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A review on battery charging and discharging control strategies: Application to renewable energy systems

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Abstract: Energy storage has become a fundamental component in renewable energy systems, especially those including batteries. However, during the charging and the discharging process, there are some parameters that are not controlled by the user. That uncontrolled working leads to aging of the batteries and a reduction of their life cycle. Therefore, it causes an early replacement. Different control methods have been developed with the goal of protecting the battery and extending its life expectancy, being the most used the constant current-constant voltage. However, several studies show that charging time can be reduced by using Fuzzy Logic Control or Model Predictive Control. Other benefits are; temperature control and an extension of life expectancy. For all these reasons, FLC and MPC have proven to be more efficient than traditional charge control methods.

Keywords: Energy storage; battery; control; energy management systems; FLC; MPC.

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1. Introduction

Electrification of remote and rural isolated areas with the national grid is not always possible due to the prohibitive costs. Therefore, many off-the-grid communities have been using diesel engines as the main power source. To meet the energy needs, governments have opted for the installation of independent renewable energy systems with battery energy storage systems (BESS) [1]. However, energy storage is one of the greatest challenges for renewable energy systems, especially in stand-alone solar photovoltaic system and wind farms, where the application of electrochemical energy storage demonstrates high response times and round-trip efficiencies [2]. Moreover, from an economical point of view, in a solar photovoltaic system, the energy storage system (ESS) represents 40% of the total cost [3 – 4].

Storage technologies are usually categorized based on time scale of applications such as instantaneous (less than a few seconds), short term (less than a few minutes), mid-term (less than a few hours), and long-term (days) [5]. Moreover of the BESS there are different types of energy storage technologies [5 – 12]: pumped hydro energy storage (PHES), compressed air energy storage (CAES), flywheel energy storage (FES), hydrogen-based Energy Storage System (HES), flow battery energy storage (FBES), superconducting magnetic energy storage (SME), and supercapacitor energy storage (SES). However, because of their localization flexibility, efficiency, scalability, and other appealing features [13], the BESS is the preferred technology [14], (see Fig. 1).

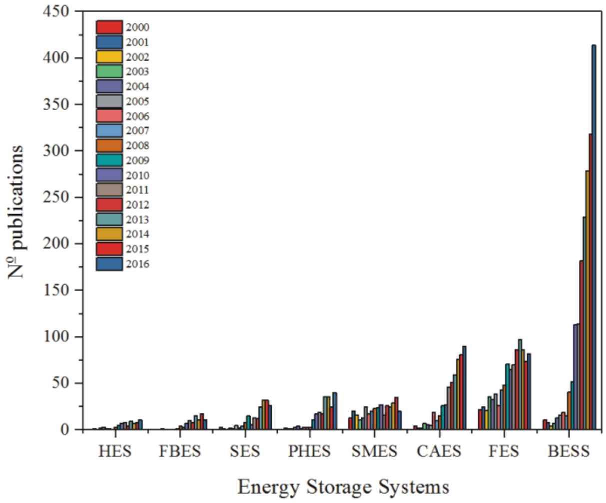

Fig. 1. Energy storage systems (ESS).

At present, there are numerous commercial batteries used in renewable energy systems, such as: lead acid, lithium ion (Li-ion), nickel cadmium (Ni-Cd), sodium sulfur (Na-S), among other. Table 1 shows the main characteristics of this type of batteries [6, 8 – 12, 15-20].

