore, various ESS technologies have been evolved in recent years which can be categorized as electrical, electrochemical, chemical and mechanical storage systems. The widely used ESS are SC, SMES, flywheel, pumped hydro storage, batteries, CAES and hydrogen tanks. Among these technologies, batteries are treated as one of the most significant and promising ESS for maintaining the stability of power system networks [6]. Furthermore, ESS in the off-grid system plays a vital role in managing the momentary power fluctuations and quality of power. Based on the analysis of various ESS, their important characteristics are listed in Table. 1. Meanwhile, the well-known different types of batteries along with their suitable applications, limitations, and features are presented in Table. 2. Furthermore, ESS plays a significant role in the advancement of electric energy systems and extending RES to power the remote locations of the globe [7]–[10].

The global energy storage market is increasing substantially, since the last decade. It is predicted that the ES market may increase more than 26 billion USD in yearly sales by the year 2022, with a compounded annual growth rate of 46.5% [11]. Countries like Australia, the USA, India, UK, Chile, Japan, Italy, South Korea, and Germany are concentrating on the leading technologies of battery storage systems. Besides that, the national policies and subsidies provided by different countries further accelerate the growth of ESS. The combination of RES and ESS can reduce the dependency on the energy import, improve resiliency and reliability of the system and also help move towards decarbonization of grid. Furthermore, the developing nations are moving towards smart cities to achieve their goals such as environmental sustainability, adequate power supply, efficient mobility and the adoption of electric vehicles, where RES and ESS play a critical role. The capacity of ESS is exponentially increasing, which doubled during the year of 2017 and 2018 to 8 GWh [12]. The current global installed capacity of ESS is shown in Fig. 1. In addition to that, the adoption of ESS for various applications is presented in Fig. 2.

It is worth noting that, every ESS has its own limitations which confines its range of application, since an ideal application demands both high energy and high power. However, ESS are limited either by their power or energy capacity. Thus, it is necessary to build a system with a combination of

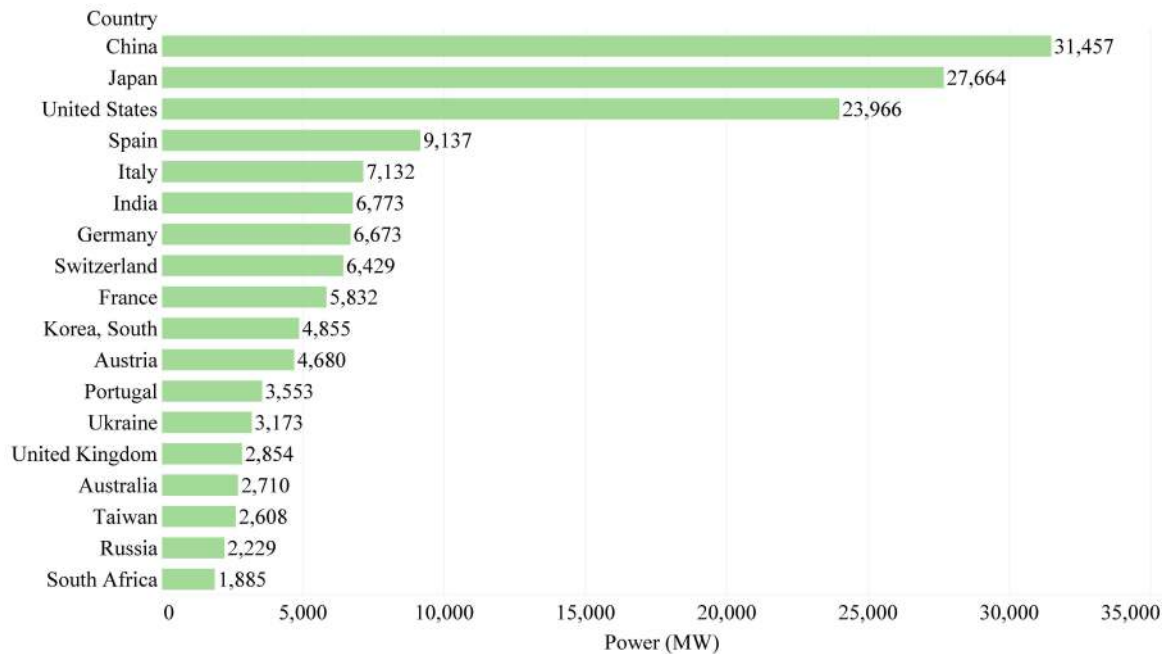


FIGURE 1. Global scenario of energy storage adoption [13].

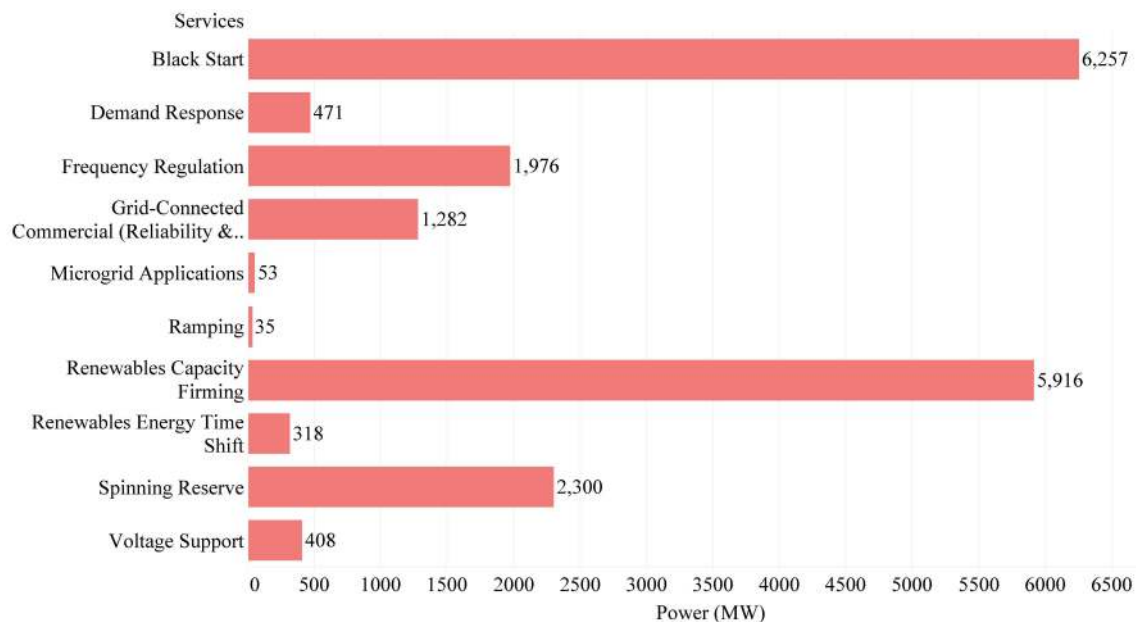


FIGURE 2. Applications of energy storage [13].

two or more ESS to form HESS [16]. For example, batteries have features of low specific power, high specific energy, less life-cycle, less capacity of self-discharge and less cost/Wh. On the other hand, the SC exhibits less specific energy, more specific power, fast charging, longer lifetime and high self-discharge [17]. Thus, the combination of battery-SC can utilize the complementary properties of each other. This combination has been popular due to its homologous working principle, ample availability, and low initial cost.

The benefits of implementing HESS are (see Fig. 3):

- Minimizes the initial cost contrasted with a single energy storage system (due to the decoupling of power and energy, the secondary storage system has to cover only the average demand for power).
- Enhances overall system efficiency.
- Improves storage capacity and lifetime of plant (minimizes the dynamic stress of the secondary storage system and optimizes the operation).

