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A review of hybrid energy storage systems in renewable energy applications

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Abstract

The use of Renewable Energy (RE) for onsite energy generation has recently increased. This is more commonly seen with the standalone system, as compared to grid connected. However, due to the unreliable nature of the Renewable Energy Sources (RES'S), various energy storage systems are available to balance the demand and supply gap. Nevertheless, hybrid energy storage systems are mostly recommended to accommodate the different characteristics, such as power density and reaction time, that accompany each specific storage. This work reviewed the available literature published on renewable energy-based hybrid storage systems for electric microgrids, applied to both standalone and grid connected systems in residential, commercial, and industrial use. Furthermore, various strategies and algorithms used for the optimal control and energy management of renewable energy-based hybrid storage systems are explored. Available gaps in the available literature and scope for future research related to energy management and control of renewable energy-based hybrid storage systems have as well been identified.

Keywords: renewable energy, electric microgrids, hybrid storage, energy control, review

1. Introduction

Over the past two decades, the use of renewable energy sources, such as solar, wind and hydropower, has significantly increased for electricity generation in both isolated and grid-connected applications [1]. These renewable energy sources (RES's) are environment friendly and may be deployed from micro to large scale as alternatives to fossil fuels [2]. One common challenge with the use of RES's, is their reliance on the variable resources and climatic conditions, making their power generation unreliable to continuously meet the load demand requirements, leading to excess or under generation [3]. Given the different and complementing characteristics, of various RES's, Hybrid Energy Systems (HES's) have been implemented to solve the imbalance problem between the load demand and the supply from RES's. These HES's may incorporate different RES's and/or Energy Storage Systems (ESS's), with the ability of increasing the available power supply [4]. With the existing energy sources as well as storage systems, different HES's topologies may be combined with generation and storage technologies, to assist with the power balance between the supply and the demand. Generally, isolated RES's employ Battery Storage System (BSS's) to solve the power imbalance problem between generation and supply [5]. Characteristics such as short production time and the ability to be easily deployed on any site that comes with batteries, influences this storage to be the storage system of choice for isolated RES's [6]. Nevertheless, more research gaps develop on which hybrid system to use as well as how to control the optimal power flow to cater for a specific load demand. In this review, various energy storage systems and their characteristics are explored as hybrid energy storage systems.

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2. Associated Hybrid Energy Storage Systems

2.1. Hydrogen (fuel-cell) and battery

In most cases, batteries are associated with solar Photovoltaic (PV) as an energy source due to its nature. However, the same theory is applied to the combination of PV with a hydrogen sub-system. The excess energy from solar PV is used to produce hydrogen to feed the fuel cell during high demand [7,8]. This influences the attention drawn by the hydrogen to be incorporated in solar powered micro grids [9]. Moreover, the two storage systems share the characteristic of being able to store solar energy for later use. However, they differ in most of their featured characteristics, such as high specific energy and reliability of the fuel cell as compared to the conventional battery [10-12]. Furthermore, long operation period and high durability, as opposed to the short operation and life expectancy of the battery [13]. Therefore, with the compliments of characteristics in both storages, as well as the slow dynamic response of a fuel cell, a reliable and efficient hybrid system may be achieved. More work based on the hybridisation of battery and hydrogen (fuel cell) is discussed below.

Ren et al [14] developed an optimization model that consist of a grid connected PV, fuel cell and the battery. The aim of the work was to find an operating and management strategy for the developed hybrid energy system, considering the economic and environmental factors. The system is said to be connected to the grid for the system to be able to sell the energy back to the grid and recharge the storage devices during cheap electricity pricing periods. Therefore, the results of this work reveal that having various storage technologies positively affect the load demand as well as using local grid electricity in consideration of ToU electricity pricing method. Using the same system components configuration, Nojovan et al [15] presented a performance improvement model of a hybrid energy system using information gap decision theory (IGDT) with consideration of the load uncertainty. The results of this work show that the uncertainty of the load may be solved by either spending more money to buy enough grid power or by a possible decrease in load while considering the system dependency on the total consumed load power.

