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Battery-Supercapacitor Hybrid Energy Storage System in Standalone DC Microgrids: A Review

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Abstract: Global energy crisis and environmental pollution increasingly promote the application of Renewable Energy Sources (RES). As a feasible option to overcome the issues of RES integration in power system such as instability and fluctuation, large scaled Battery Energy Storage System (BESS) and its associated Energy Management System (EMS) has become one of the most popular research area for future RES power system. Despite many advantages of integrating BESS in RES based power system, the highly dynamic fluctuations in generation and demand in standalone RES based Microgrid (MG) causes damaging impact on lifespan of battery, which greatly increases the operating cost of the standalone MG. In recent years, the novel concept of Battery-Supercapacitor Hybrid Energy Storage System (HESS), which contains two complementary storage devices, is been developed to mitigate the impact fluctuating power exchange on lifespan of battery. This paper critical reviews the latest works related to this area In terms of topologies, Control and Energy Management System (EMS). A case study of Standalone PV MG with HESS is presented to show its practicality and the benefits of using HESS are elaborated via Cost Function. Among the various topologies and related EMS design, the review analysis and discusses the importance of balancing the trade-off between the technological needs and economic feasibility when designing a Battery-Supercapacitor HESS in Standalone RES based MGs.

1. Introduction

Global warming and its associated environmental impacts have accelerated the development of Renewable Energy Sources (RES) and Smart-grid technologies aiming to improve energy efficiency and to reduce carbon footprint [1][2]. As the increased penetration of RESs, low voltage Microgrid (MG) has attracted increasing attentions from researchers and power industries due to its unique architecture that allows highly efficient power generation and distribution in decentralised settings [3]. MG is a small-scaled, decentralized and autonomous power grid system that may consist of multiple distributed generations (DG) and/or RESs, end-use customers, Energy Storage Systems (ESS) and power electronic converters that is operated either in standalone mode or interconnected to the utility grid [4][5][6].

Another advantage of MGs is that it allows power generation and supply to remote isolated community without the need of long-distanced, costly and inefficient high-voltage transmission and distribution infrastructures that is not economically feasible [7][8]. However, due to its relatively small capacity and the intermittent nature of RESs, conventional operations practised in the utility grids may not be applicable to MGs due to the highly dynamic supply and demand sides [9]. As a result, many works have been carried out to improve the power quality and reliability of the MGs ranging from novel system topologies [10][11][12] to intelligent power management and control strategies [13][14][15][16].

Unlike the grid-connected MGs that have virtually unlimited and strong support from the high inertia power supply, standalone MGs rely heavily on ESS to balance the unmatched profiles of generation and power consumption [17]. The ESS acts as buffer to absorb surplus energy and supply the stored energy when power deficit. Furthermore, ESSs in standalone MGs also play an important role in regulating instantaneous power variations, power quality and the system reliability [18]. The nowadays-available ESS technologies for MG applications are been listed and compared in Table 1:

Table 1 Characteristics of Different ESS Elements [16][19]

Energy Storage System	Energy Density	Power Density	Cycle life	Response time	Cost
Chemical Battery	High	Low	Short	Medium	Low
Sodium-Sulfur (NaS) Battery	Medium	Low	Short	Slow	Medium
Flywheel	Low	High	Long	Fast	High
Supercapacitor	Low	High	Long	Fast	Medium
Superconducting Magnetic Energy Storage (SMES)	Medium	High	Long	Fast	High

In standalone MG, the power flows in and out of the ESS elements varies widely depending on the instantaneous power generation and load conditions [20]. In general, the power exchange in ESS can be categorised into high-frequency components such as sudden surge in power demand or intermittent solar power generation on a cloudy day, and the low-frequency components such as natural behaviour of RESs or daily average energy consumption [21]. The high-frequency power variations generally require ESS elements with high power density with fast response time, while low frequency or long-term power variations prefer high energy density and low cost ESS elements.

Based on the characteristics of different ESS elements as shown in Table 1, none the ESS technologies fulfils all the desired characteristics to respond to high and low frequencies power variations in standalone MG applications [22]. Therefore, using single type of energy storage element in standalone MG applications limits the potential of what ESSs can offer. Among all HESS combinations, Battery-SC HESS has been the popular combination in HESS researches because of their wide availability, relatively low cost compared to other ESS elements, similarity in working principle and most importantly, they complement each other’s weaknesses rather beautifully.

HESSs have been actively investigated in other high energy demand applications such as Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEV) and have shown great performance improvement in many aspects, for example, optimising the energy recovery from regenerative braking, improving the rate of charging and prolonging the service life of battery by reducing the strain of deep discharge [23]. However, HESSs in grid scale applications are mostly still in research stage [24][25][26]. HESSs typically couple to the power network via AC or DC coupling with the aids of power electronic converters to control the power flow of different ESS elements [27][28][29]. Though modern power electronic converters allow energy sources of different characteristic to hook up together, it also increases the system complexity and cost [30]. Hence, the trade-off between economic feasibility and technical advantages exist and it is crucial in determining the financial and technical sustainability of the system.

Various Battery-SC HESS topologies had been proposed in MG applications aiming to optimally utilise the benefits of different ESS elements [31][32]. Besides having correct HESS topology and appropriate sizing of different ESS elements, energy management and control strategy of HESS is another key to improve system efficiency, maximise energy throughput and prolong lifetime of HESS [33][34][35][36][37].

This paper reviews the current trends of Battery-SC HESS in renewable energy based standalone MGs, including existing HESS topologies, energy management strategies and control algorithms. The rest of the paper is organised as follows. Section II presents the different HESS topologies available today for high power storage applications with a comprehensive analysis of HESS in standalone MGs. Section III reviews existing energy management strategies including control goals, power allocation strategies and safety measures. A case study that locates Kuching, Sarawak, Malaysia is presented in Section IV and it shows the fundamental methodology that how to evaluate HESS via Cost Function. Section V gives a thorough review of different control algorithms in energy management system and evaluation of their effectiveness, economical and technical viability for HESS in MGs and its future trend are also included in this section. Finally, the paper is concluded in Section V.

2. Battery-SC HESS Topologies

In Battery-SC HESS, the two complementary ESS elements are typically connected to a common DC or AC bus [38][39][40]. For RES based standalone MGs with ESS, coupling through common DC bus is the preferred choice due to many reasons [41][42]. Firstly, most of the common ESS elements and RESs operate in DC voltage, thus minimises the needs of power converter [43]. Also, DC bus does not require synchronization which greatly reduces the complexity of the overall system [44][45]. As a result, DC coupling is more efficient and lower cost than equivalent AC bus systems because of lower power losses and the needs of high power components [46][47][48]. In general, Battery-SC HESS can be categorized based on their connection topology as shown in Fig. 1.