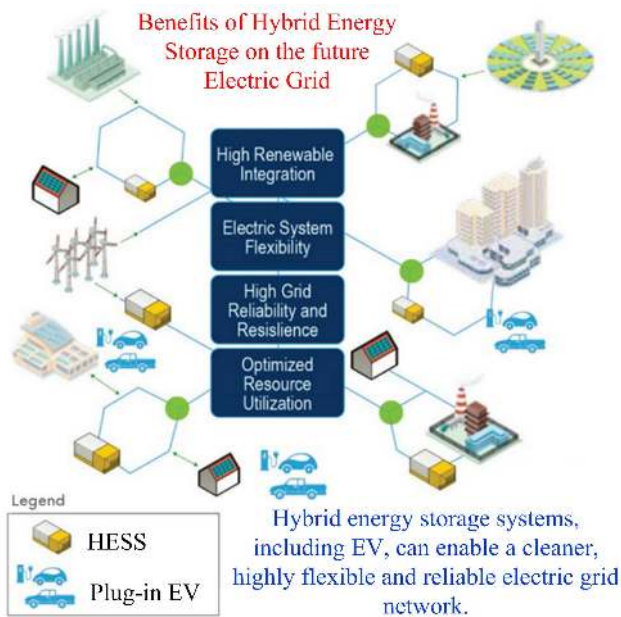
Due to these credible features of HESS, numerous researchers and industrial experts have focussed on the

TABLE 1. Characteristics of different energy storage elements [14], [15].

Type of Storage device	Energy density in Wh/l	Installation costs in €/kW	Installation cost in €/kWh	Reaction time	Self-discharge rate	Lifetime in years	System efficiency in %	Technology maturity	Application
SC	2-10	150-200	10000-20000	< 10ms	Up to 25 % in 1 st 48 h	15	77-83	Demonstration	Distributed generation and microgrid
SMES	0, 5-10	High	High	1-10 ms	10-15 %/day	20	80-90	Demonstration	Power quality, system stability, LF oscillation
Flywheel	80-200	300	1000	>10 ms	5-15 %/h	15	80-95	Commercial	FR, auxiliary service, PQ, enterprise UPS
Lead-acid	50-100	150-200	100-250	3-5 ms	0, 1-0, 4 %/day	5-15	70-75	Commercial, Demonstration	Peak load shifting, transportation, communication, national defense, reserve power supply, etc.,
Lithium-ion	200-350	150-200	300-800	3-5 ms	5 %/month	5-20	80-85	Demonstration, Commercial	All aspects of generation, transmission, distribution use.
Nas	150-250	150-200	500-700	3-5ms	10 %/day	15-20	68-75	Commercial	LR, peak load shifting, PQ, large-scale grid-connected RES etc.,
Redox-flow	20-70	1000-1500	300-500	> 1 s	0,1-0,4 %/day	10-15	70-80	Demonstration	Peak LR, large-scale grid-connected RES, UPS, emergency power supply, etc.,
Hydrogen	750/250 bar 2400/liquid	1500-2000	0,3-0,6	10 min	0,003-0,003 %/day	20	34-40	Commercial	Peak LR
Pumped hydro	0,27-1,5	500-1000	5-20	>3 min	0,005-0,02 %/day	80	75-82	Commercial	FR, peak LR, black start, phase shift.
CAES	3-6	700-1000	40-80	3-10 min	0,5-1 %/day	Ca. 25	60-70	Commercial, Demonstration	Peak LR, grid connected RES

TABLE 2. Applications, limitations and features of different types of battery technologies.

Type Energy storage	Applications						Advantages	Disadvantages
	Power Quality	Voltage Regulation	Load Leveling	Grid Extension	Voltage Regulation	Demand Management		
Sodium-sulfur (NaS)	✓	✓	✓	✓	✓	✓	High efficiency & energy density	High production cost, recycling need for sodium
Lead-acid	✓	✓	✓	✓	✓	✓	Less cost of investment	Less energy density
Lithium-ion	✓	✓	✓	✓	✓	✓	High power density, energy & efficiency	Cost of lithium is high and require recycling
Ultra Battery	✓	✓	✓	✗	✓	✓	Superior performance than lead-acid & less cost of investment	Less energy density
Metal-air	✓	✓	✓	✓	✓	✓	Less cost, eco friendly & high energy density	Less recharging capability
Nickel-cadmium	✓	✓	✓	✓	✓	✓	High energy, power density & efficiency	Involves toxic components highly

**FIGURE 3.** Benefits of HESS.

development of HESS technologies for integration of RES into the grid. Therefore, this article collates various control techniques implemented for the development of HESS. Since control techniques are treated as the heart of the system, this article presents a detailed analysis of various control techniques, their benefits and limitations along with the future perspectives.

The remaining sections of the paper are organized as follows: The different converter topologies used for the HESS

are discussed in section II. The detailed discussion on conventional control techniques of HESS and its comparative analysis is listed in section III. The intelligent control methods for managing the power flow between HESS devices are given in section IV and section V deals with the applications of HESS and discussion on case studies of real-time HESS plants implemented worldwide. Furthermore, the challenges in installation of HESS and future research directions are given in section VI and conclusions are made in section VII.

II. INTERCONNECTION TOPOLOGIES

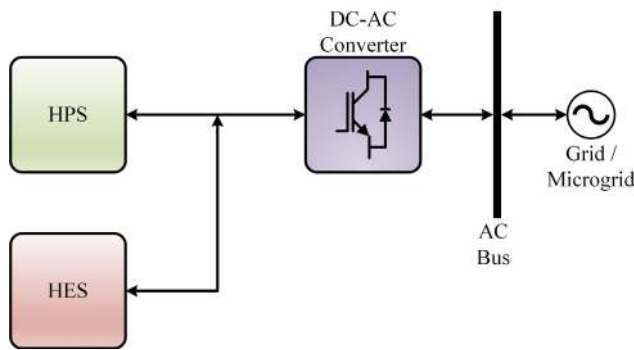
The interconnection topology of HPS, HES dictates the control flexibility, dynamic performance, efficiency and lifetime of ESS. The HPS and HES can be connected to the system directly or through power converters. The direct connection offers a simple system architecture, low cost and control complexity. Albeit, the use of power converters ensures decoupled control of HPS and HES and offers enhanced power regulation. The HESS can be either connected to the DC bus or use a separate DC-AC converter to connect with the AC bus. The interconnection topologies can be classified into passive, semi-active and active. The selection of topology vastly varies based on the system requirement and the functions of energy management system. A critical analysis of interconnection topologies is presented in Table 3.

A. PASSIVE

Passive architecture is the simple approach to interconnect HPS and HES to the system (see Fig. 4). The ESS are directly connected together without employing power converters [18], [19]. The matching of voltage levels of ESS

TABLE 3. Comparison of interconnection topologies of ESS to form HESS.

Topology	Cost	Flexibility	Range of control strategies adoption	DC bus voltage fluctuation	Fault tolerance	Space requirement	Control complexity	Recommendations
Passive [18], [19]	Low	No	Low	Yes	No	Less	Low	It can be used when the cost is the deciding factor in small capacity systems.
Semi-active [24], [25]	Moderate	Partial	Moderate	Yes when HPs is connected directly	Only HPS	Higher than passive	Moderate	It is recommended when the slight increase in the cost can be compromised to extend the battery life.
Active [26]–[28]	High	Full	High	No	Yes	High	High	It is more suitable for large capacity systems which require a superior dynamic response.

**FIGURE 4.** Passive interconnection topology of HESS.

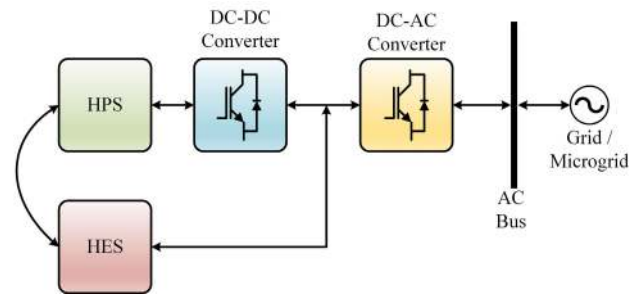
with the DC bus voltage or the load voltage is a prerequisite for direct connection [20]. The passive architecture resembles parallel operating synchronous generators, where the load is shared based on the impedance ratio. Similarly, the load is shared based on the internal resistance of ESS and its output characteristics. Where the resistance is greatly affected by the temperature and the instantaneous state of charge.