Characteristics	Pb-Acid	Li-Ion	Ni-Cd	Na-S	PSB	VRB
Capital cost (\$/kWh)	400 [6, 12], 200-400 [8, 9, 20], 50-150 [17]	2500 [6,12], 600-2500 [8, 9, 20], 900-1300 [17]	800-1500 [6, 9, 10, 20], 1500 [11], 400-2400 [17]	300-500 [6, 9, 10, 20], 500 [11], 200-600 [17]	300-1000 [17], 150-1000 [20]	150-1000 [9, 20], 600 [17]
Efficiency (%)	70-90 [6,12], 75-80 [8], 70-92 [8], 70-80 [17], 80-90 [18]	85-90 [6,12], 85-90 [9], 75-95 [17], 85-95 [18]	60-65 [6,12], 60-70 [9], 70 [17]	80-90 [6,12], 75-85 [8], 75-90 [9], 75-89 [17], 71-90 [18]	60-65 [11], 60-75 [17]	65-85 [9,17]
Operating temperature (^{0}C)	-5 to 40 [17]	-30 to 60 [17]	-40 to 50 [14]	325 [17]	0 to 40 [17]	0 to 40 [17]
Depth of discharge (%-DOD)	60-70 [8], 70 [17]	80 [17]	100 [17]	60-80 [7], 100 [17]	75 [17]	75 [17]
Energy density (Wh/kg)	30-50 [6, 9, 10, 12], 35-50 [17]	75-200 [6, 10, 12], 75-250 [9], 100-200 [17]	50-75 [6, 9, 10, 12], 30-80 [17]	150-240 [6, 9, 10, 12], 100-175 [17]	>400 [17]	10-75 [9], 10-30 [10], 30-50 [17]
Life cycles (cycles)	500-1200 [9], 500-1000 [10,20], 2000 [12], 500-2000 [17,18]	1000-10000 [9, 11, 20], 4500 [13], 1500-3500 [17], 1000-30000 [18]	1000-2500 [9], 2000-2500 [10, 20], 3000 [12], 3500 [17]	2000-5000 [9], 2500 [10, 17, 20], 4500 [12], 2500-5000 [18]	100-13000 [17]	13000+ [9], 12000+ [10, 20], 100-13000 [17]
Lifetime (years)	5-15 [6, 9, 10, 12, 17, 18, 20], 5-8 [8], 3-12 [19]	5-15 [6, 10, 12, 18, 20], 5-20 [9], 14-16 [17]	10-20 [6, 10, 12, 17, 20], 5-20 [9], 15-20 [19]	10-15 [6, 8, 10, 12, 20], 15 [9], 10-20 [17], 5-15 [18]	10-15 [10, 20], 15 [17]	10-20 [9, 17], 5-10 [10, 20]
Availability (%)	99,99 [9]	97+ [9]	99+ [9]	Up to 99,98 [9]	*****	96-99 [9]
Technological maturity level (1-lower to 5-higher)	5 [9]	4 [9]	4 [9]	4 [9]	*****	3 [9]
Response time (ms)	Fast [6, 12]	Fast [6, 12]	Fast [6, 12]	Fast [6, 12]	*****	*****
Capacity (MW)	0-40 [6, 12]; 0,001-50 [9]; 0,001-40 [17]	0,1 [6, 12]; 0,1-50 [9]; 0,001-50 [17]	0-40 [6, 12]; 0-46 [9]; 6,75 [17]	0,05-8 [6, 12]; 0,05-34 [9]; 0,4-244,8 [17]	0,005-120 [17]	0,005-1,5 [9]; 2-120 [17]

Table 1. Battery technologies in RES.

Regarding BESS used in photovoltaic systems, lead-acid is the most used technology [10, 16], due to its low cost, maturity, high reliability, fast response and low self-discharge rate [10, 21]. However, charging process is non-linear [22].

Due to the high economic cost generated by the replacement of a BESS, a charge control method and control strategy is required to protect the battery from overcharging and over-discharging [23]. The efficiency of charge control methods will depend on the amount of current used for the charging process, the level of the oscillations in the charging current, the charging voltage levels, the charging time, and the fluctuations in the temperature during the charging process [24]. Moreover, there are battery parameters such as charging rate, the permitted maximum charging current, the internal resistor, the port voltage, the temperature and humidity that changing during the charging and discharging process and cannot be directly obtained, so it is difficult to achieve the optimal operation performance by using traditional control methods.

This paper compiles the traditional control methods used to control the charging and discharging of lead-acid batteries commonly used in renewable energy systems such as solar photovoltaic and wind power. Although lithium iron phosphate ($LiFePO_4$) batteries are being used in renewable energy systems, they will not be included in this paper.