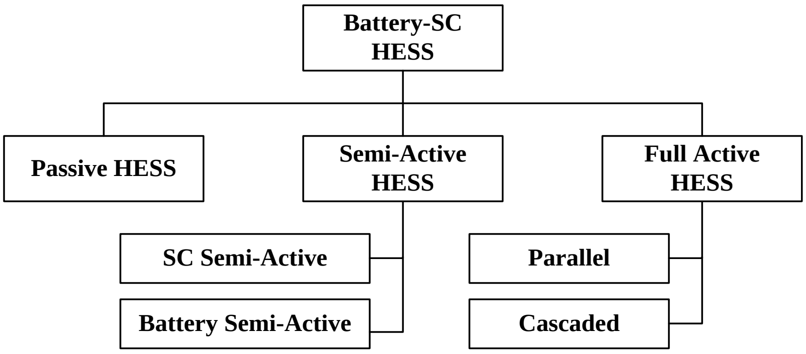


Fig. 1. *Classification of the Battery-SC HESS Connection Topologies* [49][50]

2.1. Passive HESS

Passive connection of battery and SC to the DC bus provides the simplest and cheapest structure of HESS. Passive Battery-SC HESS has been demonstrated to effectively supress transient current under pulse load conditions, increase the peak power and reduce internal losses [51][52][53][54]. As shown in Fig. 2, the battery and SC are connected to the DC bus directly and they share the same terminal voltage that depends on the State-of-Charge (SoC) and charge/discharge characteristic of battery. In some rural MG applications, the battery capacity is decided assuming three to five days as reserve without any external source of energy [55]. Consequently, the battery will be cycled approximately 20% Depth-of-Discharge (DoD) and charged/discharged in a relatively low C-rate due to the large capacity. As a result, the fluctuation in DC bus voltage will be minimal, ensuring a relatively stable system voltage.

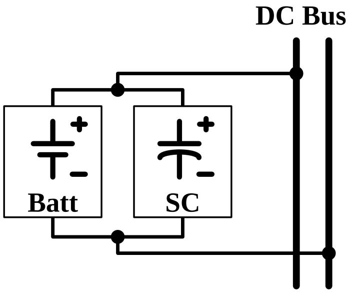


Fig. 2. *Passive HESS Topology*

However, in passive connection of HESS, the system current will be allocated to these two ESS elements based on their respective internal resistance [54]. In facing of the uncontrolled power flow, the battery may experience surge and fast variations of charging/discharging currents in sudden power demand. It will cause the battery functional deterioration and considerable lifetime reduction. Therefore, the power handing capability of SC is not fully utilised. Also, as the voltage variation of battery terminal is small, the SC will not be operating at its full SoC range which results in poor the volumetric efficiency [52].

2.2. Semi-Active HESS

To overcome the drawbacks of passive connection of HESS, power electronic converters are employed as an interface between ESS element and DC bus to actively control the power flow to and from ESS elements [56]. In Semi-Active HESS topology, only one of the two ESS elements is actively controlled as illustrated in Fig. 3. The Fig. 3(a) shows a SC Semi-Active HESS topology in which only the SC is interfaced to the DC bus via bidirectional DC/DC converter and the battery is directly connected to DC Bus [57]. In this topology, the DC/DC converter isolates the SC from DC Bus and decouples from battery terminal voltage. In this setting, the SC can be operated within a wider range of voltage, thus improves the volumetric efficiency significantly. The direct connection of battery also ensures stable DC bus voltage [58]. However, the direct connection of battery unavoidably exposes the battery to sudden high charging/discharging current that has negative impact on battery lifetime [59].

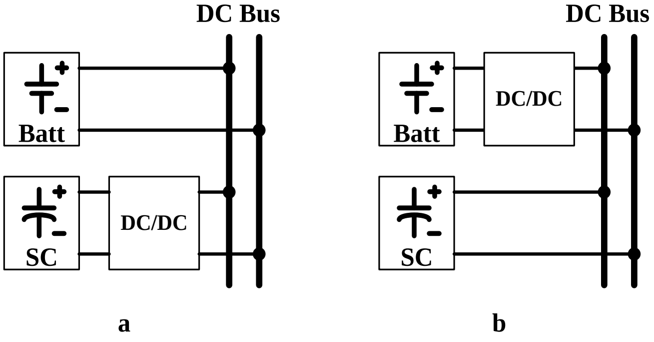


Fig. 3. *Semi-Active HESS Topologies*
a SC Semi-Active HESS Topology
b Battery Semi-Active HESS Topology

In Battery Semi-Active HESS configuration as shown in Fig. 3(b), the battery is isolated by DC/DC converter, while the SC is directly connected to DC Bus [24][60][61]. Unlike Passive or SC Semi-Active HESS topology, Battery Semi-Active HESS is friendly to the battery. The battery current can be maintained at a relatively gentler manner regardless of power demand fluctuations. Also, the terminal voltage is no longer required to match the DC Bus voltage, allowing the sizing and configuration of battery more flexible and efficient [62]. However, similar to Passive HESS topology, the volumetric efficiency of Battery Semi-Active HESS is low because most systems do not allow the SC to operate in its full SoC range. The linear charge/discharge characteristic of SC also causes large fluctuation in DC bus which may result in poor power quality and system stability. To maintain a relatively stable DC bus voltage, the SC needs to be extremely large which is not financially viable.

Though implementing active power flow control increases the manoeuvrability of HESS, it also comes with an increased system cost especially for the integration of the high power components of power electronic DC/DC converters [42].

2.3. Full Active HESS

In Full Active HESS topologies, the power exchange of battery and SC are both actively controlled via bidirectional DC/DC converters to further enhance the flexibility of the HESS and improve the overall system performance and cycle life [59]. Two of the most common Full Active HESS topologies are presented in this paper, namely Parallel Active HESS and Cascaded Active HESS as shown in Fig. 4.