For instance, in a battery and SC hybrid, the high power pulses are absorbed by SC due to its low impedance. Thus, SC is analogous to a low pass filter. Furthermore, the charging and discharging characteristics vary considerably which offers poor regulation of voltage and load. The power balance of the system is given by Eq. 1. Where P_{gen} , P_{hess} , P_{load} are power generated, power exchanged by HESS (negative during power consumption) and power consumed by load respectively. The power exchanged by HESS is the sum of power contributed by HPS and HES as given by Eq. 2.

$$P_{gen} \pm P_{hess} = P_{load} \quad (1)$$

$$P_{hess} = P_{hps} + P_{hes} \quad (2)$$

Initially, this topology has been used for pulse loads [21], vehicular applications with battery-SC hybrid and later adopted to power system applications [22]. Lately, battery-SC with passive interconnection has been used to mitigate the intermittency of RES in isolated microgrids [23]. However, this topology did not gain much attention due to the following limitations:

**FIGURE 5.** Semi active topology of HESS.

- No control flexibility and the power sharing varies based on the source impedance.
- ESS are vulnerable to cascaded failure during contingencies as they are directly connected to the system.
- The voltage of ESS should be strictly matched with the DC bus or load voltage.

B. SEMI-ACTIVE

This topology is the extension of passive topology with one power converter to control HPS. Where a bidirectional DC-DC converter is used to control the power exchanged by HPS along with an appropriate control algorithm (see Fig. 5). The power exchanged by HESS with this topology is given by Eq. 3. Where α denotes the controllability of HPS and determines the power share of HPS.

$$P_{hess} = \alpha P_{hps} + P_{hes} \quad (3)$$

The peak power requirements of the system are satisfied by HPS and the remaining demand is met by HES. In a study, the semi active topologies with controlled SC and controlled battery have been analysed. The power converter of SC is oversized to handle the pulse power output. Whereas the topology with controlled battery has variations in DC link voltage [24]. So, relatively high energy storage is necessary to maintain the DC bus voltage whenever a HES is interfaced with a converter. Recently, a battery-SMES hybrid has been used to support the WES in an isolated microgrid. The SMES has been used to extend the lifetime of battery by absorbing high frequency power variations. Similarly, a battery-SC hybrid has been used to suppress the fluctuations of small WES.

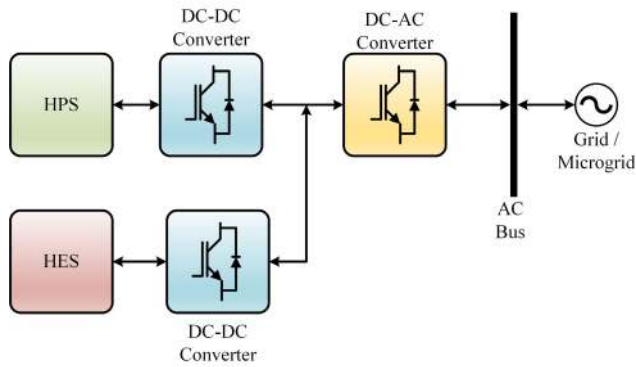


FIGURE 6. Active topology of HESS.

Where the SC has been interfaced using bidirectional DC-DC converter and the battery is directly connected to the DC bus [25]. Although it offers partial flexibility there are a few limitations as follows:

- The DC bus voltage varies when a HPS is directly connected to the system.
- The DC-DC converter should be designed to handle the large power spikes when interfaced with a HPS.

C. ACTIVE

The active topology employs separate bidirectional DC-DC converter to control HPS and HES (see Fig. 6). This topology offers the highest possible controllability with the decoupled control of both the ESS. It facilitates the energy management strategy to exploit the complementary characteristics of HPS and HES. Furthermore, it accommodates the adoption of wide variety of control strategies. However, all these advantages come at the expense of increased power conversion losses and high cost of converters. The power exchanged by HESS with this topology is given by Eq. 4. The variables α and β represent the controllability of HPS and HES respectively. The control strategies determine these variables based on several factors like SOC, frequency of power variation and deterioration rate of battery.

$$P_{hess} = \alpha P_{hps} + \beta P_{hes} \quad (4)$$

By far, this topology has been widely utilized in the application of HESS in power system. This can be subdivided into parallel active and series active topologies. The parallel topology employs two separate set of converters for interfacing HPS and HES in parallel [26], [27]. Whereas the series topology has cascaded HPS and HES with power converter to decouple it from the DC bus [28]. The series topology is often neglected as it demands the power converter to be rated to the total power rating of HESS. So, parallel active topology has been widely used for power system applications. Various advantages of this topology are:

- Improved flexibility with decoupled control of HPS and HES.
- A wide range of control strategies can be employed.



FIGURE 7. The goals of implementation of EMS.

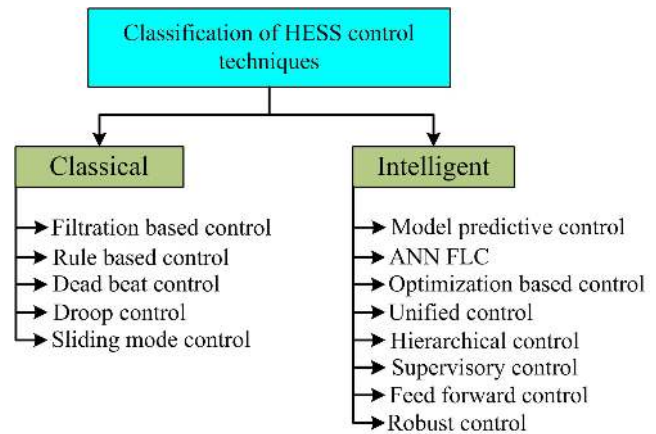


FIGURE 8. Detailed classification of HESS control techniques.

- The voltage levels of ESS are independent of system voltage.
- It has inherent fault tolerance capacity with converters decoupling ESS from the system

III. CLASSICAL STRATEGIES

Design and implementation of optimal controller is the most significant concern in HESS. The selection of suitable control technique for HESS relies upon an array of parameters. To name a few, extension of storage lifespan, reduction of power intermittency, power quality, controller response time, expense of controller and structure of hybridization. Implementation of a suitable realistic controller technique is essential to accomplish consistent, effectual and safe operation of HESS. The implementation of EMS focus into two levels of architecture, a lower level control system which controls the DC bus voltage and maintains the current flow. Whereas the high level control focus on allocation of power, SOC monitoring and other objectives of the system. [29], [30].

The goals of implementing HESS for off-grid system include optimizing micro grid performance, improving stability of system and reducing the cost of operation (see Fig. 7). To achieve these goals, different techniques were proposed and they are classified in this article as classical and intelligent control strategies (see Fig. 8).

A. FILTRATION BASED CONTROL TECHNIQUES

The power transfer between ESS can be classified into HF and LF components. The HF components are the result of sudden variation in load or irregularities in power generation

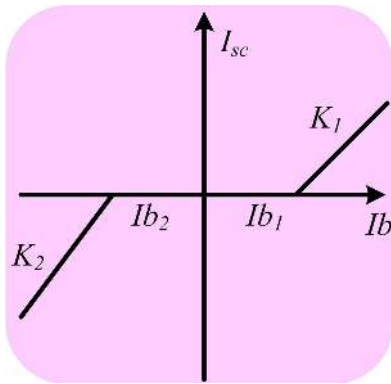


FIGURE 12. State machine control [30].

controls like simple implementation and easier process involvement. In [43], the authors regulated the SC to respond for transient power demand and minimized the stress on battery to enhance its lifespan. The developed deadbeat controller is shown in Fig. 13.

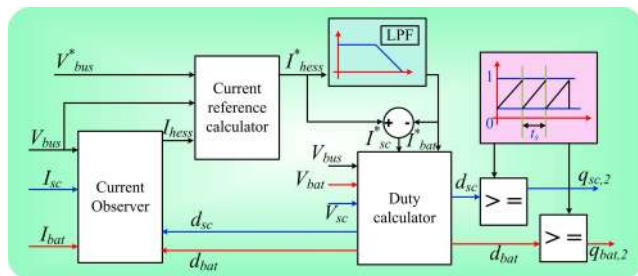


FIGURE 13. Control scheme of deadbeat control for HESS [43].

D. DROOP CONTROL

A HPF based droop controller and VCD is incorporated together to regulate battery and SC in [44]. This hybrid controller is proposed to provide solutions for effective power sharing, avoid voltage fluctuations, and limit the SOC of battery and SC. Furthermore, in [44] they have implemented decentralized controller via VCD and VRD for SC and battery to limit low and high frequency components. Incorporation of SOC recovery loop is feature of this work, which smooths the dynamics of transient power sharing.