Regarding battery management systems, our research focused on Fuzzy Logic Control (FLC) and Model Predictive Control (MPC) due to the leading role in the battery control (Fig. 2). Where the power input can be supplied by the grid, a photovoltaic system or wind power system.

Fuzzy Logic Control (FLC) and Model Predictive Control (MPC) have proven to have higher performance than traditional charging control methods in terms of energy management, thus improving charging time, charging efficiency, states of charge (SOC) and life battery expectancy. The strategies used, goals, and the results reached with these controls are detailed.

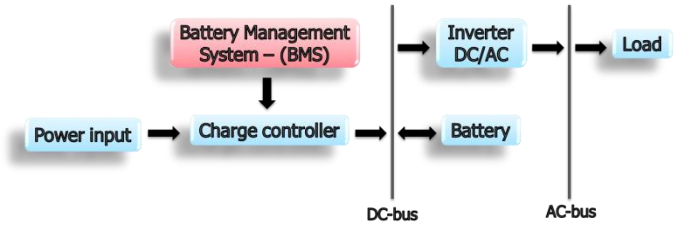

Fig. 2. Battery control scheme.

The paper is structured as follows: Section 2 describes the traditional methods used to control the charge and discharge of batteries, the time and the state of charge reached. Section 3 the strategies, and the fields where the FLC and MPC controls have been applied. The obtained results are presented and discussion in Section 4. Section 5 concludes by stating possible avenues for future research while summarizing the papers principle contributions.

2. Traditional charging control methods

The main goal of a charge control method is to increase the SOC. Moreover, additional specifications such as battery performance, charging time, protecting the battery from overcharging and over-discharging, and increasing its useful life are needed too.

As battery charging process is non-linear [22], different methods have been developed to effectively battery charging control. Control methods commonly used in battery charging are: constant current (CC), constant voltage (CV), two-step charging (CC-CV), pulse charging (PC), reflex charging or negative pulse charging (NPC), trickle charge or taper-current (TC) and float charge (FC) [25-27].

2.1. Constant current (CC*)*: this method consists of charging the battery with a constant current. This method limits the current to prevent the over current of the initial charge [28]. The voltage value will depend on the charging current whereas the charging time and the SOC can be easily calculated [29]. As voltage is not usually controlled, this can cause battery overcharging and temperature rising, resulting in the degradation of battery life [25, 27].

2.2. Constant voltage (CV***):*** it is used to charge the battery by applying a constant voltage on its terminals. During the initial stage of charging the charge current is high. As the battery voltage reaches the charger voltage setting, the charging current decreases [27]. This type of control is used in applications that require extended charging periods to reach full charge. As it requires a long charging time, this will cause temperature rises and degradation of the battery life.

2.3. Constant current – Constant voltage (CC-CV): this charging method is also known as the two-step method, because it combines both CC and CV. CC is applied at the initial charging stage until the battery voltage reaches an over-charged stage or a pre-defined voltage. In the second stage, the charging method switches to CV to maintain the battery voltage, so it avoids overvoltage [25, 29].

Research shows that, the CC-CV charging method is the most efficient for battery charging regardless of the battery type [30]. Also, it is the most used control method [31-33]. However, charging speed and efficiency of the CC-CV charging strategy are very low [34]. Moreover, the CC-CV is not suitable for rapid charging, because the CV charging stage extends the charging time, it rises the battery temperature, and it reduces battery lifecycle [35-36].

2.4. Pulse charging (PC): this charging method consists of periodically applying a pulse current to the battery. Batteries are completely discharged and recharged periodically in what is called an equalizing charge [37]. This will allow the battery voltage to become more stable. In this charging method, it is important to take into account the charging frequency, pulse peak and pulse width, because they are related to the capacity and the charging time. This method it can reduce the polarization to prevent the battery temperature rise [28], is the weak point of this charging method is its complexity.