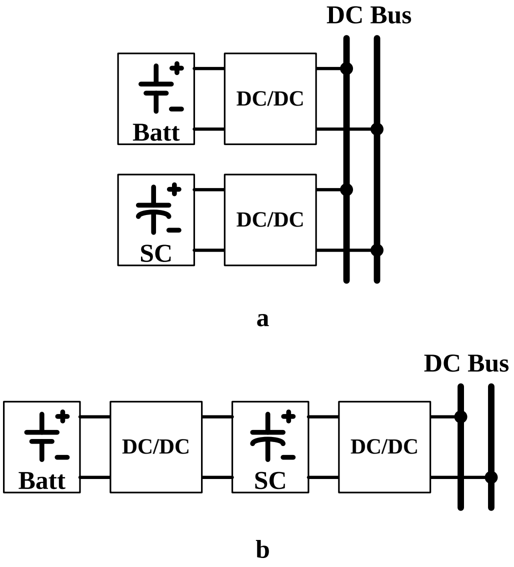


Fig. 4. *Active HESS Topologies*
a Parallel Active HESS Topology
b Cascaded Active HESS Topology

In Parallel Active HESS topology, the battery and SC are both decoupled from the DC bus by bidirectional DC/DC converters as shown in Fig. 4(a). Parallel Active HESS has been one of the most common topology for grid scaled storage applications which allows full control on both ESS elements [63]. With Parallel Active HESS topology, the performance, battery life and DC bus stability can be improved through carefully designed control strategy [64]. For instance, the battery, as high energy density ESS can be programmed to meet the low-frequency power exchange, while the SC is controlled to response to the high-frequency surge power. In addition, the DC/DC converters to maintain DC bus voltage stability can regulate the DC bus voltage. The decoupling of battery and SC allows both ESS elements to operate at a wider range of SoC that greatly improves the volumetric efficiency of the HESS.

In cascaded topology, two bidirectional DC/DC converters are cascaded to isolate the battery, SC and DC bus as illustrated in the Fig. 4(b) [65]. The bidirectional DC/DC converter that isolates the battery (left) is normally current controlled to provide smooth power exchange from the battery. This releases the battery from harsh charge/discharge process due to the intermittency of RESs and loads. The bidirectional DC/DC converter that interfaces the SC and DC bus (right) is voltage controlled to regulate the DC bus voltage while fulfilling the high frequency power variations [66]. Since the SC has wide operating voltage, a large voltage swing between the SC and DC bus is expected. As a result, the power losses in the DC/DC converter will be higher because it is difficult to maintain optimal efficiency within a wide range of SC voltage [65].

As the number of power converter increased, the overall coulombic efficiency of the HESS will also be reduced due to the power losses in power converters. The main disadvantage of Full Active HESS topologies is that the system operation is extremely reliant on the reliability of DC/DC converters and its control system. Full Active HESS topologies require sophisticated control algorithm to actively allocate power between ESS elements and maintain the stability of the grid at the same time.

3. Energy Management System

Although the hybridization of ESS elements of different characteristics has demonstrated great potential in complementing the limitations of homogenous ESS in MG applications, it also creates power management and control problems. Especially for HESS with actively controlled DC/DC converter(s), a properly designed EMS is the key in ensuring harmonised operation while achieving the objectives and control goals of HESS implementation.

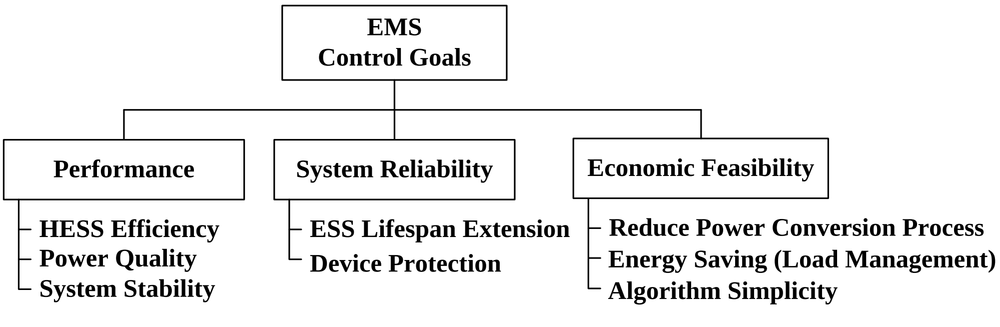


Fig. 5. *EMS Control Goals*

Generally, the objectives of HESS implementation in standalone MG systems can be classified into two main categories: (1) improving MG performance and (2) enhancing system reliability as shown in Fig. 5. For performance improvement, the roles of EMS are mainly to maximise the efficiency of the HESS such as volumetric efficiency, coulombic efficiency and system cost optimization, while maintaining system stability and power quality at the DC bus. On the other hand, EMS also plays an important role in ensuring robust system operation in all possible loading conditions, protecting the ESSs from extreme conditions and extending the useful lifetime of the ESSs. Additionally, economic factors are also important aspects that EMS needs to consider and optimize. Generally, the total economic cost will increase gradually in pace with the structure complexity of HESS from passive to fully active topology [49] .

However, a corresponding functionality of HESS will decrease accordingly. Considering the trade-off between the economic cost and functionality, the design of EMS requires addressing the economic feasibility before the overall system be the reality. In facing of surge current demand and renewable energy source intermittence, battery in HESS always needs to be charged/discharged immediately and then sooner be discharged/charged. The highly number of power conversion process of battery causes unnecessary energy waste which decreases the system efficiency and economic cost [67]. Similar problem also happens on the power electronic converters inside the topology [68]. Thus, mature EMS needs to address this problem and try to prevent the battery from the frequently power conversion process via the usage of SC. Secondly, the load forecasting or load management could be integrated into the EMS and it can effectively reduce the waste of electricity consumption due to the user poor habits. The last concern is about the EMS simplicity. The EMS with complex algorithm may lead to heavy computation task which requires high cost microprocessor. Moreover, due to complexity, it requires appropriate security structure to face the possible unstable conditions during the operation. Thus, it is important to maintain the simplicity of EMS.

Fig. 6 depicts a typical EMS structure for HESS in standalone MG applications. In general, the EMS can be divided into two levels: the low-level control system controls the current flowing in and out of ESSs based on the reference signal generated by high-level control and regulates the DC bus voltage. While high-level control system performs power allocation strategy, SoC monitoring and control and other sophisticated energy management strategies to achieve the above-mentioned control goals.

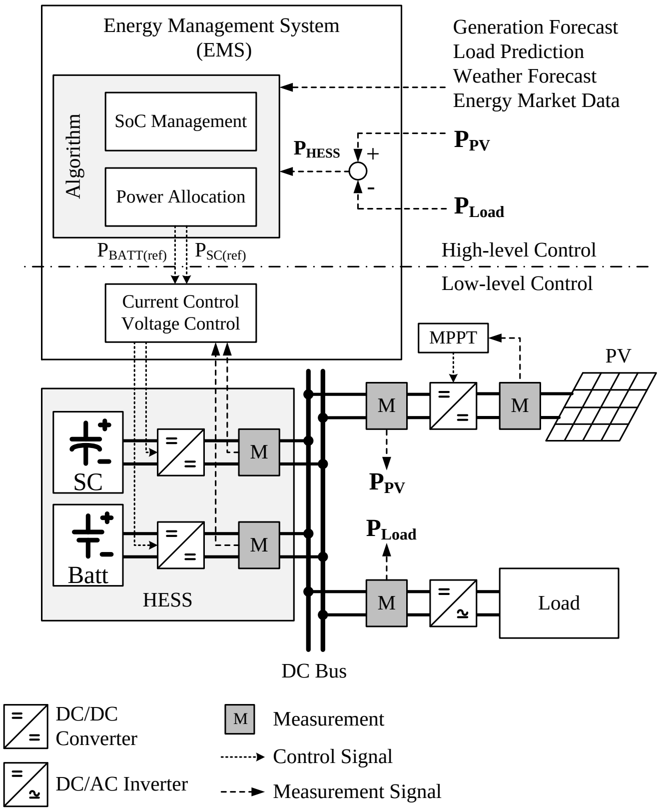


Fig. 6. Typical EMS Structure for Standalone PV DC Microgrid with Parallel Active HESS

