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Harmonic compensation from battery energy storage systems (BESS)

Compensación de armónicos a partir de sistemas de almacenamiento con baterías

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Abstract

Non-conventional renewable energies (NCRE) are increasing their percentage of participation in the country's energy matrix every day, mainly due to the need to reduce CO_2 emissions. However, the intermittent nature of the NCRE requires the integration of energy storage systems to ensure the availability of the resource at any time and place. Although batteries are commonly used in these applications, these batteries significantly contribute to the overall system cost. The inclusion of NCRE, as well as the connection of various linear and non-linear loads in the electrical system generates power quality issues, such as harmonics. Considering the above and as a strategy to justify the cost of the system, it is possible to use the batteries charging and discharging process as an alternative to solve those previously mentioned power quality issues. In this article, the use of battery energy storage systems (BESS) is examined as a preliminary solution to reduce these phenomena. The study is based on test cases where modifications are made to the load requirement and the rated capacity of the battery. The results show that through these modifications it is possible to achieve a significant improvement in power quality, reducing total harmonic distortion (THD) effectively.

Keywords: battery energy storage system; harmonics; microgrid; power quality.

Resumen

Las fuentes no convencionales de energía renovable (FNCER) cada día incrementan su porcentaje de participación en la matriz energética del país, principalmente por la necesidad de reducir las emisiones de CO2. Debido a la naturaleza intermitente de las FNCER, es necesario integrar sistemas de almacenamiento de energía para garantizar la disponibilidad del recurso en cualquier momento y lugar. Las baterías son los dispositivos que se usan con mayor frecuencia en estas aplicaciones, sin embargo, incrementan sustancialmente el costo del sistema. La inclusión de FNCER, así como la conexión de diversas cargas lineales y no lineales en el sistema eléctrico generan problemas de

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calidad de la potencia tales como los armónicos. Considerando lo anterior y como una estrategia para justificar el costo del sistema de almacenamiento de energía, es posible buscar alternativas para mitigar armónicos a partir del proceso de carga y descarga de las baterías. En este artículo, se analiza el uso de sistemas de almacenamiento de energía basados en baterías como una solución preliminar para mitigar estos fenómenos. El estudio se basa en casos de prueba donde se realizan modificaciones en la exigencia de carga y la capacidad nominal de la batería. Los resultados demuestran que mediante estas modificaciones se logra alcanzar una mejora significativa en la calidad de la potencia, reduciendo la distorsión armónica (THD) de manera efectiva.

Palabras clave: armónicos; calidad de la potencia; microrredes; sistema de almacenamiento con baterías.

1. Introduction

Renewable energy sources have high significance in current times due to their contribution to the reduction of carbon dioxide (CO_2) and the strengthening of the country's energy matrix. These sources, that are usually photovoltaic and wind power, form energy local grids by means of power electronic systems that are incorporated into the energy system of the country. The inclusion of new sources changes the system dynamic, in this sense, the system stability is affected and the sensitivity to power quality issues is increased [1]. Another aspect to bear in mind is the intermittent nature of such sources, in this way, systems for energy storage must be incorporated [2]. Currently, Battery Energy Storage Systems (BESS) are predominantly used, mainly with lithium-ion batteries. The inclusion of batteries allows to increase the energy resource availability. However, it also substantially increases the cost of the microgrid, for this reason, on one hand, it becomes necessary to optimize the use of the battery to prolong its lifespan and on the other to use the battery on complementary services in addition to the energy storage ones. The complementary service of greater impact in the grid is the solution of power quality problems [3], in this case, different authors have made research to use BESS systems. One of the application trends is the mitigation of voltage sags. Castilla and collaborators develop a mitigation strategy from the injection of reactives from the battery in function of the positive and negative sequence components [4]. In the same line, Xie develops a battery storage system (BESS) and a Superconducting Magnetic Energy Storage System, (SMES) [5]. Other authors have approached sag mitigation from the compensation in sequence with Dynamic Voltage Restorers (DVR) [6]–[9]. Solutions directed to the effect mitigation of current harmonics are highlighted as well [10]–[13] by using the battery as an active harmonic filter. These authors demonstrate the viability of BESS as an ancillary service in the grid, instead of implementing two independent systems, a single system can improve the power quality and the energy resource availability from sources with an intermittent nature. This allows the cost and complexity of the final system to be reduced.