2.5. Reflex charging or negative pulse charging (NPC): this is an improvement on the PC. The concept of applying a reflex charging started with the patents by W. Burkett & J. Bigbee and W. Burkett & R. Jackson [29, 38] in 1971. NPC consist of performing the following charging sequence: a positive charging pulse, a rest period (no charging), and a discharge pulse (burp) [38]. This method can reduce the polarization to prevent the battery temperature from rising. However, it also may reduce the charge efficiency [39-40].

2.6. Trickle charge or taper-current (TC): A trickle charge is a continuous CC charge at a low (about C/100) rate, which is used to maintain the battery in a fully charged condition. IT is designed to compensate the self-discharge of the battery [37]. This method can charge the battery up to 100% by using a very small charge current. This method is typically used for

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SLI (Starting Lighting, Ignition SLI) battery applications but it is not suitable for batteries that are susceptible to be damaged from over-charging.

2.7. Float charge (FC): this method involves a CV charge after the charge process has been completed in which the capacity of the battery is maintained at its maximum value against self-discharge [41]. This method is used for stationary batteries mainly lead acid batteries [37].

These traditional charging control methods have been incorporated in commercial inverters such as Victron Energy, sunny island of SMA solar technology among others. The latter controls the charge of the battery in three phases: CC (I phase/bulk phase), CV phase (absorption phase/Vo phase), and float charge/V phase (Fig. 3).

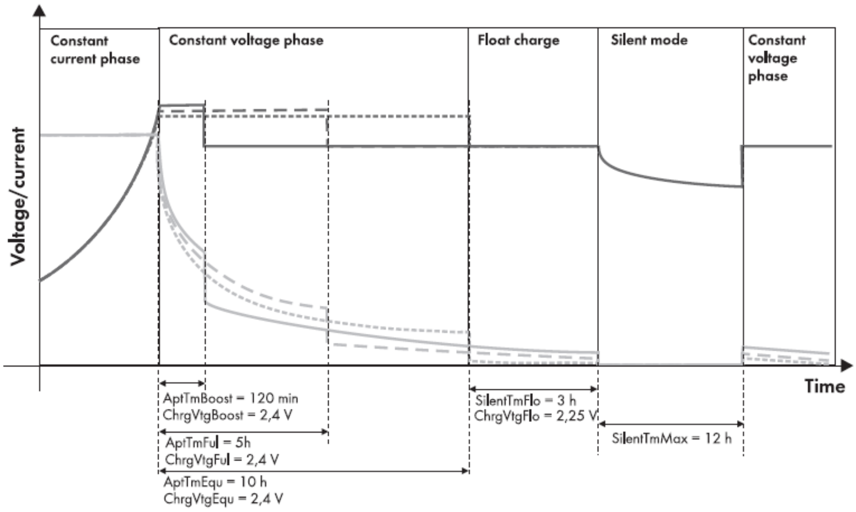

Fig. 3. Sunny Island charging phases with sample values for an AGM battery [42].

3. Battery management systems

As the process of battery charging and discharging is complex, it required the design of a robust supervisory control over the classic controller presented in section 2.

FLC and MPC are especially suitable to battery charging management because they do not requiring precise knowledge of mathematical system models and they have high flexibility.

3.1. Fuzzy logic control (FLC)

In 1965, Lotfi Zadeh first proposed fuzzy theory [43]. Between the applications of fuzzy logic, fuzzy control (FC) has been one of the fields where fuzzy techniques have obtained greater amount of successful results when they work with complex nonlinear systems or even nonanalytic ones [44-45].

FLC is composed by a knowledge base, which incorporates the information given by the operator of the controlled process following some linguistic control rules pattern [46].

In general terms, the input variables used in a FLC are battery voltage and temperature, and the output membership function generates current.

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3.1.1. Fuzzy Logic Control of Energy Storage Systems in stand-alone applications

A FLC was developed by Bandara et al. [24] to charge a lead acid battery. The FLC charges the battery at two stages. At the first stage, it uses a high current that charges the battery until 70% of its full capacity. At the second stage, the battery voltage is maintained at a set value and the current is left to decrease exponentially. Rahim et al. [47] showed a battery charger with a digital signal processor which included FLC as a control algorithm. This approach produced a higher charging current and it supported a higher input supplies. Thus, the charging time could be reduced.