Zhou et. al. adopted the parallel active topology and proposed a modular HESS scheme that splits the single battery bank into multiple smaller battery modules [69]. The SC module and battery bank modules are all interfaced to DC bus using Dual-Active-Bridge (DAB) DC/DC converters. The authors employed a linear filtering approach to remove high frequency power fluctuations and distribute the smoothed power demands to each battery modules based on their SoC level. The SC module will respond the high frequency power exchange though cascaded inner current control loop and outer voltage control loop. A simple SoC management scheme for SC module is implemented where the battery modules will charge the SC when the SoC level is lower than a pre-set threshold. The EMS mainly focused on balancing the charge/discharge current among different battery modules. But it neglects the impacts of battery SoC variation in long-term operation which may affect the system stability and longevity of the battery. Moreover, the proposed modular HESS topology requires a large number of DC/DC converters that dramatically increase the system loss and overall cost.

To address the issue of high charge/discharge rate and possible delay in converter's response, *Kollimalla et. al.* adopted the linear filtering approach to decouple the high and low frequency components of the power requirement and added a rate limiter to prevent high charge/discharge rate of the battery [63].

An additional compensator is implemented to compensate the slow response of battery charge/discharge. The proposed EMS mainly focuses to regulate the DC bus voltage and mitigate battery stress through limiting the battery current. However, the authors assumed that the ESSs work within the acceptable limits throughout the operation and do not take into consideration the SoC control of battery. This may cause the battery to experience deep discharge during extreme conditions which may lead to lifetime reduction of the battery.

Choi et. al. presented an EMS scheme in Battery-SC HESS to achieve two objectives: (1) to minimize the energy loss caused by the internal resistance of the SC and (2) to mitigate the fluctuation of current flowing in/out of the battery bank [33]. The author mathematically formulated the two objectives in order to obtain the optimal solution to control the current flow in each ESS elements. The two objectives were formulated into convex optimization problems which are norm approximation and penalty function approximation, respectively, and then they combined the two problems into a single multi-objectives function. In order to obtain the optimal solution, boundary parameters were found through Multiplicative-Increase-Additive-Decrease (MIAD) principle. The values of the boundary parameters critically determine the feasibility and optimality of the solution and the algorithm can adjust the boundary parameters effectively. However, the control strategy only considers the characteristics of ESSs and lacks the consideration of the interactions among the HESS and other components in MG. Thus, the optimal EMS scheme tends to be application oriented in the HESS and the specifically optimized solutions may only suitable for one specific system.

The aforementioned energy management strategies for HESS mainly focus on solving the short-term power demand variations and power sharing between SC and battery. However, the impacts of SoC drift in battery caused by long-term energy variations are not addressed. Specifically in renewable based MG applications, seasonal variations in renewable energy generation and load demand must be carefully addressed to ensure reliable operation in all possible loading conditions.

To accurately monitor the battery SoC and to address the long-term SoC variation, *Xue et. al.* proposed an actively controlled, parallel connected Lithium-ion battery and SC HESS in PV based system that employs a multimode fuzzy-logic power allocator to solve the problem of supply-demand mismatches [70]. Based on the batteries and SCs SoC conditions, the fuzzy-logic controller selects the appropriate operating mode to allocate power demand to the ESS elements. To avoid overly charging or discharging the ESSs, the controller allows the power exchange between the battery and SC and their individual power contribution can be optimally adjusted. The EMS control strategy guarantees all ESSs operate within their safe operating range and compensates transient mismatches among the generation and load.

Because most EMSs rely heavily on the centralised controller to manage the power flow among different ESSs and DC bus, possible malfunction in any communication link may result in severe consequences on ESSs and the entire system. To address this potential risk in centralised EMS structure, hierarchical controller architecture for HESS was proposed in [71] to protect the ESSs and to enhance the power quality and system reliability. In normal operating mode, the centralised controller allocates power to ESS modules based on their ramp rate, while assigns ESS with highest ramp rate to perform the voltage regulation. To protect the ESSs from over-charge/discharge, an autonomous SoC recovery algorithm is implemented to reassign appropriate ESS to take over the voltage regulation role. In the case where the centralised controller fails to work, distributed HESS control at individual ESSs will be activated to ensure stable MG operation. However, hierarchical control strategy requires heavy computations with complex structure and the EMS response time might affect the system control accuracy compares to conventional centralized control strategy.

Due to the complex and non-linear characteristics of battery and SC during the charging/discharging operation, simple power allocation method such as linear filtering via filter is not sufficient to allocate the power demand to the ESSs optimally that still can ensure the HESS performance and prolong their lifetime. Therefore, advanced supervisory control algorithm for the EMS is essential for operational optimizing of any HESS. A number of different intelligent and complex control algorithms, such as Deterministic Rule Based Strategy, Fuzzy Logic Control, Linear Programming, Genetic Algorithms, Dynamic Programming, Neural Network, Self-Adaptive Algorithms and etc., have been studied in the literatures [17][72][73]. Fig. 7 illustrates an overview of the basic classification of existing EMS algorithms in HESS energy management concept. The algorithms are generally distinguished into two classes which are Rule-Based approaches and Optimization-Based approaches [74][75][76].