The other widely used type of droop controller for power management of HESS is the VID. It is developed with the combination of VCD and VRD controller. Due to this combination, the controller is able to manage high and low frequency power sharing among SC and battery. However, this method, fails to control voltage deviation. To nullify this effect, authors in [45] introduced SVR controller for batteries to manage the bus voltage. In addition to that, SVR is developed to act under fast recovery of SOC irrespective of the leakage current [45] and the control scheme is shown in Fig. 14. Furthermore, an EDC presented in [46]. This method is also developed with the combination of VRD and VCD to control the power flow of HESS in DC microgrid.

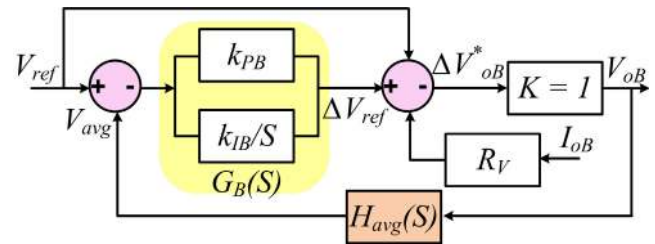


FIGURE 14. Secondary voltage controller [45].

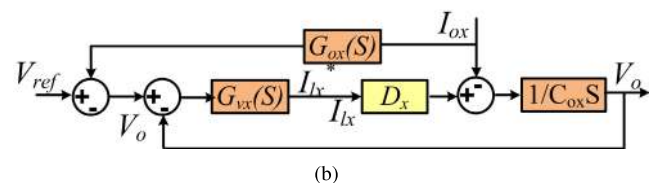
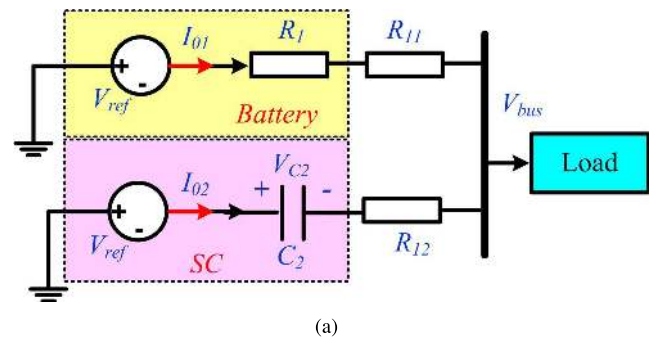


FIGURE 15. (a) Equivalent circuit (b) and control architecture of extended droop control [46].

The authors focused to maintain constant power of battery by avoiding fluctuations of high frequency. The Fig. 15 shows the proposed control structure with the combination of VRD and VCD.

A dynamic droop control technique, with the consideration of frequency as a control function is proposed in [47]. The proposed system has been successfully implemented in the Uligam Island in Maldives. This proposed method, effectively manages the synergistic operation of two different kinds of ESS even though both (battery, SMES) has dissimilar integral behavior. The droop control is extensively used as it can control the different control units and generate precise droop values. The droop range selection for the battery and SMES is shown in Fig. 16.

The architecture of frequency control function used to propose dynamic droop controller is given in Fig. 17. Through rigorous research on droop control techniques, ref [48] proposed a novel ID control to improve the performance of VID. The proposed co-ordinated control between V-P and ID, fundamentally develops the HPF/LPF to acquire optimal dynamic power allocation between considered ESS. The dynamic power sharing can be accomplished at decentralized level which is the additional feature of ID. The control schemes proposed for ID and V-P are shown in Fig. 18 and Fig. 19 for a better insight.

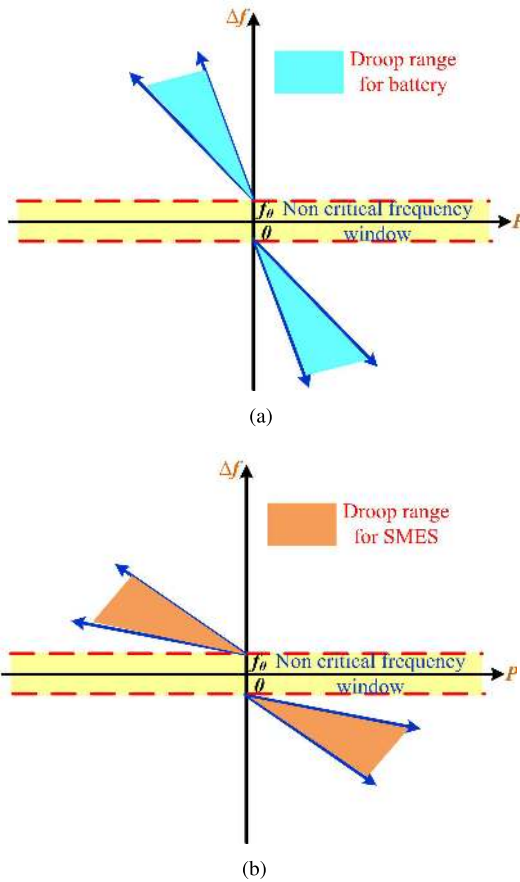


FIGURE 16. The selection of droop ranges; (a) battery, (b) SMES [47].

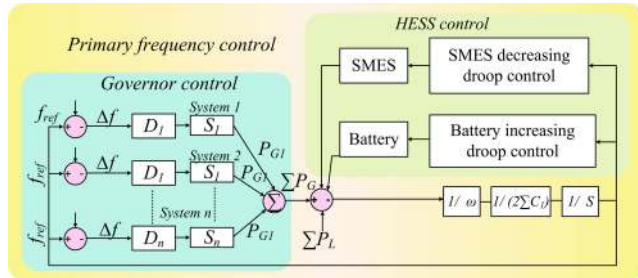


FIGURE 17. Primary frequency control concept of the MG system with HESS [47].

The combination of cache control and adaptive droop is implemented in [49] to integrate PV and wind system with HESS. The cache control is preferred to combine dissimilar features of storage devices and an adaptive droop is used to achieve coordinated control of battery for long term operation. In addition to that, it also controls the online SOC, and schedules the SOC of BESS. The cache control scheme proposed is shown in Fig. 20.

E. SLIDING MODE CONTROL

Sliding mode control is a type of non-linear control which toggles between the control laws based on the state vector. Abeywardana et al., in [50] implemented improved SMC

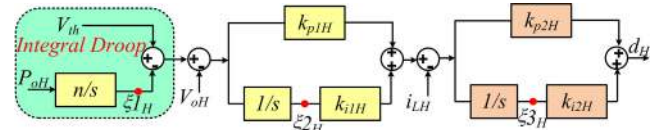


FIGURE 18. Integral droop and double PI controller [48].

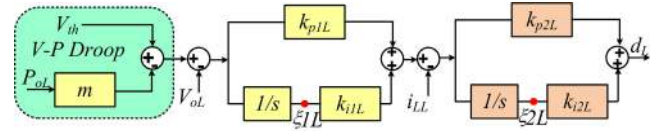


FIGURE 19. Traditional V-P droop and double PI controllers [48].

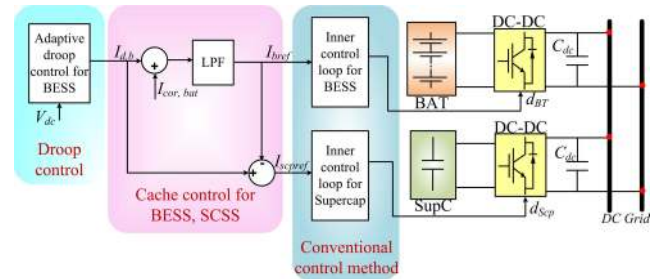


FIGURE 20. Cache control scheme applied for BESS and SCES [49].

technique by resolving the problem of variable switching frequency in conventional SMC. With this, authors minimized the power dissipation and design complexity of system. By combining the hysteresis control to the SMC an adaptive SMC is proposed in [51] with an aim of managing multimode HESS to overcome fluctuations in current. From the carried-out literature, the comparative analysis between conventional control strategies for HESS are tabulated in Table. 4.