Huang et al. [48] used a single crystal processor as the basic controller and a digital signal processor to get the feedback of the voltages, temperature, and current of the batteries. This approach allowed them to lower the battery temperature about four degrees. Kim et al [49] proposed a fuzzy PID controller to improve the frequency control performance of microgrid islanded. The control strategy was based on primary control action of the BESS and a secondary control action of the energy management system. The control is composed of FLC and a conventional PI controller, connected in series. The gains of conventional PI controller and fuzzy PID controller were determined by the PSO algorithm. The showed simulation that with the proposed control, the performance is improved compared to a conventional PI.

Welch et al. [50] showed that using particle swarm optimization (PSO) the optimized FLC achieves performed better by 26.13% in energy usage than un-optimized FLC. The charge strategy was improved about 5.22% respect to [51]. Fu-shun et al. [52] observed that using a PIC6014 microcontroller as control core in the design of the FLC, the battery charge time is reduced two hours compared to the three stage control method. Swathika et al. [53] show that using a FLC the voltage of the battery can be controlled effectively than with a conventional controller. Also, the ISE (Integral of Square Error), IAE (Integral of the Absolute value of the Error) and settling time can be reduced considerably in comparison to a PI control. Safari et al. [54] developed an optimized FLC based on the particle swarm optimization (PSO) algorithm. In the control design took into account the weekly operation and maintenance (O&M) costs and the loss of power supply probability (LPSP). The results of the simulation showed that optimized FLC reduces fluctuations in batteries SOC extending life battery expectancy. Moreover, can be lowered O&M costs and LPSP by 57% and 33%, respectively and average SOC can be increased by 6.18%. Reducing the investment cost by up to 18% in the capacity of autonomous hybrid green power system (HGPS) equipment. Improving what was presented in [50]. Berrazouane et al. [55] adopts the idea of an optimized FLC but, contrary to [50] and [54] use cuckoo search (CS). The CS was used to adjust the shape of the system membership functions of FLC to achieve a better performance instead of using a conventional FLC or optimized FLC based on PSO algorithm. The results of the simulation showed that with the proposed control loss of power supply probability, excess energy, and levelized energy cost the results were improved compared to optimized FLC based on PSO or a non-optimized FLC.

3.1.2. Fuzzy Logic Control of energy storage systems in grid connected applications

Yin et al. [22] divided the charging process into two stages. At the first stage, they implemented a fuzzy control to determine the proper start charging time and to prevent overcharging or

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insufficiently battery charging. At the second stage, they used the normal charging method. However, during the simulation, the temperature was not taken into account in the inner loop of the control unit.

Contrary to [49], Haoran et al. [56] take into account the SOC of the BESS in the control of the microgrid where the FLC was used to maintain the SOC of the BESS above a certain level and to mitigate the fluctuation. Thus, the FLC adjusts the active power output reference of the BESS based on the SOC and the target active power for the grid-connected operation. In island mode, the FLC adjusts the active power output reference of the BESS based on the SOC and the active power command for frequency control. Arcos-Aviles et al. [57] divided its strategy into two stages: At the first stages, it minimizes the power peaks and fluctuations in the grid power profile and it maintains the lead-acid battery SOC above 70%. At the second stages, it performs an off-line optimization process based on a set of evaluation quality criteria. With to simple moving average strategy the proposed control reduced maxima and minimum grid power in 61% and 15% %, respectively, and 53% and 4%, respectively, with respect to the fuzzy based on microgrid net power trend. The strategy proposed by Derrouazin et al. [58] consisted in leading to optimal use of available energy resources beyond a threshold to withstand the load demand, giving priority to the highest source of power, while enough available energy is routed directly to the battery through a charging/discharging regulator system. This allowed them to have improved energy efficiency about 7% compared with the classical FLC. Paliwal et al. [59] reveal that incorporating battery charging efficiency as a battery SOC function offers a more practical approach to system planning. Also, conclude that assuming a constant value of efficiency can hamper the efforts to come up optimum system, because the charging efficiency obtained can be higher or lower than the constant assumed value affecting charging power drawn by storage and consequently the energy availability in the battery. Teo et al. [60] design a control based on Fuzzy Inference System (FIS) to determine the charging/discharging rate of the ESS depending on the RES and current SOC of the ESS. Power variation range (PVR), power quality (PQ) and battery dynamic range (BDR) were the quality indices they took into account to evaluate the effectiveness of the proposed fuzzy controller. The maximum and minimum power of the grid was reduced. Hussain et al. [61] proposed a control strategy were where the controller decides the mode of BESS operation: subservient mode, resilient mode or in emergency mode. In subservient mode, the BESS is fully controlled by the EMS while in resilient mode minimize the operation cost of the microgrid. The goal of the emergency mode operation is minimize the load shedding during the emergency period. Respect to the latter, load shedding can be reduced by 92%.