Considering the different contributions in the state of the art and the need to assess the contribution of the battery in the mitigation of power quality problems, in this project the preliminary analysis of the compensation system performance is presented in parallel with supply by means of battery application in low voltage systems.

2. Methodology

The target of this article is to make a preliminary analysis of a system for harmonic mitigation from a Battery Energy Storage System (BESS). To do so, different control strategies with intelligible frameworks are incorporated.

The proposed system is composed of three key components. First, a battery bank is chosen which acts as an energy storage system, allowing the injection and absorption of reactives into the electric grid. Secondly, a DC - AC converter is picked out which allows the interaction between the battery and the grid. In this project, a DC - AC converter, two - level three - phase bridge will be used. Thirdly, a LCL filter is chosen to filter out the high frequency components in voltage waveform and output current of the DC - AC converter. The second and third components attached to the battery fulfill the role of shunt active power filter (SAPF) [14]. PQ theory is used to identify the references currents, which provides possibility for controlling the currents injected at the grid. In the electric grid, two types of loads are connected in parallel: a PQ load and a harmonic content load. The PQ load with active components (P) and reactives (Q) in the energy consumption, corresponding to the performance of a RL load. The harmonic content load introduces distortions into the electric grid. This configuration consists of a source of direct current connected to a three-phase rectifier, being a common application the connection of a constant current engine. The whole configuration of the system can be observed in Figure 1.

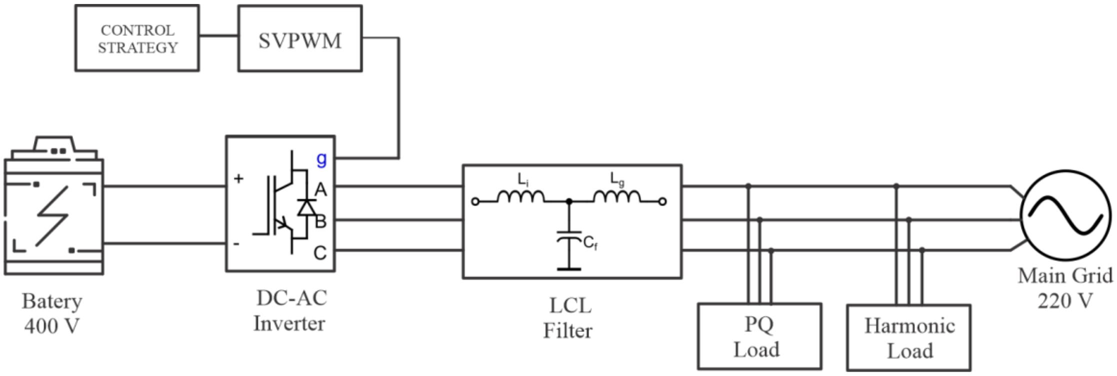

Figure 1: Design of BESS system proposed.

2.1. Reference frames and transformations

The framework proposed by O'Rourke et al [13] to simplify the mathematical process in the implementation of a PQ control strategy by means of the transformation of electric variables are used.

The conversion of the three-phase variable framework to fixed variables is made by means of Clarke Transform [15]–[17]. The three-phase system control is simplified by getting a DC reference in a synchronous framework by means of the use of Park Transform [15].

2.2. Control Strategy Design

Two control loops are designed, one is internal and the other, external so as to control the current and power (active and reactive). In this process, the signals V_{ABC} and I_{ABC} are directly measured from the three-phase grid of Figure 1. Akagis PQ theory [18] and the strategy for harmonic compensation generated by the connected loads to the electric grid are applied.

2.2.1. Internal control loop

The internal loop is a control loop that allows control of the current components (Figure 2). It has a feedback voltage that increases the DC - AC converter output impedance and decreases the probability of resonant harmonics. The system uses the rotating frameworks (d-q) in the input parameters, the PQ reference signal generated by the external control is compared to the current components measured in the three-phase grid (I_{ABC}) and the current signals measured in the load (I_{ABC} LOAD).