IV. INTELLIGENT CONTROL TECHNIQUES

To overcome the limitations of classical control based EMS techniques, a real-time, intelligent based techniques such as adaptive PMP, meta-heuristics and MPC, are developed for the application of energy management in HESS. The systems implemented with these techniques were proven to have enhanced control performance, however, the time taken for the calculations at each cycle is high and the system cost is also high [57]. The detailed discussion on intelligent control techniques developed for HESS are discussed in following subsections.

A. MODEL PREDICTIVE CONTROLLER (MPC)

MPC is a plant process optimization technique that forecasts the effect of future control decisions on the changing state of the plant. It is an efficient and systematic technique used to deal with restricted multivariate control problems typically in process control of industries [58]. The greatest benefit of MPC is that it enables optimization of the current time frame while preserving the future time frames. MPC is likely to predict future incidents and can thus take corrective steps [59].

TABLE 4. Comparison of conventional control strategies of HESS.

Controller technique	Features	Limitations
Filtration based control [27], [32]–[36], [38]	<ul style="list-style-type: none"> These strategies are straightforward, financially savvy and widely preferable for real-time implementations. 	<ul style="list-style-type: none"> Designing of filter components is complex and selection of cut-off frequency decides the system performance. Requires accurate mathematical model of considered system. The effectiveness of reducing the peak power demand of battery using FBC is less, it can process only the frequency of power demand.
Rule based control [39]–[42]	<ul style="list-style-type: none"> Working with this type of controller is easy, involves less computation and simple to implement. 	<ul style="list-style-type: none"> The controller performance is not accurate, if there is an increase or decrease in the number of ESS. This method is more sensitive to change in parameters. Rigid in nature, not suitable for implementing in real-time system conditions as it involves predetermined thresholds, rules and operations.
Droop based controller [44]–[47], [49]	<ul style="list-style-type: none"> These techniques are highly reliable, decentralized and can be implemented with ease. 	<ul style="list-style-type: none"> Power sharing capability among the energy storage devices exhibits less accuracy. It is limited by slower response, and it is preferable where the response time can be relaxed.
Integral droop control [48]	<ul style="list-style-type: none"> It overcomes the limitations of LPF/HPF. Fully autonomous and decentralised control system. 	<ul style="list-style-type: none"> Slower response when compared to traditional droop control.
Dead beat control [43]	<ul style="list-style-type: none"> This type of controller require minimal amount of sensors than regular PI controller based techniques and also exhibits faster response during sudden change in load conditions. Fast dynamic response and high control accuracy. Simple process in implementation. 	<ul style="list-style-type: none"> Highly sensitive to change in parameters of controller and requires exact model of the system.
PI [52]	<ul style="list-style-type: none"> Easy and simple to design. 	<ul style="list-style-type: none"> The response of the system will be poor, if the operating point of the system is not within limited range. Uncertainty with respect to parameter variation.
LPF/HPF [32], [53]	<ul style="list-style-type: none"> Easy to implement and simple in structure. 	<ul style="list-style-type: none"> It experiences repetitive LPF/HPF enforced in power converters, which results in system instability.
multi-mode fuzzy logic [54]	<ul style="list-style-type: none"> Faster response 	<ul style="list-style-type: none"> Real-time implementation of this technique is a challenging task.
Hierarchical control [37], [55], [56]	<ul style="list-style-type: none"> Highly effective in controlling the vulnerability of connected sources and loads. Accurate load balance and power sharing capabilities among the energy storage devices. 	<ul style="list-style-type: none"> The chances of communication failure in the system are high.
Sliding mode control [50], [51]	<ul style="list-style-type: none"> High robust controller. Less sensitive to change of parameters. 	<ul style="list-style-type: none"> Involves complex design procedure.

In [60] the authors implemented an off-grid based wind/PV HESS via MPC to observe the SOC, load variations and levels of hydrogen tanks. The simulation findings reveal that the projected battery capacity and total device performance in comparison to the state controller system have improved by 12.23% and 14.65% [60]. Furthermore, to control the discrete/continuous dynamics in HESS system, MPC with MLD system is proposed in [61]. By using MPC, future control inputs and future system responses can also be predicted and it exhibits optimal control scheme. It has the capability of controlling numerous control variables in a large scale system. The control scheme of MPC proposed by authors in [62] is shown in Fig. 21.

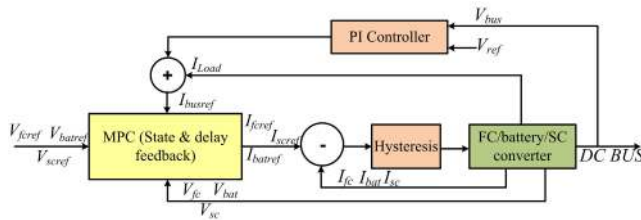


FIGURE 21. MPC based control scheme [62].

A hybrid system combination of fuel cells and SC are controlled with a MPC in [63]. In this work, the SC are interlinked directly in parallel with load and the fuel cell is connected to the load via DC-DC converter. The main limitations of the work carried-out by the authors are listed as follows: authors did not permit the gradual current changes to the considered power sources, the performance of the system may be affected due to rapid current changes as only the first order model of SC is considered. While designing the controller no actual DC-DC converter is considered. Moreover, the system performance has been evaluated only through simulation studies. Its major drawback in the reliance of MPC on mathematical model of the system.

MPC strategy is proposed in [64] with a combination of SC and batteries as energy storage devices. The main features of the work implemented are: the proposed MPC technique ensures the SOC of battery and SC are maintained within the limits, it gives unique steps to deal with the controller. On the other hand, the limitations exist in this work are, since by using of two state space models for two converters, the system is highly computationally insensitive as opposed to classical MPC. In addition to that, this method is not capable of regulating DC bus voltage. By extending the same concept given in [64], authors in [65], proposed less complex controller for effective management of HESS. Even though this proposed method, behaves less complex, the consideration DC bus voltage as constant will not be applicable in real-time DC microgrid system. Therefore, the limitations has to be addressed for its implementation in microgrids. The direct control of converters using MPC based EMS for HESS are shown in Fig. 22.

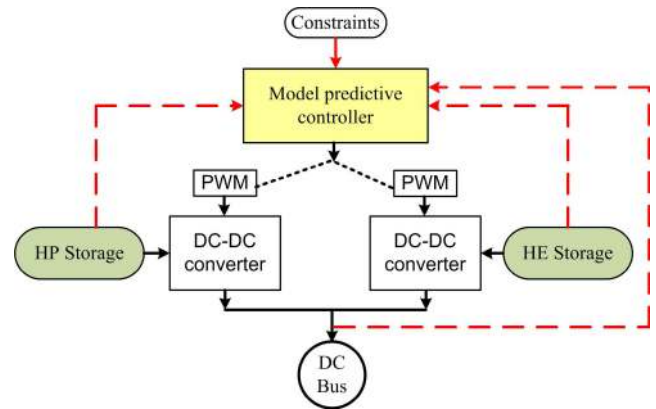


FIGURE 22. MPC controller based direct control of converters for HESS [66].

B. NEURAL NETWORK AND FUZZY LOGIC

In search of the trade-off between complexity and efficiency, other suitable methods for real-time EMS are proposed based on fuzzy logic, neural networks and RL [67]–[69].

Smart control strategies like FLC and ANN are way more effective than the conventional control strategies [70], [71]. Smart control strategies can enhance the system dynamic behavior without requiring the exact system model, yet they don't guarantee optimum performance [72].

ANN is a mathematical model which was developed with the desire to recognize and process parallel data. The ANN consists of several machine neuron layers. These layers are divided into three types; namely input, hidden, and output layers. Thanks to its non-linear and adaptive mechanisms, generalization abilities and design independence with regard to parameter systems, hence ANN is ideal for use in control systems [73], [74]. However, due to its 'black box' nature and the instructional issue in the network [73], [74], ANN lacks rules to define the structure (cells and layers). In a study, an ANN control system is designed to learn how to efficiently exploit system resources over time by adjusting the energy storage system's control strategy to change power production. However, the main disadvantage of a control strategy based on ANN is that the learning and tuning process needs historical data [64]. In [69] an ANN-based control strategy for an off-grid wind / PV power network with a HSS / battery HESS is proposed. The ANN-based management strategy uses a feedback loop to learn from new experiences and data in a new way. Compared with conventional methods, the proposed system has quick response [69]. However, the computational complexity depends on the number of data sets used to train the ANN [64].