3.2. Model predictive control (MPC)

Model Predictive Control (MPC) is an advanced control method which provides the sequence of optimal control variables over a finite time horizon by solving an optimization problem. Therefore it is widely used in many fields [62-69].

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3.2.1. Model Predictive Control of Energy Storage System in stand-alone applications

Perez et al. [70] designed a control that anticipates the future saturations of the ESS. The MPC allowed the system to reduce its power production during the first hours. To obtain the optimal performance of the battery Pezeshki et al. [71] focus on two goals: Energy operational cost and smooth loading.

Based on a nonlinear model predictive control (NMPC), Dizqah et al [72], developed an energy management strategy that manages the energy flow across a standalone DC microgrid. The NMPC continuously solves an optimal control problem (OCP) and finds the optimum values of the pitch angle and three switching duty cycles. The control had three main goals: voltage level regulation, proportional power sharing, and battery management. While Morstyn [73] used a convex formulation of the DC microgrid dynamic optimal power flow problem. It is, based on a static voltage-current model and linear power flow approximations. Simulations were made on a real-time digital simulator (RTDS) which used non-linear battery models and switching converter models. In [74] this method does not assume that real and reactive power flows are decoupled; allowing line losses, voltage constraints, and converter current constraints have been addressed. The simulation was carried out in real time for an islanded microgrid based on the IEEE 13 bus prototypical feeder, with distributed li-ion BESS and intermittent PV generation. The computational time was reduced by a factor of 1000.

Kujundžić et al. [75] used a full-state observer to solve that problem some states of the model cannot be directly measured. Also, resort to converting the model to a non-minimal state space form which uses the plant input and outputs as state variables. Added additional constraints to the MPC problem to keep the voltage of every battery below the upper threshold voltage level provided by the manufacturer. This caused the MPC algorithm to decrease the charging current. Causing a slower charging compared to a standard MPC method. The algorithm was validated on a valve regulated lead acid (VRLA) battery through simulation tests and experimentally. An advantage of using MPC algorithm with respect to CC-CV method was its ability to take into account the constraints on the maximum temperature and the maximum voltage of individual batteries. While Zeng et al [76] proposed combine an MPC and hierarchical optimization to maximize the RES generation and to minimize the variations between the intraday schedule and day-ahead schedule. This combination facilitated the integration between BESS and RES. The goal was to maximize output using appropriate charging and discharging control strategy for ESS based on the prediction of renewable power output, demand and network capability in future time horizon. The method was applied as a case study to the modified IEEE-30 bus test system and northwest power grid of China. Li et al. [77] presented a BESS control algorithms based on MPC to mitigate wind power intermittency. The MPC algorithm considers two practical aspects: the efficiency loss of BESS and the smoothness in wind power scheduling. They compare performance between the horizon-based revised MPC and the instantaneous heuristic algorithm, and came to the conclusion that MPC shows the best performance.