Bruni et al [16] explored the effect of sizing and energy management on the environmental efficiency of a hybrid power system that comprises of PV with battery and fuel cell. From this work, the authors discovered that the use of renewable energy sources (RES's) is not affected by the management's strategy but by the sizing of the system components. The results also reflect on the improvement of the fuel cell's convention efficiency, as well as its life span due to proper choice of thresh hold voltage. Han et al [17] presented a hierarchical energy management system that features PV and battery-hydrogen energy storage device. With the system depending on the energy of a non-dispatchable renewable energy source, the electrolyzer is used to store the excess energy by producing hydrogen gas to fill the demand gap. Torreglosa et al [18] presented an energy dispatching model using model predictive control (MPC) for a standalone hybrid system, comprised of PV and wind as source of renewable energy generator. where battery and hydrogen are used as a storage device. The results of this work show a higher global efficiency of the modelled hybrid system, where the operating limits of both the battery state of charge (SOC) and hydrogen tank level are kept at the desired state. Khiareddine et al [13] presented a similar optimization model with the aim of sizing the system's components. The results of this work revealed an increase in life span of a battery as well as reduction on the cost of the system through hybrid energy sources.

Kamel et al [19] proposed a control strategy for an energy management of a DC microgrid. The PV was the only energy source, accompanied by fuel cell, battery and supercapacitor to operate as a hybrid storage system. In this work, the characteristics of the system's components ware used to the system's advantage. Based on the results the PV covers the load demand during day, while the fuel cell compensates the PV's failure to meet the load. This allows the battery to maintain a healthy SOC as well as the direct current voltage (VDC). Castaneda at al [20] presented a sizing method and control strategies for managing the energy of an off-grid hybrid energy system. The system integrated a battery and a hydrogen subsystem with PV as the source of Renewable energy (RE). The results of this work show that the system successfully meet the load energy demand while keeping healthy energy reserves in the battery as compared to using conventional battery and sole hydrogen system. Jalloulic and Krichen [21] analyzed generation management of an off-grid PV system with the aim of finding the best component sizes as well as choosing the most economical storage device to store excess energy should it be there. The hybrid energy system (HES) consists of a battery and a hydrogen subsystem. Considering the variable load demand as well as intermittent irradiation, the developed system's results give an optimal solution to the gap between generation and supply.

2.2. Battery and supercapacitor

Most of the PV powered micro grid systems are re-designed to feature a hybrid storage that consist of a battery with any other storage depending on the on the nature of the load or terrain, with the aim of improving the service life of the battery [22]. Apart from the hydrogen (fuel cell) and battery, there is supercapacitor storage system in the family of the electrochemical [23]. Unlike the fuel cell, the supercapacitor has a faster charge/discharge rate as well as high power density [24] and known to have longer life cycle as compared to the conventional battery [25]. Therefore, hybridization of supercapacitor and battery stands out due to its unique bus configurations i.e., four various topologies that are mostly used includes the basic parallel, passive, active and semi-active [26]. While some of these configurations are used to control the power flow as well as the voltage of the system, the passive topology is found to be the mostly used due to being cheap and easy to apply phenomenon. However, it come with drawbacks such as disability to control the power flow [22, 26]. More research has been conducted bellow, with different configuration being used to fit specific systems and scenarios.

Jing et al [22] presented a study of a battery-supercapacitor based hybrid energy storage system for a stand-alone PV powered system. This work discusses factors that affects the efficiency of a battery as well as different hybrid configurations to relieve the stress from the battery. With the use of a three level HESS configuration compared to both passive and semi active HESS. The results of this work reveal that the three-level configuration is the best solution for off-grid rural application. Using the same configuration, Chang et al [27] proposed an optimal control strategy with the aim of extending the battery's life span as well as reduction of the dynamic stress. In this work, a low pass filter was used together with fuzzy logic controller (FLC) instead of the usual filtration buffed controller or FLC alone. The results of this work show an improvement in the battery's life, while allowing the supper capacitor to operate within the healthy range of the SOC. Ma et al [26] developed a batter-supercapacitor energy storage with hybrid renewable energy sources (PV-wind). With the aim of accommodating long hours of charge/discharge as well as short peak power surges, the authors used passive configuration which as well prolongs the battery's life. Using the same renewable resources for an off-grid system with hybrid storage system (battery-supercapacitor).

Abdelkader [28] proposed a multi objective generic algorithm using a different approach of optimization with the aim of sizing the system components. Discrete Fourier transform is used to manage the frequency as well as the power supply system. Therefore, the simulation results prove the proposed algorithm to be the best option to explore renewable energies. Cabrane et al [29] have analysed the behaviour of a battery-supercapacitor hybrid energy storage system for PV installation. With the aim of reducing the battery's stress, the authors have explored all available configurations of a Battery-supercapacitor storage system. However, they opted for a fully active configuration to take advantage of the controllable voltage topology for both battery and capacitor. The results of this work show a decrease in the current charge/discharge rate as well as reduction on the battery's stress level.

