Control to SMES using a Two Level Converter (2LC) and Neutral Point Clamped (NPC).

Control para SMES usando un convertidor de dos niveles (2LC) y un convertidor de diodos enclavados (NPC).

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ABSTRACT
This paper presents a methodology for charging/discharging control of a Superconducting Magnetic Energy Storage (SMES) systems, using a two stages DC/AC conversion namely, A DC/DC stage for the SMES control and a DC/AC stage for grid integration. A comparison between two different typologies of DC/AC converters is also presented. The first topology is a Two Level Converter (2LC) and the second topology is a Neutral Point Clamped (NPC) converter. As main result, the 2LC provides better response that the NPC, because the first topology request less energy in the SMES than the second topology. Finally, the 2LC performance is better with low energy stored than the NPC.

KEYWORDS: Energy storage, Superconducting Magnetic Energy Storage, Two Level Converter, Neutral Point Clamped converter.

RESUMEN
Este artículo presenta una metodología para el control de carga/descarga de sistemas de almacenamiento de energía por superconducción magnética (SMES), utilizando una conversión DC/AC de dos etapas, una etapa DC/DC para controlar el SMES y una etapa DC/AC para la integración con la red. También se presenta una comparación entre dos tipologías diferentes de convertidores DC/AC. La primera topología es un convertidor de dos niveles (2LC) y la segunda topología es un convertidor de diodos enclavados (NPC). Como resultados principales, el 2LC proporciona mejor respuesta que el NPC, ya que la primera topología solicita menos energía en el SMES que la segunda topología. Finalmente, el rendimiento de 2LC es mejor con baja energía almacenada que el NPC.

PALABRAS CLAVE: Energía Almacenada, Almacenamiento de Energía por Superconducción Magnética, Convertidor de Dos Niveles, Convertidor de Diodos Enclavados.

1. INTRODUCTION

Colombia has a clean energy matrix which is dominated by large hydropower generation and a minor percentage of thermal generation. However, this mix can jeopardize long term reliability due to the effects of El Niño southern oscillation and the global warming. Therefore, new renewable energy technologies such as solar and wind, are required in order to diversify this energy matrix.

High penetration of renewable energy can affect the energy quality and produces transient and voltage stability problems in distribution networks. The superconducting magnetic energy storage (SMES) technology can mitigate some stability problems such as voltage sag, voltage surge, frequency control, fluctuations in demand and generation, among others [1].

An SMES requires a rectifier/inverter converter to make the connection to the AC grid, which controls its charge and discharge of energy. The typologies used to integrate the SMES with the distribution network can be divided in: Thyristor-based converter, voltage-source converter (VSC) with DC-Chopper and pulse-width-modulated current source converter (PWM-CSC) [2]. These typologies in turns, can be integrated with multilevel converters such as Cascade H-Bridge (CHB), Neutral Point Clamped (NPC) and Flying Capacitors (FC) [3].

This paper presents the results of early research about the use of energy storage devices in the Colombian power system. This technology is not well understood in the Colombian context and hence it is important an early approach from the power electronics point of view. A simple analysis is performed by considering two scenarios for interconnecting SMES to the distribution network. In the first scenario, a classical VSC is used with the 2LC and a DC/DC converter to control the charge and discharge of the SMES. In the second scenario, the 2LC is replaced by a multilevel converter NPC.

The paper is organized as follows, in Section II, the proposed system is discussed, next in Section III a simple vector-control is presented. Results are presented in Section IV followed by conclusions and references.

2. PROPOSED CONVERSION SYSTEM

The SMES can provide high rates of energy in short periods of time, however it requires two bidirectional converters, which can charge or discharge the energy stored and control the power supplied to the distribution network. Figure 1 depicts the proposed system used to make the connection of the SMES with the distribution network, using a DC-Chopper, a DC-Link capacitor, a DC/AC converter and a coupling inductance.

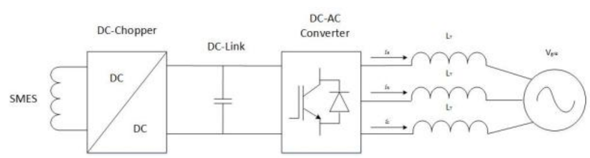


Fig 1. Proposed system to connect the SMES with the distribution network.