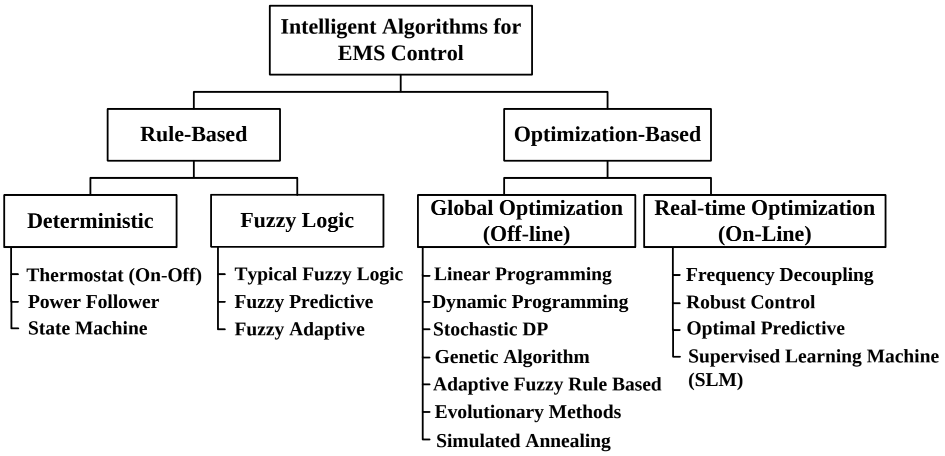


Fig. 7. *The Classification of Intelligent Algorithms for EMS Supervisory Control in HESS*

3.1. Rules-Based Approach

Rule-Based Approach controls the power exchange of HESS based on the specific integrated rules which are based on mathematical models, experts and experiences [77][78][79]. Rule-Based Approach is an effectively method for real time energy management which is widely used in HESS applications. In Thermostat Control Strategy, the battery operates with constant power at its optimal efficiency point and it will be turned off or on according to the SoC-threshold (lower or upper) which applied to the SC. In Power Follower Control Strategy, the battery can be set as the main energy storage and the EMS will adjust the battery charge/discharge power which follows the power demand. As a compensate ESS, the SC covers the difference between the power demand and battery response. Unlike the aforementioned two concepts, the State Machine Control Strategy allows multiple rules to control the power flow in HESS. The pre-defined rules can be designed based on the allowable upper and lower SoC limits of SC and battery, maximum charge and discharge rates, load and generation powers, etc. In pace with the real-time operation states of HESS, load and generation power, the algorithm selects the appropriate operation mode to optimize the power distribution between SC and battery. The Deterministic Rule-Based concept is widely used due to its simplicity, less computational intensive and reliability [77][80][81][82][83]. However, the rules are generally designed to execute power distribution among ESSs based on the initial model and optimal conditions which may not accurately reflect the actual conditions of HESS components in long run. A further improvement of this concept is the Fuzzy Logic Control Strategy. A simple flow chart is presented in Fig. 8.

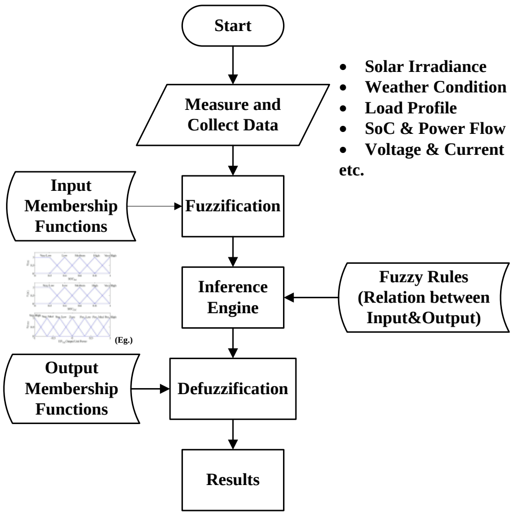


Fig. 8. *Fuzzy Logic Flowchart*

Similar to the previous deterministic concept, the rules still are defined on the basis of expert experience or heuristic. Nevertheless, the transition between different rules is achieved in a smoothing ways via the fuzzy-rules and membership functions and the tune action can easily help the HESS to achieve nearly optimal operation. Thus, compare to the Deterministic Rule-Based Approach, Fuzzy Rule-Based concept performs much smoother, flexible and logical [70][84][85][86]. Fuzzy Rule-Based Control Algorithms are widely applied in MG with HESS and it also is been integrated with other intelligent algorithms to form hybrid control strategy which achieves more optimal power performance in different HESS applications [87][88][89][90].

3.2. Optimization-Based Approach

To realize the optimal power distribution solutions in HESS, the Optimization-based Approach employs modern optimization algorithms. The available algorithms contains the Linear Programming (if the system is convex and could be mathematically represented via a set of linear functions), Dynamic Programming (DP) (both deterministic and stochastic), Evolutionary methods such as Genetic Algorithm (GA), Simulated Annealing (SA), and Particle Swarm Optimization (PSO) [91][92][93][94][95]. These algorithms can be divided into Global Optimization and Real-Time Optimization according to the off-line or in-line control. Unlike the Rule-Based group, modern optimization algorithms and their corresponding optimization process are all much more complex and require a significantly heavy computation capability and time consumption [74].

In Fig. 9(a), the flow chart of GA is illustrated. Based on the genetic process of biological organisms, GA can provide optimal solution to help EMS manage the power flow in the complex real HESS application. In GA, a series of meteorological conditions, constraints, and other corresponding data are collected before the start. According to the pre-defined fitness function, the percentage of selection and rate of mutation, the GA computes to provide an iterative procedure until a predefined termination criteria or maximum iteration number are reached. Fig. 9(b) presents a typical flow chart of DP algorithms [78]. Three iteration loops are designed to execute the backward iteration from time step N to 1. Every loop is employed to calculate the corresponding value as the flow chart shown. The Cost-To-Go function will be updated at each time step and the iterative procedure ends until the corresponding optimal solution of the objective function. One computation cycle will generate one state and the whole process can be called state iterations. Finally, DP will generate a Look-Up table that contains the optimal decision variable at each state and it helps the EMS effectively manage the power flow of the HESS. Similar to GA and DP, other algorism in Global Optimization concept all needs iterative process that requires heavy computation. The main feature or task of them is to minimize a cost function and the function is designed according to the related parameters, conditions, constraints of the system. Thus, the key in the utilization of Optimization-Based Approach is the accurate mathematical model of the ESS elements in HESS. Because most of the ESS elements are non-linear features, it is quite difficult to mathematically formulate the HESS model accurately over long period. In addition, due to the different industry production process and aging problems of the ESS elements, these unfavourable factors will increase the complexity of the overall system and reduce the system reliability and stability [96][97][98].