The proportional controller receives the error signal as input by combining it with the voltage and the three-phase grid frequency to generate the output signal.

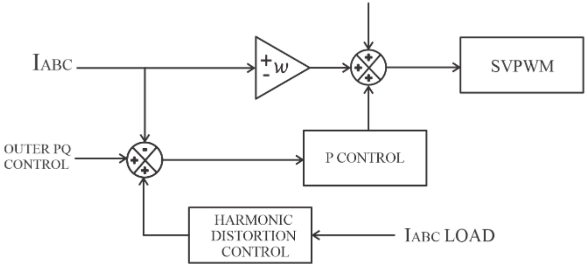

Figure 2: Internal control loop scheme.

2.2.2. External Control Loop

The PQ external control loop allows control of active and reactive power independently. The instantaneous powers are calculated in real time in the three-phase electric grid and they are employed as reference by means of Akagis PQ theory [18], the equations (1) and (2) allow to determine the active and reactive power reference:

$$P = \frac{3}{2}(V_d i_d + V_q i_q) \qquad (1)$$

$$Q = \frac{3}{2}(V_q i_d - V_d i_q) \qquad (2)$$

The PQ control, shown in Figure 3, guarantees that the controlled parameters of the system do not present permanent state error.

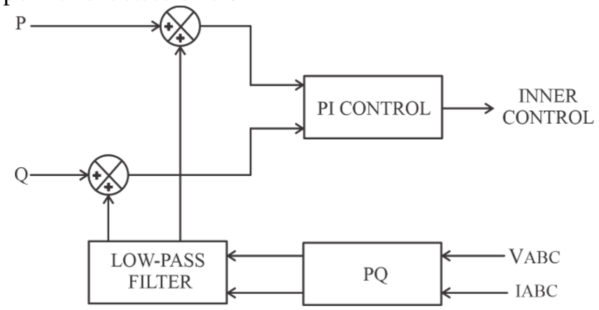

Figure 3: External control loop scheme.

2.2.3. SVPWM

From the internal and external loop control signals, the activating and blocking commands of the DC - AC converter transistors must be generated. In this case Space Vector Pulse Width Modulation (SVPWM) is used by using as input variables the voltage in a fixed framework α β.

In SVPWM, the DC-AC converter is controlled by means of eight possible commutation states that involve every branch [4]. From the eight available vectors, a vectorial diagram with a 60% separation is traced, including two null vectors in the center aiming to generate the desired voltage in the converter output, controlling the duration and the frequency of the voltage pulses [5]. The SVPWM technique allows to obtain a high-quality output signal with low harmonic distortion, assuring an efficient operation of the converter.

2.3. LCL filter

The high frequency voltage components and those of the DC - AC output current converter is dimmed by means of a LCL Filter (Figure 4) located between the converter and the three-phase grid as it is observed in Figure 1.

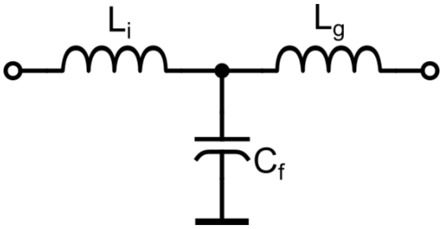

Figure 4: LCL filter topology.

The filter design is made to smooth current waveforms and voltage signals [19]. For the design, the parameters of Table 1 must be had in mind.