On contrary to ANN, FLC is understandable and insensitive to parameter variations. In addition to that, the FLC does not need an exact program and training method model. The FLC algorithm is based on the rules and MF. In [75], the authors proposed FLC for an HSS / battery HESS wind / PV power off-grid network. The proposed control strategy aims to minimize the cost of HSS and regulate level of hydrogen

and SOC of battery. The results show that the proposed program optimizes the consumption costs by achieving a cumulative savings of 13 per cent over the regular program with RBC [75]. Indeed, FLC's MF are typically calculated by a trial and error process. This approach takes time and does not ensure optimal results [70], [71], [73], [74]. As the number of variables increases, the process of MF optimization becomes more complex. A multi-mode fuzzy based controller is introduced by authors to overcome the limitations of haar wavelet method which fails to consider the impacts of SOC [54]. The proposed multi-mode fuzzy is verified under long and short term scenarios. As a short term ac side performance is observed and in long term scenario, the problems of battery aging and efficiency are improved. The aforementioned goals are achieved by allocating FLC to three power sharing modes.

The NFC takes advantage of the inference ability of FLC, learning and process data in parallel features of ANN. The NFC applies neural learning rules for defining and optimizing MF of FLC. This methodology increases the accuracy of the fuzzy model in a limited period of time. In [76] the REPS control strategy was launched with the ANFIS [76]. MF of FLC are tuned and configured using the back-propagation adaptive error process. In the large scale operation (one-year simulation), the proposed system is compared with the RBC. The results of the simulation show that the two systems can provide the necessary energy while holding the SOC battery within operating limits. The program proposed strategy increases the performance by offering higher efficiency for battery and hybrid system [76].

C. OPTIMIZATION BASED METHODS

In addition to the above discussed FLC and ANN based controllers few other modern optimization based control techniques were also implemented for effective management of HESS. As the bio-inspired algorithms have capability of handling multi objective functions effectively and provide optimal solution which is proved in various fields of applications [77], [78]. Therefore researchers introduced the combination of FLC with optimization algorithms for effective framing of rules, which are discussed as follows.

PSO is a computational approach that optimizes the problem by iteratively trying to develop a solution for a specific objective. In [79], the authors proved that the PSO optimized FLC can be used for an HSS / Battery HESS off-grid PV / Wind power network. The MF of FLC are calculated by PSO algorithm and the network proposed is combined with an optimized FLC system. Results from the simulation show that the O & M and LPSP costs of the proposed system are 57% and 33% lower than optimized systems [79]. With the motivation of PSO+FLC technique, WCA is proposed which is enlivened by the normal water cycle. In [80] off-grid HESS using WCA with FLC is proposed. MF of FLC are optionally tailored using WCAs to reduce LPSP and O & M costs. The combination of FLC with LPF control strategy is implemented in [53], where the LPF is used to attenuate high dynamic components of battery and FLC was focused

to manage peak current of battery. To get better performance of the FLC, the membership functions are optimized via PSO. The control scheme proposed in [53] are presented in Fig. 23. The proposed system has been successfully implemented and tested in real-time rural house hold applications.

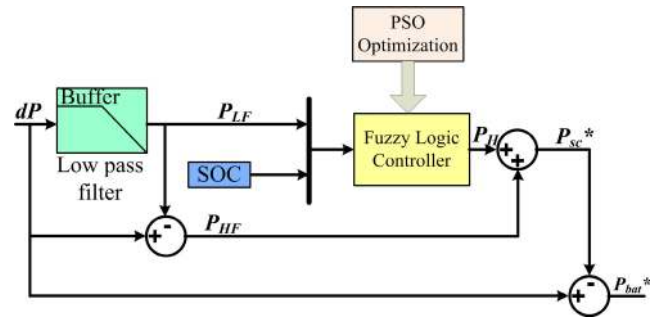


FIGURE 23. FLC controller with PSO [53].

Chia Y Y *et.al.*, in [81] proposed a predictive energy management system based on SVM for battery / SC HESS. The predictive SVM-based strategy correctly predicts the demand with a precision of 100% and a classification time of 0.004866. With a load prediction, the proposed system reduces the battery stress and prolongs the battery life by operating the SC at 200 ms before demand for maximum power takes place [81]. However, the amount of SC power is uncontrollable. The other innovative predictive management technique for a battery HESS is proposed for off-grid wind power system [68]. Based on the predicted wind and load profile, the strategy adapts the operation of the batteries and FC so that the network does not face blackout when the wind is weak or the energy reserves are inadequate [68]. However, the proposed predictive analysis approach has a pre-determined threshold which limits its application.

A hybrid on-grid HESS using predictive control is developed in [82]. The proposed system forecasts daily and weekly photovoltaic power output, wind speed, electric demand, electricity hourly price data and ambient temperature. The daily / weekly FLC is optimized by using SFL and PSO according to the predicted daily and weekly parameters. The simulation findings reveal that 9.27 per cent of SOC for weekly SFL-optimized FLCs, regular SFL-optimized FLCs, weekly PSO-optimized FLCs and regular PSO-optimized FLC are up by 17.8% and 16.89% respectively and weekly operating costs are raised by weekly SFL-optimized FLC, daily SFL-optimized FLC, weekly PSO-optimized FLC, and daily PSO-optimized FLC. The other optimization based EMS for HESS using MIAD is introduced in [83]. In this work, the authors proved that the proposed algorithm has less iterations to accomplish the objectives. The considered objectives are reducing fluctuations in battery current flow, diminishing the energy losses produced by SC.

D. UNIFIED CONTROLLER

A unified EMS for the DC microgrid with HESS is developed by Tummuru *et al.*, in [84]. The proposed technique

proved the extension of life span of SC and battery under various operating conditions. The performance achieved by the proposed system gives superior than the EMS implemented in [85] with respect to voltage regulation, charge and discharge rates of battery and processing time. The similar type of unified controller given in [86] has features of faster dynamic voltage regulation, effective power sharing under any sort of disturbances, reducing fluctuations in rate of charge/discharge of battery, and power quality enhancement. The developed unified controller is presented as a flowchart in Fig. 24.

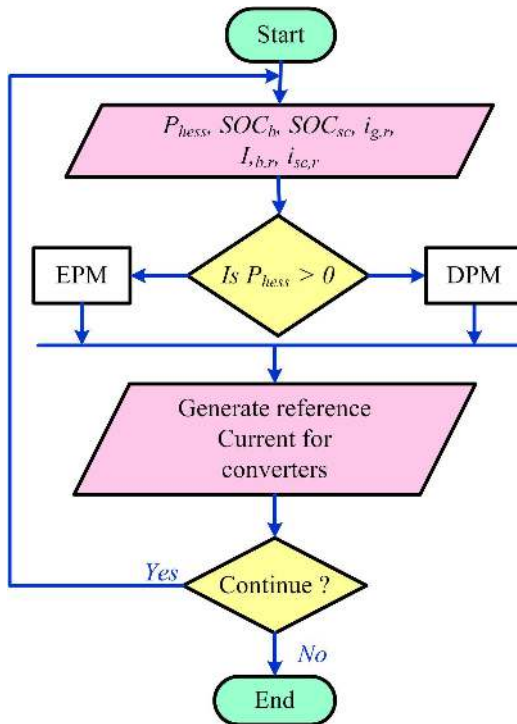


FIGURE 24. Flow chart of the unified controller for EMS of HESS [86].

Supervisory power management for HESS with hybrid microgrid is implemented by authors in [87], [88]. In these works, the authors have focused on cooperation between grid and microgrid. In addition, the adequacy of HESS to deal with various conditions from the PV and grid were also analyzed. Another control technique named FJC is proposed in [26] for control of HESS in DC microgrids. In this system, the efficiency of the system is improved by the use of SC to cater for the unmet load by batteries.