3.2.2. Model Predictive Control of energy storage system in grid connected applications

A control system based on MPC was proposed by Khalid et al. [78] for the reliable operation of the BESS for primary frequency regulation. A frequency predictor was used to optimize the performance of the controller using multi-step ahead predictions. Two scenarios were presented. A first scenario where the BESS operation was adjusted between 40% to 80% and a second one where the BESS was adjusted between 10% to 50%. In the first case, the maximum battery SOC was reached at ~17 min, while the minimum battery SOC was reached at ~70 min. In the second case, the maximum battery SOC was reached at ~80 min, while the minimum battery SOC was reached at ~12 min.

Ferrarini et al. [79] developed a MPC to store energy that was not used by a building and to deliver it when the building load requires it, instead of buying it from the grid. Two MPC controls were designed: the building MPC and the battery MPC. The goal of the building MPC was to optimize the temperature control. Additionally, the battery MPC had as main goal to minimize the power flow at point of common coupling (PCC). The PCC power flow was successfully maintained around 50% value until the battery reaches a SOC of 90%. Wang et al. [80] used a MPC to optimize and distribute the PNM prosperity energy storage project in New Mexico. The storage system was divided into two BESS units, a large slower moving unit for energy shifting and arbitrage and a small rapid charging unit for smoothing. The first goal was to provide energy arbitrage and to smooth the intermittent output from the PV array. Additionally, the second goal was to minimize the excessive charge-discharge cycles of the BESS units. Petrollese et al. [81] proposed EMS based on Optimal Generation Scheduling (OGS) combined with Model Predictive Control (MPC), which optimizes the short-term microgrid operation. The OGS was used to compare the expected power produced by the renewable generators with the expected load demand for the following days and determines the scheduling and evolution of the state of charge of the different energy storage systems for the next few hours to minimize the operating cost of the overall microgrid. The MPC has goal of the real-time control in order to guarantee the stability of the microgrid. A stochastic approach was implemented to weather and load forecasting uncertainties. By working simultaneously the OGS and MPC, the computational load is reduced as achieved in [74].

Matthiss et al. [82] used an MPC to maintain high levels of self-consumption, reduce the peak feed-in power for improved grid compatibility and to minimize energy costs. Four battery charge algorithms were implemented: charge at the earliest opportunity, linear delayed charging, peak shaving, and a model predictive control (MPC). Additionally, energy prizing was used as an additional parameter to the optimization process. The results show that using a MPC the use of wind energy is improved by 35% and the energy costs could be reduced about 25%.

4. Results and discussion

This research shows that in renewable energy systems with battery energy storage the most used control method for controlling the charging and discharging of lead acid batteries is CC-CV. However, this control requires a long time to charge the battery. This prolongation in the charging time generates battery temperature rises, so it produces battery irreversible damages. Moreover, during the process of battery charging and discharging, traditional controls leave some aspects uncontrolled.

In order to solve these events, simulations and, in some cases, experimental tests with FLC and MPC are being carried out. Generally, these controls are being used in the energy management of stand-alone microgrids and grid connected microgrids. These controls have been proven to be more efficient than a traditional control. Fig.

4 shows some results achieved using FLC or MPC in renewable energy systems with batteries energy storage. When comparing these results with a traditional control, we have found some advantages. The load shedding can be reduced up to 92%; the implementation of these controls, allows maintaining the SOC above 50%, thus avoiding deep discharges that lead to the deterioration of the battery. Through energy optimum use, the maximum and minimum power of the grid can be reduced by 61% and 15% respectively. This rational and efficient use of energy allows reducing microgrid energy costs by 25%. Also, the operation and maintenance and loss of power supply probability can be lowered around 57% and 33% respectively. Regarding to energy storage system in batteries, the charging time is reduced about 40%, which leads to a decrease in temperature about 26% and a reduction of the investment cost in energy storage capacity about 18%. So, it allowed some approaches to extend the life expectancy around 5%.