A dynamic power allocation of a battery-supercapacitor energy storage system for an off-grid PV power system is proposed by Jing et al [24]. With the aim of solving the problem of charge/discharge stress of a battery, a novel hybrid storage system topology is used. The work was conducted with consideration of the financial and technical viability. The simulation results have shown that the proposed system may positively change the life span of the battery as well as lower the operating costs of the conventional PV-battery system.

2.3. Hydrogen and supercapacitor

The hybridization of fuel cell and supercapacitor has similar operation as that one of battery and fuel cell. In that kind of a configuration the fuel cell is used as a battery to store the renewable anergy when the resource is available and the capacitor to store excess generated energy to accommodate the high transients and rapid load fluctuations [30]. However, in some research work, the fuel cell is used as the source and the supercapacitor as the main storage to supply and absorb the power during load transients [31,32]. The integration of these two-energy storage systems obeys the required parameters of an energy storage system i.e., high energy and power density [33-39]. Where the fuel cell delivers high energy density and the capacitor with high power density [40]. Moreover, the main drawback of the fuel cell is its inability to respond fast to charging that is caused by limited power slope to further prevent fuel shortage and improve its service life. While the super-fast response of a supercapacitor compliments most of the fuel cell's characteristics [41]. The following reviews advocates for the mentioned principles as well as the configurations of the fuel cell-supercapacitor hybrid systems.

Luta and Royi [30], performed an optimal sizing of hybrid fuel cell with supercapacitor storage system for off-grid renewable applications using PV as the source of renewable energy. The authors choose the components sizes based on the system's technical feasibility and its cost effectiveness. The supercapacitor is used to cover the transient peak and rapid fluctuation demand; the results show how the integration of both systems will affect the overall cost of the proposed system. However, the system is found to be expensive to be implemented for a commercial load. Jayalakshmi et al [31] has as well used the same configuration with PV and Fuel cell as the main sources, the supercapacitor used as load power stabilizer in a power control hybrid system for stand-alone applications. Three control strategies are used i.e., maximum power produced tracker (MPPT) used for PV, inverter controller to regulate voltage and frequency variations as well as current control for total power balancing. The results of this work prove the control strategies to be positively effective on the voltage and frequency. Therefore, the end user receives constant voltage with less distorted frequency.

A hybrid power system based on fuel cell, photovoltaic and supercapacitor is proposed by Ferahtia et al [32]. With the aim of managing the power system to provide high quality energy to a variable load demand while considering fluctuating solar irradiance as well as the state of fuel cell. The SC was used for response to the peak transient period, the results of this work show that the DC bus voltage stability was achieved. Onar et al [41] proposed a dynamic modelling, design and simulation of a hybrid power generating system that comprises of wind turbine, fuel cell as well as a supercapacitor. The authors aimed to reduce voltage variation on the equipment. The system accommodates the variable energy generated by the wind by charging the fuel cell to meet the load demand. While the supercapacitor is used to meet the peak powers that are above the fuel cell limits. The system is recommended for stand-alone application as well as remote located areas with non-ideal wind speed since is found to be successfully accommodative to variable wind speed. Thounthong et al [40], proposed an energy management of a hybrid power source that is composed of fuel cell as the main source, solar PV, and supercapacitor as the storage device. The capacitor bank is charged by the fuel cell as well as the solar PV when the solar is available. To validate the proposed system, a test bench was developed. The results show an improvement in the system performance due to SC's fast response and controlled fuel cell.

Martin et al [42], analysed the energy and frequency of a microgrid based on fuel cell and supercapacitor. With the idea of replacing a lead acid battery as well as the size the components of the developed microgrid in the Navarre university laboratories. The complete system comprises of a wind turbine and PV hybrid renewable energy systems and a lead acid battery (which is to be replaced) as the storage device. The behaviour of the FC and SC was characterized under both steady state and dynamic modes of operation. Further comparison was made between sole use of FC and the combination of FC and SC. The results of this work prove the integrated storage system of FC and SC to be more efficient than the FC alone by at least 8.5%.

2.4. Battery and pumped hydro storage (PHS)

The current trend in the energy storage system research field has shown an increased interest in the use pumped hydro storage systems (PHSs). This ESS may be in two different setups known as open and closed loop as shown in figure…, requires low maintenance, has a long lifespan, can produce high energy density, is environment friendly and has high roundtrip conversion efficiency; these characteristics makes PHS well suited to support the fluctuation of RESs such as isolated hydrokinetic (HKT), PV and wind energy conversion systems [43-49]. However, some of the challenges observed when operating existing PHSs are the low power, which necessitates either large water flows and/or large net height between the upper and lower reservoirs, as well as the slow response rate when balancing lower power deficits [50]. Therefore, PHSs can be used in hybrid configurations with other ESSs to take advantage of the resultant energy storage capabilities and further support the stochastic power generated from RES. Like renewable energy systems, the different storage technologies currently available have their own technical properties. Therefore, they can also be combined in hybrid storage system (HSS) topologies this hybridization provides excellent characteristics which cannot be offered by a single ESS [51]. Many research works published in the last decade looked at the operation control of hybrid storage systems with topologies such as battery-supercapacitor, fuel cell-battery-supercapacitor, fuel cell-supercapacitor or battery-pumped hydro storage.