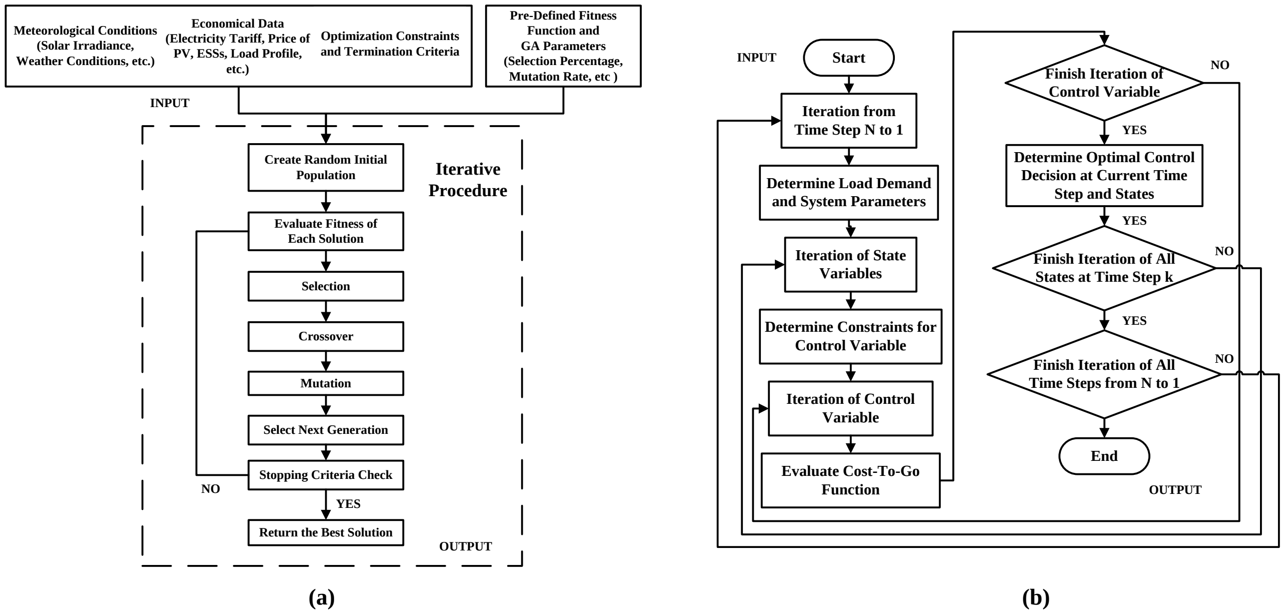


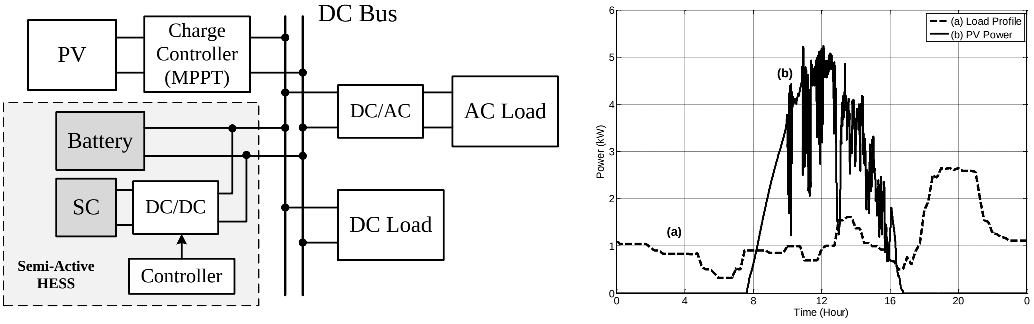
Fig. 9. Algorithm Examples of Global Optimization Approach
a Genetic Algorithm Flowchart
b Dynamic Programming Flowchart

In Real-time Optimization group, the Frequency Decoupling Control applies different filters to split the power into different frequency components and then EMS distributes the power among the ESSs in HESS. The Supervised Learning Machine (SLM) uses Support Vector Machine (SVM), power electronic switches and sensors to accurate control the HESS. It uses intelligent software instead of conventional hardware of power electronic topology which resulting a significant loss reduction from switching operation. In [99], the paper applied this idea and the results showed a 10.23% cost reduction.

For future trends of the HESS control algorithms development, a trade-off technological needs and economic feasibility requires to be considered. Advanced algorithms and their corresponding EMS can provide a high power quality and improves the system stability. However, the system complexity and component costs will upgrades accordingly. For the coming days, similar to the idea of HESS, the Hybrid Algorithms (HA) could be a desirable solution that combines different fundamental algorithms from the optimization approach, rule based approach to form complementary novel algorithms, and it can overcome aforementioned shortages. As a typical example in recent publication, [100] designed an Iterative-Pareto-Fuzzy algorithm to optimally control the autonomous MGs with HESS.

4. Case Study

Standalone Photovoltaic (PV) system is commonly used in rural settlements which are not connected to the grid. However, the intermittent nature of solar irradiance and the relatively large fluctuation in the load (when compared to the energy generated) may cause instability [22][101][34] and therefore limits the use of PV system. The use of energy storage system (ESS) could increase the reliability and efficiency of the system [31]. However, battery could perform a long lifetime in supplying steady charge/discharge demand and its cycle life will deteriorate significantly when it is subject to the PV outputs in a fluctuate way under different weather conditions. As mentioned before, in an islanded MG, the hybridization of ESS with different operation ramp rates minimize the DC bus variation and prolongs the battery lifetime in HESS. The SC is preferred to compensate the PV output variations which provide a steady state to the battery. Considering a standalone PV system with Battery-Supercapacitor HESS for a rural community in Sarawak, Malaysia (1°14’20.5”N, 112°02’10.7”E). Its topology is shown in Fig. 10(a). An actual local solar irradiance data for a typical partly cloudy day were recorded and is used to simulate the 5 kWp PV power generation system as shown in Fig. 10(b). The load profile was estimated based on survey data collected from the rural community which contains DC and AC load.

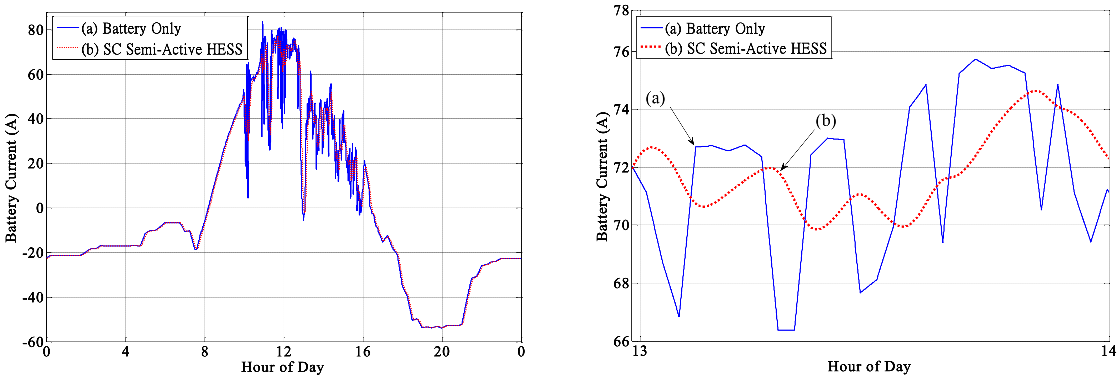


(a) (b)

Fig. 10. *Case Study Presentation*
a Standalone PV DC Microgrid with SC Semi-Active HESS
b 5 kWp PV Generation and Load Profile in a Day of Kuching, Sarawak, Malaysia

In order to fairly display the benefits of using HESS in PV standalone system, under the same PV power, battery capacity and load profile, a Battery-only and the Semi-Active HESS are simulated via

Matlab. Fig. 11(a) below shows the variation of the battery current in 24 hours and its enlarged view is illustrated in Fig. 11(b). Compared to the Battery-only case, the SC Semi-Active HESS delivers the stable battery current. The battery peak current also is reduced which helps in mitigating the battery stress.