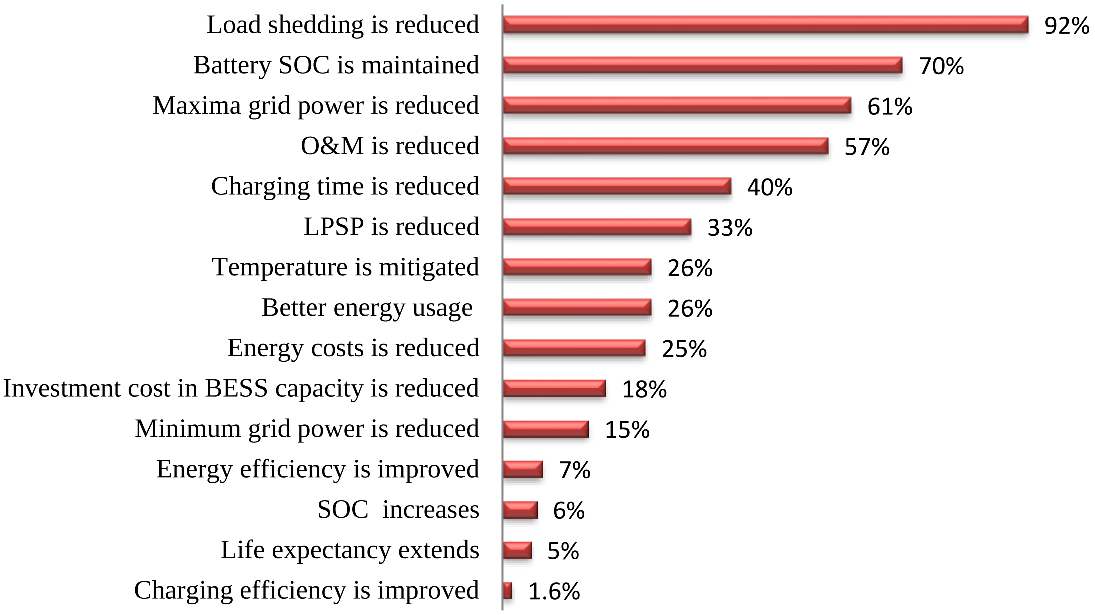

Fig. 4. Main advantages of FLC or MPC with respect to traditional controls methods.

Despite the advantages of FLC and MPC controllers compared to traditional controls, it is required an implementation of these types of controls in real environments with large-scale energy storage systems, because many of the results have been achieved through simulation. Moreover, parameters such as dynamic selection of battery SOC limits and the influence of ambient variables such as relative humidity or SOH prediction were not studied. Finally, these controls are also being implemented to control the charging of lithium iron phosphate ($LiFePO_4$) batteries as shown in [83-85].

5. Conclusions and future work

Renewable energy systems have been a short-term solution in the mitigation of energy needs in isolated areas where there is no energy service grid connected. Many of these systems have battery energy storage to giving energy in those hours where natural resources such as sun or wind are not present. In in a connected microgrid, the BESS is used to minimize active power exchange at the point of common coupling of the microgrid.

A control and control strategy is required to optimize the energy management and to avoid overcharging and overdischarging in the energy storage system. Despite of being the constant-current constant-voltage (CC-CV)

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the most used control method for battery charging and discharging, other method such as FLC or MPC have shown better performances. The main benefits are: reduced charging time, improved charging efficiency, mitigation of the temperature rises, and maintenance of the battery SOC within secure limits. Moreover, they reduce of the investment cost in energy storage capacity and they extend the life expectancy.

Most of the papers consulted based their results on simulations and in some cases on experimental tests with VRLA batteries. Therefore, much more real experiments are needed to extend the conclusion to real systems.

The extension to other types of batteries such as OPzS lead-acid batteries and lithium iron phosphate ($LiFePO_4$) batteries is also a hot research topic. However, the high cost of $LiFePO_4$ batteries becomes a constraint for large-scale implementations in RES.

Future work will focus on experimental application of FLC and MPC in the energy management of a grid-connected system located in Departamento del Chocó – Colombia (in Spanish).

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