The subsequent compiled literature reveals that very few studies have analysed the optimal energy management of integrated PHSs with other ESSs to support RESs. Guezgouz et al [52] presented an energy management model for an HES composed of a PV and wind supported by a HSS (PHS-BES). The work opened a path to the concept of HSSs operating in conjunction with non-dispatchable RES's such as PV or wind supplying isolated loads. Bhayo et al [53] analysed a HES composed of a PV, a BSS, a hydro system and a PHS for optimal energy management, considering the excess generated power. The results have demonstrated that integrating a rainfall-based hydropower system with an optimally sized water storage situated at a specific net water head resulted in a substantial reduction of the PV size as compared to system without rainfall-based hydropower system. Javed et al [54] proposed a novel operating strategy for a hybrid PHS-BSS operating with an isolated RES. The results obtained based on energy output analysis have shown that during peak power demand periods, PHS comes into operation when the minimum SOC is almost reached, while low power shortages are met by the BSS. Abdelshafy et al [55] presented an energy management model to minimize the cost as well as the CO2 emissions of a grid-connected double storage system consisting of a PHS-BSS supplied by a HES. The research findings have demonstrated the techno-economic and environmental effectiveness of the proposed model.

Kumar and Biswas [56] studied the feasibility of combining a PHS and a BSS supplied by a PV. The results revealed that utilizing a small BSS with PHS can significantly reduce the upper reservoir size, which can subsequently decrease the excess energy generated. Ma et al. [57] analysed the combination of BSS and PHS for the RES suppling a microgrid in an isolated island in Hong Kong. Several options have been analysed i.e. advanced deep cycle BSS, conventional BSS, PHS without BSS, and PHS combined with BSS. Sensitivity analysis revealed that PHS becomes even more cost-effective by increasing the upper reservoir capacity. Bento et al [58] proposed an optimal dispatch model for a grid connected/stand-alone HES, supplying power to an industrial prosumer using a HES made of BSS and PHS. Different scenarios were analysed to highlight the techno-economic effectiveness of the developed model.

Hemmati and Saboori [59] reviewed the emergence of hybrid energy storage systems in renewable energy and transport application. The Authors focused on the concept, principles, control topology as well as management strategies. They have as well explored various energy storage categories to discover the suitable technology that can cover all the needs and ideal characteristics of renewable resources for optimization purposes. Therefore, hybridization remains the optimum solution to most system's reliability and efficiency problem.

Guezgouz et al [60] proposed an optimal hybrid pumped hydro-battery storage scheme for standalone renewable energy systems. With the grey wolf optimizer used as the sizing methodology, the results reveal an increase in reliability at a low cost. However, special attention is considered during design phase to accommodate the meteorological variations of the future. Bhayo et al [61] presented a power management optimization model of a hybrid solar PV-Battery with PHS system for off-grid electricity generation. Instead of the common PHS system with two reservoirs, this system features one storage tank that is fed by water from the roof and gutters. The system analysis was conducted with comparison of various configurations i.e., PV-battery-hydro, PV-battery-PHSs and PV-battery. The findings of the work show a reduction on the installed PV capacity by at least 13.12% from the conventional PV-battery configuration integrated with rainfall based hydro power. This system is recommended for tropical areas with climate of high potential of solar and rain annually. Abdelshafy et al [62] proposed a grid connected hybrid optimized energy management strategy powered by renewable energy resources (Wind-PV). The battery is used to store excess energy and meet the load demand when the PHS is defeated. The cost of the electricity is reduced by at least twenty-two percent, which as well affects the grid energy exchange by five percent of annual demand. The components sizes increase with an increase in load demand.