FFSVM to manage the power flow between batteries and EDLC is proposed in [89]. An asymmetrical cascaded multi-level converter is used to manage the HESS. In each mode of operation, either battery or EDLC is chosen to give or receive the power and other storage devices are used to maintain the output voltage. As per the DC and AC voltage reference the FFSVM produces switching times and sequences of the state vector.

A hierarchical control strategy to control power flow between SMES and batteries is proposed in [55]. Empirical

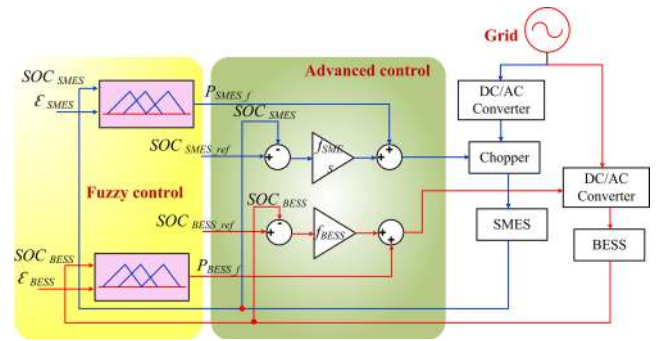


FIGURE 25. Hierarchical controller for HESS [56].

mode decomposition tool is used for signal analysis and to achieve effective power allocation to eradicate the time delay unlike traditional methods. The structure of hierarchical control is shown in Fig. 25. The usage of SMES is increasing in HESS than SC due to its features such as efficiency high, low self-discharge, long life span and high power rating levels. Based on the complete analysis carried-out from the literature, the different intelligent control techniques used for power management of HESS for the application of microgrids are tabulated in Table. 5.

V. CASE STUDIES AND APPLICATIONS

A. REAL-TIME CASE STUDIES

A variety of HESS combinations are common in simulation software's such as HOMER and MATLAB, real life applications are not as common though. A lot of pilot and demonstration projects are currently taking place in different parts of the world. Limited information is known about these projects as the companies and governments involved don't provide detailed information about these projects until noticeable progress is achieved. Most of the real life HESS applications are for renewable energy sources integration, frequency control and back-up power. They are considered to enhance the operation of the grid and to save money for the clients by lowering energy wastage and improving efficiency. A few examples of real-time scenarios of HESS implementation are:

- A 1.2 MW SC/Battery HESS in North Carolina, United States was installed by Duke Energy in 2016 to handle peak demand response, load shifting and support. The hybrid SC-battery HESS provides multiple service applications, extended operational life, rapid response, real-time solar smoothing and load shifting. Benefit of this combination is that it provides long term grid support and easily integrates renewable installations [91].
- A 11.5 MW Li-ion, NaS battery HESS commenced operation in 2018 in Varel Niedersachsen, Germany. The energy service provider EWE and its Japanese partners, Japanese industrial development agency NEDO, Hitachi Chemical, NGK Insulators and Hitachi Power Solutions worked on the unique project. The purpose of the HESS combination was to balance out frequency fluctuations

TABLE 5. Critical analysis of intelligent control strategies of HESS.

Controller technique	Features	Limitations
ANN [67]–[75]	<ul style="list-style-type: none"> • FLC is less sensitive to change of parameters and easy to implement the controller. • The exact system model and training process is not required. 	<ul style="list-style-type: none"> • This method consumes high computational time as membership functions are tuned by trial and error basis.
Evolutionary methods [53], [79]–[81]	<ul style="list-style-type: none"> • These methods can handle multiple objective functions to optimize at a time and gives better response than conventional techniques. 	<ul style="list-style-type: none"> • The selection of parameters can be done on random values which may take time to give optimized solutions and sometimes results may not be accurate as expected.
Multi objective [68], [82]	<ul style="list-style-type: none"> • Several objective functions and constraints can be controlled at a time. 	<ul style="list-style-type: none"> • This type controller behaves like evolutionary methods.
MPC [58]–[65]	<ul style="list-style-type: none"> • With help of this controller can predict the future behavior of system and its performance. These can also be optimized at regular intervals. • Provides uniform approach to design control system. • Easy incorporation of constraints. • Can also control high scale system with numerous control variables. 	<ul style="list-style-type: none"> • Without accurate model of the system, the controller will not function. • High computational burden. • Computationally intensive.
Robust control [90]	<ul style="list-style-type: none"> • This controller gives superior performance than conventional controllers and is less sensitive to change in parameters. 	<ul style="list-style-type: none"> • The implementation of this type of controller is complex due to involvement of immense calculations in every switching period.

from renewable energy sources in the regional electricity network. Li-ion battery will act as a high power provider with its ability of quick discharge while the NaS battery will act as a high energy provider which is suitable for long term storage [92].

- A 1 MWh VF/Li-ion battery HESS was developed for Monash University, Australia by redT energy storage solution in 2018. The largest behind the meter Commercial and Industrial ESS to be installed worldwide. The main purpose of the HESS is for storing and dispatching energy from multiple sources including a 1MW solar panels [93].
- A 20 MW brand new concept of power to heat/battery storage was developed in Bremen Germany by AEG power solutions. Energy is stored in a battery and an electrical heating system which are then connected to a converter. Its main function is frequency control for power operations and renewable energy sources integration [94].

An overview of world wide real-time implementation of HESS are tabulated in Table. 6.

B. APPLICATIONS

HESS is predominantly deployed in the following sectors Power sector, Transport sector and Renewable energy sector. The applications of HESS in electric power system include

grid stabilisation, frequency regulation, backup power and renewable energy sources integration.

1) POWER SECTOR

HESS in the power sector is used for ancillary services like FR or VR and backup power for the grid. Traditionally single ESS were used for such services but due to their limited capability in terms of energy, power density and dynamic response, HESS became the better alternative [66]. Battery/SC and battery/flywheel are the most common combinations of power sector HESS. They are used in microgrids where lifecycle of batteries is increased due to less stress from charging and discharging. Overall HESS application in the power sector is for grid stability, FR, back up and power quality services.

2) TRANSPORT SECTOR

Peak power demand from sudden accelerations in EV draws a lot of energy from batteries, which means that the duration of power supply will be reduced and lifecycle of the battery will also be lowered. Increasing the battery capacity to deliver more power can solve the problem but this will be expensive and will add more weight and volume. Alternatively the HESS combination of a battery/super-capacitor or battery flywheel will effectively manage large fluctuations from sudden accelerations and regenerative braking [97], [98].

TABLE 6. HESS real-time case studies.

S.No	Combination	Location	Capacity (MW & MWh)	Company	Application	Year
[91]	SC/Battery	United States	1.2 MW	Duke Energy	Peak demand response, load shifting and support	2016
[92]	Li-ion/NaS battery	Varel Niedersachsen, Germany	11.5 MW	EWE, NEDO, Hitachi Chemical Co, Hitachi Power solutions Co Ltd and NGK insulators	To balance out frequency fluctuations in the regional electricity network	2018
[93]	VFB/Li-ion battery	Monash University, Melbourne, Australia	1 MWh	RedT	The hybrid system will act as a flexible platform, integrating with building management systems and EV charging stations whilst enabling cutting-edge “peer-to-pool” energy trading.	2018
[94]	Power to heat/Battery	Bremen, Germany	20 MW	AEG Power Solutions	Frequency control power	2018
[95]	lead-acid batteries and lithium-ion capacitors	Japan	1.5 MW	Hitachi Ltd and Shin-Kobe Electric Machinery Co Ltd	Renewable energy integration	2014
[96]	Li-ion batteries/hydrogen storage	Cerro Pabellón, Chile	125 kWp PV plant	EGP	Grid stability	2017

The battery performance and lifetime will also be increased due to the HESS combination by reducing the charging/discharging rate and battery stress [99].

HESS is also used in electric trains to flatten fluctuations from various acceleration and deceleration cycles. They can be installed on the train or railway substation. They are utilized to reuse regenerative energy from vehicle breaking so that large power is feedback to the source during deceleration and power will be drawn during train acceleration [100].