(a)

(b)

Fig. 11. *Simulation Results*
a Battery Current
b Enlarged View of Battery Current

To validate the effectiveness of the SC Semi-Active HESS in mitigating the stress on battery, based on [102], a modified version of the cost function *Cost (T)* is derived which is shown as,

$$\mathrm{Cost}(T) = \sum_{t=0}^{T} n_1[i_b(t)]^2 + n_2\left|\frac{di_b(t)}{dt}\right| + n_3\big[\max\big(b(t)\big) - \min\big(b(t)\big)\big]^2 + n_4\left|\begin{array}{l} 1 \;\; ;\text{if } [i_b(t)\cdot i_b(t-1) < 0] \\ 0 \;\; ;\text{if } [i_b(t)\cdot i_b(t-1) \geq 0] \end{array}\right. + n_5$$

Where T is the total operating time, ib(t) stands for the battery current, b(t) means the SoC of battery, while n_1, n_2, n_3, n_4 and n_5 are positive constants. Five life-limiting factors are considered:

(1) Charge/Discharge Rate, it evaluates the battery operation rate as fast or slow;

(2) Dynamicity of battery current, it captures the effect of undesirable fluctuation in battery current;

(3) Depth-of-Discharge (DoD), it penalizes the impact of deep discharge;

(4) Charge/Discharge Transition, it considers the effect of cycling and

(5) Calendar life, it simply shows how long the battery could be expected to services which is always provided by producer.

The value of *Cost (T)* in some period can effectively displays the healthy deteriorate speed during the battery operation. Generally, the lower value of *Cost (T)* means friendly to the battery lifetime. Fig. 12 shows the results of *Cost (T)* in 24 hrs. The SC Semi-Active HESS performs lower around 33% than the Battery Only case, which indicates slower battery healthy deteriorate under similar operation condition.

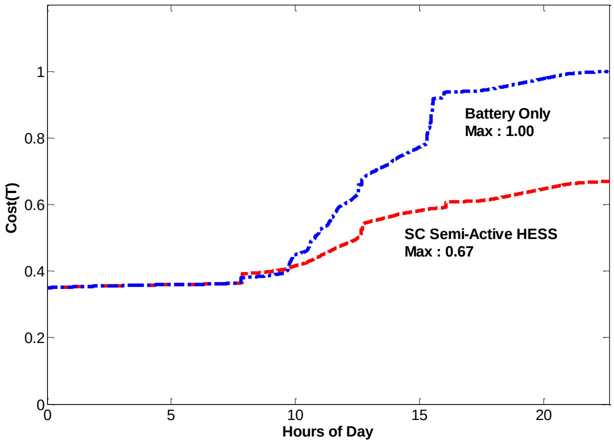


Fig. 12. *Cost Function Results through the day*

5. Analysis and Discussion

5.1. DC Microgrid Extension

In this paper, the aforementioned HESS configurations are all based on the DC bus. The renewable energy sources like PV topology generate DC electricity and it can be coupled directly to the DC bus. Under the help of DC/AC converters, the PV generation, AC or DC loads and HESS may form the DC MG. In rural area, the remote distance for connection to the grid and lack of advanced control hardware maintenance requires the power system to have a robust control solution [103] [104][105]. Due to the number reduction of DC/AC/DC power conversions like AC MG and the simply architecture, the DC MG becomes more popularized in rural area and it always is built in small power capacity [106] [107] [108] . In DC MG, the preferred HESS topologies are Passive and Semi-Active topologies. As presented before, the usage of power electronic converter may require more complex control algorithm which needs highly maintenance and economic cost [109].

As the century-long energy topology, in larger MGs, the AC bus still is required [44]. In Fig. 13, as the DC MGs extensive version, the architecture contains AC and DC buses and they all connected their own distributed sources and HESS [38] [94]. The connections of two buses are the interlinking converters. Apart from the islanded MG, as an optional function for the rural area future development, the MG can have the ability to connect the utility grid via AC bus. In DC-Coupled part, the control system just needs to modify the voltage and manage the power flow in HESS. The situation is different in AC bus, the EMS of HESS need to control the frequency and voltage simultaneously and transfer the energy between the DC and AC in bidirectional way. Moreover, in larger MG, the overall system performance such as power quality and system stability is more important than the rural area applications. Thus, for the AC-Coupled part, the Fully Active HESS will be the favour topology.

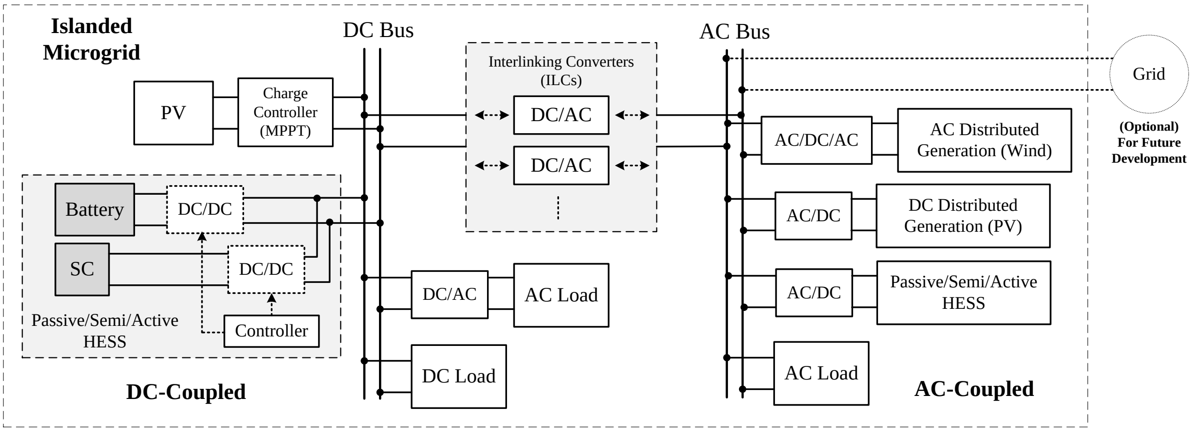


Fig. 13. *DC Microgrid Extension*

5.2. Topologies and EMS Discussion

From the literature, there are wide variety of HESS designs and control strategies used in the MG applications aiming to improve the MG operation in many different aspects. However, there is no single unique HESS solution for all MG systems. In fact, to determine an ideal HESS design and control strategy, a detailed analysis on the system requirements, end user expectations, physical/environmental constraints and both technical and economically feasibility have to be considered. Since the scope of this paper is to review HESS in standalone MGs, the following discussion and analysis will focus on off-grid MG systems, specifically for remote area applications.