Table 1. LCL filter design parameters

Design parameters	
Grid voltage	220 V
Rated battery voltage	400 V
Grid frequency	60 Hz
Commutation frequency	10 kHz
Converter output power	1 kW

The design is made with the following mathematical [20]:

The inductance next to the converter is calculated by means of equation 3.

$$L_i = \frac{V_{DC}}{16 \cdot f_{switcheo} \cdot \Delta I_{L-max}} \tag{3}$$

Current fluctuation is limited to a maximum of 10% represented by ΔI_{L-max}:

$$\Delta I_{L-max} = 0.01 \frac{P_{outinversor} \cdot \sqrt{2}}{V_{red}} \tag{4}$$

The capacitor has been designed having in mind the fact that the electric grid accepts a maximum power variation of 5%.

$$C_f = \frac{0.05 \cdot P_{outinversor}}{V_{red}^2 \cdot \omega_{red}} \tag{5}$$

Finally, the inductance by the grid's side L_g is calculated:

$$L_g = r . L_i \tag{6}$$

In Table 2, the obtained values for the system filter design are presented.

Table 2. LCL filter design

LCL filter parameters	
Component	Value
L_i	3.9 mH
L_g	2.34 mH
C_F	10 µF

Figure 5 shows the Bode diagram of the designed LCL filter.

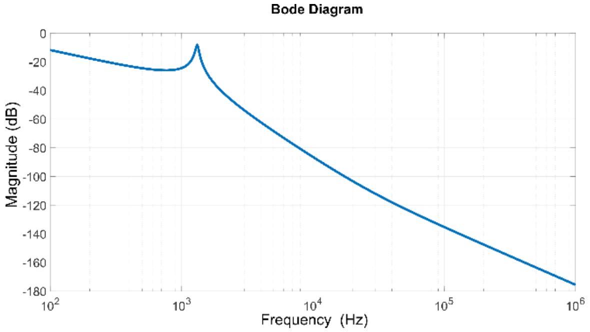

Figure 5: Magnitude Bode diagram of LCL filter.

3. Results

Two test cases in the three-phase system with a rated voltage of 220 V were conducted for BESS systems in the power quality phenomena mitigation of the grid.

At MATLAB Simulink, a battery model including the data of a commercial battery with a rated capacity of 63 Ah (10 A) [16], [21]

Initially in the harmonic load, a current source of 10 A was used. In the PQ load, an active power of 1 kW and a reactive power of 200 VA were adopted. As measurements of reference, the results shown in Figure 6 and Figure 7 were obtained:

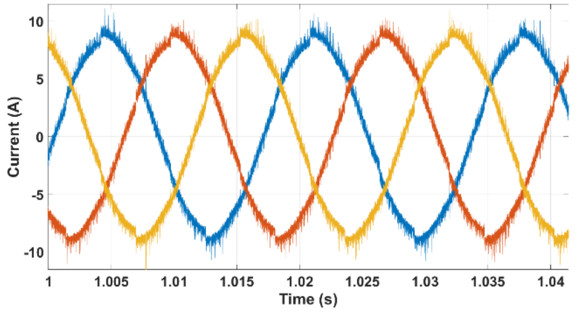

Figure 6: Current waveforms in the electric grid.

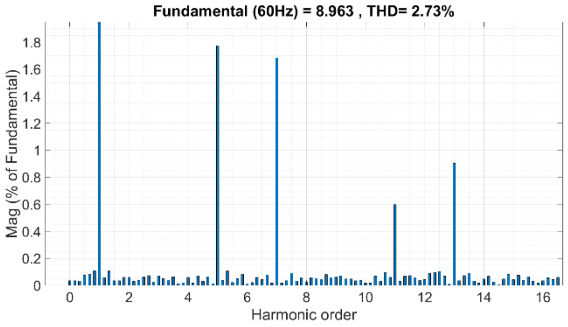

Figure 7: Harmonic spectrum of the current in the electric grid.

Current THD (Total Harmonic Distortion) measurements in the grid are analyzed in both test cases, just as the percentage of the existing harmonic components in the current signal regarding fundamental components. Figure 8 shows the current wave measured at the equivalent load (PQ load + harmonic load), with its deformation. Figure 9 shows the output current waveforms of the DC - AC converter.

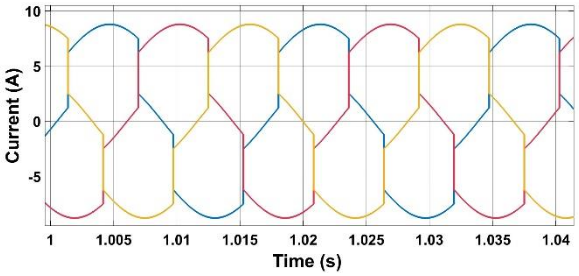

Figure 8: Current waveforms in the equivalent load.