3) RENEWABLE ENERGY SECTOR

HESS in renewable energy sector is mainly used to improve the power quality and system efficiency of renewable energy sources. HESS aids integration of intermittent renewable sources into the grid by providing long term energy balancing, short term power quality and frequency regulation services. It is used instead of a single ESS to meet peak power demand in some systems [100]. A HESS is a better solution in terms of cost effectiveness, practicality and durability for complete system implementation [5]. It is used to increase the storage and system lifetime by optimising lifespan and reducing dynamic stress on the high energy storage unit [101]. The noticeable observations and applications of HESS were tabulated in Table 7.

VI. CHALLENGES AND FUTURE DIRECTION

The investments on ESS is showing an increasing trend in the recent years. It is primarily dictated by the RES and micro-grid infrastructure development in the present system. The batteries and SC are widely used for grid connected systems and EV applications due to its easy accessibility. In addition to that, the conventional ESS like pumped hydro storage and CAES were also used in wide range of applications. However, to improve the successful development of HESS technologies, the following challenges should be encountered:

- Creating awareness among public for enhancement of HESS technologies towards achieving the reliable power supply to the consumer.
- Providing support on infrastructure development, installation and regular maintenance should be guaranteed to increase the installation capacity of HESS.
- Providing incentives for investment in HESS technologies is necessary which will bring attention towards the growth of HESS in the market.
- The upgradation of poor energy markets and weak grids is required which will attract the power distribution company towards deployment of HESS.
- The universal guidelines for HESS selection and its operating procedures should be improved according to the present technological development.
- The research on HESS technology is stagnant on laboratory scale with only theoretical perspective, so, development of projects to promote commercialization and industrialization of HESS technology is necessary.
- It is advisable to come up with HESS solutions with the support from researchers, economical advisors, electricity companies, consumers and social organizations.

The advancement of HESS needs modernization and breakthrough in long lifespan, minimal cost and high security. In addition to that, the following recommendations are worth addressing in near future:

- An intelligent EMS controller with superior performance of HESS will facilitate the adoption of smart grids or microgrids in near future. So, HESS can enable the development of microgrids ranging from medium scale to large scale towards the transition of smart-grid.
- The innovative approach of “energy internet” for future energy supply and distribution system will highly depend on the performance, flexibility and reliability of HESS [108], [109]

TABLE 7. HESS applications in various fields.

Ref.	Section	Category	Key points	Summary(merits/demerits)
[55]	Transport	SMES/BES	A novel method of making high power fast charging load controllable is designed to generate real time power demand for HESS.	High energy density of Battery energy storage (BES) and rapid response of SMES can limit the power change rate and power magnitude of fast charging stations. SMES with its low self-discharge rate, long cycle life and high efficiency brings down the operation cost compared to other high power devices.
[56]	Renewable Energy(PV systems)	Power heat/battery, Power heat/battery/hydrogen, SC/battery, Battery/battery	A modular experimental test bed for HESS systems has been described in its components, structure and functionality.	Double low pass filtering and peak shaving based power flow decomposition principal approach was presented. Configurations of four HESS for decentralized PV systems was presented. ESS coupling architecture and energy management concepts like hierarchical control and optimization based energy management were discussed.
[66]	Microgrid, Renewable Energy	SC/battery, FC/battery, SMES/battery, FC/SC, battery/flywheel, FC/flywheel and battery/CAES	MG and RES challenges can be solved by HESS. The services HESS can provide are: 1)Renewable system intermittency improvement. 2)Storage lifespan improvement 3)Power quality improvement HESS. 4)Stability	A comprehensive review of Microgrid (MG) application of HESS from different point of view was presented. HESS sizing, applications in control and electrical systems for the adaptation of MG and current. Connections and configurations of HESS and optimization control of the process were discussed.
[102]	Transportation (BEV)	SC/Battery	HESS performance in terms of lifetime extension can be improved by continuously variable transmission (CVT). BEV dynamic and economic performance is increased by CVT.	Electrified CVT performance for a BEV equipped with HESS was studied in the paper.it showed that regardless of powertrain configurations by the addition of SC to ESS, the charging current in the battery was controlled.
[103]	Microgrid	Battery/Flywheel	Enhanced performance of the MG is noticed due to the HESS. Lifecycle of the battery has increased and improvement of the quality of power during grid integration is noticed.	A dynamic analysis of a HESS consisting of battery and flywheel coupled to a PV generation plant and a residential load up to 20 kW is provided.
[104]	Microgrid	Battery/SC	MG with the aid of HESS can be installed in isolated areas saving money without the need for costly inefficient transmission and distribution infrastructure.	Development and technological advancements of SC/battery HESS in standalone MG system was discussed and reviewed in this paper. The effectiveness of EMS in HESS for mitigating battery stress was presented in a case study.
[100]	Electrified transport, Renewable energy	Battery/SC, Battery/SMES, Battery/flywheel, CAES/ SC, CAES-SMES, CAES/flywheel, CAES/battery, Fuel cell/SC, Fuel cell/ SMES, Fuel cell/battery, Pumped hydro/ power supplier ESS	Suitable for transport and utility services. Transport includes private EV and electrical powered train. The electrical powered train is variable with so many accelerations and deceleration's. HESS can be used to reuse regenerative energy from braking. Reliability, stability and power quality issues from renewable energy integration can be mitigated.	Outstanding features of HESS materialise in specific applications that single ESS units cannot perform. HESS enhances the performance in several applications that use single ESS. HESS is used as an energy source in several applications ranging from grid support to transport sector.
[105]	Power systems	Battery-SC	Frequency regulation in electricity market	A substantial amount of money can be saved by regulation service provider from using HESS instead BES alone for frequency regulation in power system operation.
[106]	Power systems, Renewable energy integration (PV)	Battery- SC	The combination reduces stress on the battery, hence increasing its lifespan.	A new control scheme and a selected combined topology to control battery and SC power sharing was proposed. Based on the PV power curves, a method for ESS sizing and hybrid distribution was introduced.
[107]	Transport (EV)	Battery-SC/Fywheel	Primary ESS is Li-ion battery while the secondary ESS is either a flywheel or SC. During high power demand the secondary source delivers/recovers energy. It also increases the lifetime of the battery.	The reduction of battery intervention during start up and regenerative braking of EV was the main objective of the paper. This is to increase the lifecycle of the battery, respond to dynamic requirements of the vehicle during extreme braking and traction operations and to enhance capacity performance. In terms of energy density, volume, power density and cost, flywheel is better suited than SC for EV application. SC is more convenient in terms of weight and specific power. Breaking energy recovery while driving is better achieved by SC.

- Development of new battery technologies namely aluminium, lithium-air, sodium-ion and graphene are need to replace with current batteries with substantial development in lifespan and performance [110], [111].
- Advancements in battery technologies will further increase the adoption rate of HESS for grid connected applications [112].
- Novel combination of ESS across different medium (mechanical, thermal) will widen the options of HESS for various applications. For instance, hybridization of fast responding high power ESS with high energy ESS like CAES, thermal energy storage and pumped hydro storage can be developed.
- The development of new control strategy for HESS via multi objective optimization by taking into consideration of technical and economical limitations is yet to be targeted.
- There exist inadequate research works have been carried-out using predictive controllers for

implementation of HESS, with the improvement of these techniques for HESS, penetration of renewable energy can be further increased.

- As authors proposed in [113], a reconfigurable ES bank to change the configuration of battery bank dynamically to minimize the load on each battery and enhances the performance of HESS and give long life span. Performing research on these type of system bringing these into regular usual market is challenge in the present world.

VII. CONCLUSION

In this article, an extensive review of various control strategies implemented for HESS is presented. The different control strategies used for autonomous and grid connected microgrids are elucidated. The recently published articles on HESS are critically reviewed and noticeable characteristics of each control technique are summarized in tables. In addition to that, a detailed discussion of the pros and cons of intelligent and conventional control techniques are also presented.

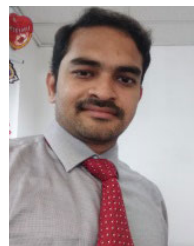
As an added value, HESS adopted in real-time applications throughout the globe is analyzed and discussed. Finally, a pathway for the future researchers to carry out their research in this area is laid out, and the main challenges faced towards the implementation of HESS is presented. Therefore, this article helps the researchers and practitioners to have a complete idea on control technologies implemented for better coordination of ESS forming the HESS, thereby driving the penetration of RES into the grid.

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