From the literature review of HESS topologies and EMS control strategies, it can be concluded that most of the improvement efforts put on the ESSs are aiming to mitigate the stress on batteries while enhancing the performance of the MG, for example, maintaining the power quality, maximising the HESS efficiency and optimizing the cost of electricity. In order to achieve the set control targets, most researchers emphasized on developing better HESS topologies, enhancing the system performance and introducing sophisticated control strategies for EMS. As a result, the Full Active HESS topology is commonly used as it allows full control of the HESS in more dimensions. This, however, increases the system complexity and most importantly, creating additional uncertainty and making the MGs more vulnerable to components failures. The system will be highly relying on the DC/DC converters and its associated control system to guarantee reliable day-to-day operation. These drawbacks will be further intensified if the MGs are located in remote area where technical support is not conveniently available.

On the other hand, the passively connected HESS provides simple and robust way to mitigate battery stress at low cost while scarifying the efficiency and controllability. It can help the system to achieve stabilization due to the feature of passivation [110]. Theoretically, the passively connected battery-SC configuration works equivalently compared to a low-pass-filter. The smoothing effect on battery power exchange is purely determined by the SC capacity and internal resistances of battery and SC. The response time of the parallel-connected SC is typically in the range of seconds which is completely incapable of handling the fluctuations in the range of minutes that are commonly logged in RES integrations.

Especially for standalone MG in remote areas, system reliability and robustness should be prioritised while designing HESS to enhance battery lifespan [111]. Considering the effectiveness of stress mitigation and system robustness, the SC semi-active topology as depicted in Fig. 3(a) is the most suitable HESS solution for standalone MG applications. Because the capacity of battery in standalone MG is usually large, connecting the large battery bank passively to the DC bus ensures robust MG operation, while the actively controlled SC allows great volumetric efficiency and most importantly, capable of handling much wider range of power exchange fluctuations.

Apart from the three HESS topologies discussed above, there exist many other sophisticated HESS topologies and control strategies in the literature. In [15], the conventional centralized battery bank is divided into a distributed architecture based on microbank module with individual DC/DC converter and EMS for each module. Based on the battery recovery effect, a self-configurable control strategy was developed to combine the microbank modules dynamically in different configurations which the authors claimed to improve the energy efficiency in the system. Similar concept is also proposed in [112], the energy storage within the MG system consists of multiple banks of heterogeneous energy storage elements. As the smallest unit, the heterogeneous energy storage element consists of the battery and SC via properly designed charge management strategies. The global charge allocation algorithm will distribute an optimized power requirement to different heterogeneous energy storage banks and the maximum charge allocation efficiency will be utilized. In [113], it used two kinds of batteries and a SC to form the Full Active HESS and the modular boost multilevel buck converters were applied. Compared to single battery Full Active HESS, this HESS topology can be configured in many different capacity and optimal SoC management which prolongs the battery lifetime. Owing to the usage of power electronic converters, the HESS with reconfigurable, modular, multilevel characteristic could be one of the future development trends of power management system. However, it may not be suitable for standalone MG applications in remote area.

5.3. Limitations and Future Trends

RES based MGs need the ESS to overcome the shortages of intermittence and fluctuation. As the most popular and mature energy storage technology, the chemical battery with high energy density is the popular choice to play the ESS role in RES based MGs. However, the lifetime of battery is sensitive to its operation parameters such the charge/discharge rate, DoD, transition rates and etc which causes short service lifetime under unfriendly working conditions. Moreover, due to low power density, the battery also unable to response the high variation of power demand thus limits its usage. To compensate the battery weakness, the SC with high power density is involved to form the Battery-SC HESS. Thus, the key objective of Battery-SC HESS is to maintain the battery current as smooth as possible during operation and help the HESS response the variation power demand of RES based MG. For future trends, in the development of energy storage technology, the usage of mature long life service and novel battery technology will replace the Battery-SC HESS concept [114][115][116].

Before the advanced battery technologies become truth with valuable feasibility and practically, the concept of Battery-SC HESS still could be a charming choice for energy storage system in the application of MGs [117]. The research topics of Battery-SC HESS are mainly located on two parts, the topology design and its EMS design. For future development, to balance the trade-off of the economic feasibility and technological stills is main topic in the following research works. Generally, in rural area, its economic limitation and robust requirement make the Passive and Semi-Active HESS more suitable. The reduction of the power electronic converter usage will help the HESS achieve the features such as low cost, less control, robust and easy to control. In larger MG applications or utility applications, the Full-Active HESS will be widely used. The main limitations are the complex control structure and operation efficiency. Under the help of power electronic converters, novel HESS topologies and their relate EMS design could be the hot topic in future research. For example, in [67] , a storage bank topology was published and it can dynamic reconfigure the combination of battery. This kind of novel topology can accelerate the realization of the Smart Grid and Energy Internet Concepts [118][119][120].

In current publication works, the design of EMS varies in different applications and there is not a specific standard to evaluate its performance. Generally, different topology needs its specific EMS. Because of the usage of modern power electronic converters, the EMS mainly controls the power flow among different components via the microprocessor. Thus, the possible limitation or future research interest of EMS is how to design effectively algorithm with less computation and performs stability and robust with less bugs. As discussed in previous section, simple or single algorithm has its own advantages and disadvantage. Thus, for future development, the Hybrid Algorithm way should an uprising topic.

6. Conclusion

A critical literature review of the Battery-SC HESS in standalone MG applications was presented in this paper. The existing HESS topologies are categorised into three main groups which are Passive HESS, Semi-Active HESS and Full Active HESS. Their corresponding characteristics, advantages, disadvantages and possible applications were discussed and compared. Due to the actively controlled interfaces between ESS and DC bus, EMS is essential in managing the power flowing within the HESS for mitigating battery stress while maintaining high level of performance. Typical structure of EMS for Standalone PV MG application with multilevel control system was presented in this paper and the existing EMS was presented and compared. A cost function was applied to a sample standalone PV MG with SC Semi-Active HESS and it shows the benefit of HESS in the view of battery lifetime extension. The limitations and future trends in HESS is analysed and discussed.

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