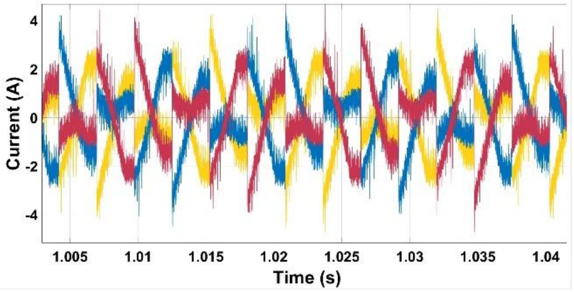

Figure 9: Output current waveforms of the DC - AC converter.

3.1. First Case

In the first test case, variations in the load requirements are performed to know the system performance. Specially, variations in the load with harmonic content were carried out by sequentially increasing the current requirement. The portrayal of the first test case is presented in Table 3.

Table 3. Test Case 1, load requirement variation

Current load (A)	**%THD**	**Harmonic %5**	**Harmonic %7**
10	2.73	1.7735	1.6837
20	4.6002	2.7953	1.9691
30	6.5637	4.1411	2.8968
50	10.3411	6.5678	4.6309

Initially, a load requirement of 10 A is applied, which resulted in a THD less than 3%. As the current requirement in the load increases, a slight increment in the percentage of harmonic distortion reflected in the electric grid is observed. In particular, fifth order harmonics prevailed followed by those of seventh order.
The obtained results show that the control system is able to efficiently mitigate the harmonic distortion phenomenon in the electric grid, thus warranting an optimum level of energy quality in presence of variations in current demand.

3.2. Second case

Variations were made from the rated capacity of the battery reference to assess their impact in the system performance. Table 4 presents the results of the second case. The first column shows the variation in rated capacity of the battery, while the other columns contain the THD and the magnitude of the fifth and seventh harmonics, expressed as a percentage of the fundamental signal.

Rated capacity (Ah)	**%THD**	**Harmonic %5**	**Harmonic %7**
1	4.98	4.1471	1.6378
5	4.39	2.9472	1.8791
10	4.31	2.8581	1.9392
63	2.73	1.7735	1.6837

Table 4. Test case 2, rated capacity variations.

In the second test case, a different situation is observed from the one of the first case in some aspects, as shown in Table 4. With the rated capacity of the battery reference (63 Ah) is obtained a low THD in the grid. However, as the rated capacity of the battery decreases, a slight increment in the harmonic distortion is produced and which is reflected in the grid. The demand variation in the load was not significant, but it was enough to remark its effects in the signal.

As in the first case, fifth order harmonics were identified as the predominant ones followed by the seventh order harmonics. The results highlighted the importance to consider the rated capacity of the battery in presence of harmonics in the grid. To tackle this situation, it may be considered the incorporation of renewable energy sources as a solution to compensate for the necessary energy capacity for the system.

4. Conclusions

This article proposes a system to mitigate phenomena related to power quality in the electric grid. So as to achieve it, the use of energy storage systems based on batteries has been proposed and also specific control strategies have been implemented.
The analysis made in the test cases provided information about power quality performance regarding different variables. A slight harmonic distortion increment was observed in the first test case, as the current load increased. On the other hand, a fact was discovered in the second test case, as the rated capacity of the battery decreases, a slight increment in the harmonic distortion was produced.
It is important to carry out additional tests in different cases with the incorporation of new energy sources to get a more complete and precise assessment of the system performance. Nevertheless, the obtained results so far suggest that the system allows to acceptably mitigate power quality problems in spite of harmonic distortion variations in the electric grid in response to current demand and rated capacity changes in the battery.

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6. Conflict of interest

The authors of this project express there is no conflict of interest, be it economical, professional, or personal ones that might have inadequate influence on the obtained results during the research.

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