Kumar and Biwas [63] presented a techno-economic optimization of a standalone PV/PHS/Battery system for a low load demand. The authors prioritized sizing the components as well as optimizing the RES using the levelized cost of energy as the objective function at hundred percent reliability. Firefly algorithm and grey wolf optimization (GWO) method ware compared for sizing both the RES components as well as the storage system. The outcome of both performances exposes the GWO method as the best based on the cost of energy and system reliability. While on the other hand the overall results reveal that integrating a small battery bank with the PHS reduces the capacity of the upper reservoir as well as improving the power supply reliability by at least ten kilowatts. Zhao et al [64] proposed a hybrid electric hydro storage solution to remote located areas. With the idea of solving the energy and water crisis in remote locations that have enough solar. The system features solar PV as the RES, while the PHS system is used as support energy storage/generator as well as a water storage system. The results of this work concluded that the turbine generator works when there is not enough energy to charge the battery to a level of handling heavy load. That is, for as long as the battery can charge to safe working limits, then the turbine does not operate. Therefore, the PHS guarantees a reliable system operation.

Destro et al [65] designed components as well as optimized a system that features a hybrid storage sub-system. The system is comprised of PV, diesel engine and a reversible heat pump plus a boiler. Battery and PHS are used as storage. The authors used the PSO methodology to size the components and optimize the system operation. The performance of the traditional cooling system and that one of reversible pump ware compared, where the reversible heat pump was found to be more feasible by reducing the size of internal combustion engine and boiler. On the contrary, this solution increases the number of installed PV and required extra space for cooling tanks.

3. Conclusion and Recommendations

This paper reviewed the available literature published on the hybridization of various energy storage systems for electric microgrids applied to both standalone and grid connected systems. Based on the review conducted on the available publications on hybrid storage systems, the following were observed:

- With reference to the available energy storage systems, the PHS system has gained a lot of attention as a single storage due to its low maintenance, long life span and high energy density. However, it is accompanied by challenges such as low power density which makes it necessary to either have large water flow or large net height between the reservoirs.
- Hybrid energy storage systems are commonly known for electric vehicles rather than residential, commercial, and industrial areas. Therefore, many research works have concentrated on combinations such as battery-supercapacitor, fuel cell-battery and supercapacitor-fuel cell. However, the compiled literature reveals that a few studies have analysed optimal management of PHS integrated with other storage to support RES's in this area.
- Several studies have developed an optimal management algorithm of hybrid renewable energy systems to ensure optimal power flow. However, these studies considered optimal energy management solely

from economic perspective without the inclusion of optimal sizing as well.

- Several authors have analysed the use of hybrid renewable energy systems to improve load satisfaction with one energy storage device applied to a standalone system. However, due to the unreliable nature of the resource, a gap still exists between demand and supply.
- Other studies have concentrated on the use of hybrid energy storage system instead of single storage to improve the reliability of hybrid renewable system. This proved to improve the security of load supply for the standalone system. However, none of these studies have developed an optimal energy management and power control algorithm for a grid connected hybrid energy storage system applied to residential, commercial, and industrial areas.
- The hybrid energy storage system may positively enhance the reliability and resiliency of a microgrid system featuring a battery as part of the hybrid energy system as well as improve the life span of the battery since it depends on the number of charges and discharges.
- Majority of the studies develop energy management strategies in which they exclude sizing and operation control in their objective. Therefore, the combination is rarely analysed as a joint operation.
- Most of energy management systems usually do not obtain accurate results due to losses such as electrical, mechanical, hydraulic and precipitation which are not taken into consideration. Therefore, available literature demonstrates that considering precipitation as well as optimally sizing the water storage of a PHS may result in subsequent reduction in PV size as compared to a system that ignores such losses.

After reviewing the available content, it can be said that a hybrid energy storage system may be usefully considered for renewable energy based microgrid for application in either residential, commercial, and industrial area. While considering the behaviour of the storage system given the dynamics of the load and all system losses to achieve accurate results. Furthermore, several studies have developed an optimal energy management algorithms of hybrid renewable energy system to ensure optimal power flow. However, these studies considered optimal energy management solely from economical perspective without the inclusion of optimal sizing as well. Hence, to ensure optimal operation both technically and economically, the combination of both sizing and control optimization needs to be taken into consideration. Nevertheless, to improve the reliability of the hybrid renewable energy system, several studies have concentrated on the use of hybrid energy storage system instead of using single energy storage system. This proved to improve the security of load supply for the standalone system. However, none of these studies have developed an optimal energy management algorithm for a grid-connected hybrid energy storage system. Hence, to ensure optimal operation of a grid-connected hybrid energy storage system, an optimization approach needs to be developed to ensure optimal operation of the integrated short-term and long-term energy storage capacity devices. The reason being that the lifespan of the integrated storage devices is not the same.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Both authors contributed to the research and writing of the paper. Therefore, all authors have approved the final version.

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