2.1. DC-Chopper

The DC-Chopper is a DC/DC bidirectional converter used at the process of charge, freewheeling and discharging of the SMES. This converter have two diodes and two switching elements governed by a modulation signal that control the power through the SMES. Figure 2 shows the performance of the SMES connection with a DC-Chopper converter and a DC-Link capacitor [4].

This configuration have three operating modes to connect the DC-Chopper converter with the SMES, using a DC-Link capacitor to reduce the harmonic contents in the DC current through the DC/DC converter and the DC/AC converter. Figure 3, presents the operating modes to perform charging, freewheeling and discharging of the SMES, respectively.

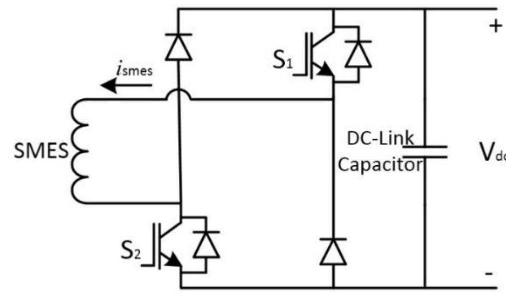


Fig 2. DC-Chopper circuit

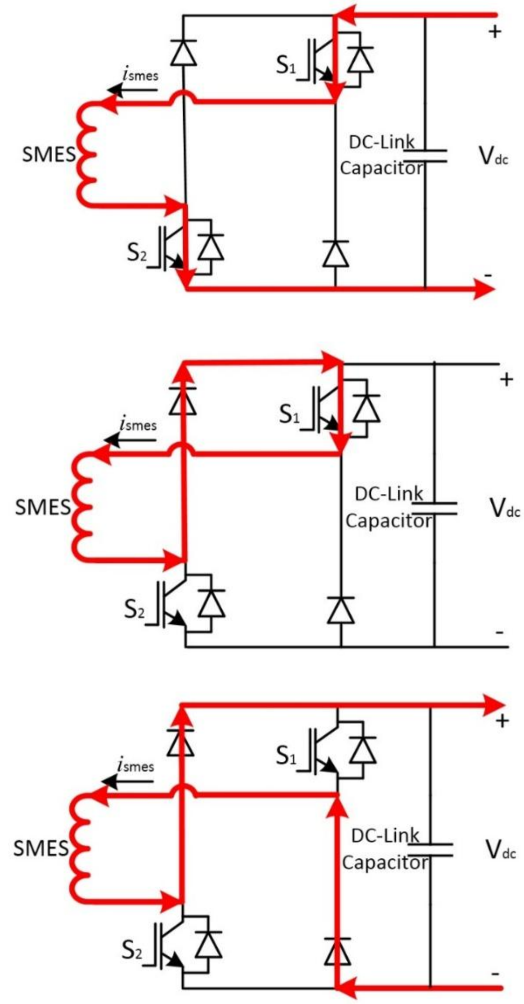


Fig 3. Operation modes. a) charging mode b) freewheeling mode c) discharging mode

2.2. Two Level Converter

The 2LC is a bidirectional DC/AC converter that present two different power converter types to connect the SMES with the network and mitigate some stability problems due the integration of distributed generation. These converters types are Voltage Source Converter (VSC) and Current Source Converter (CSC) [5]. The figure 4 present the 2LC topology connected to the distribution network.

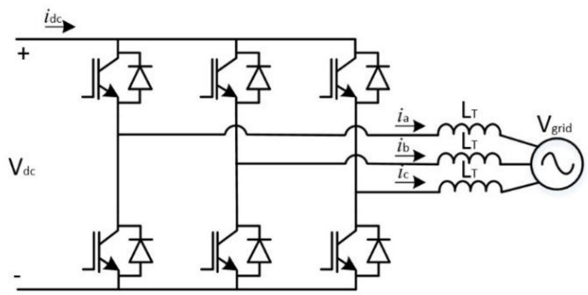


Fig 4. Circuit model of the 2LC.

A 2LC topology was used to connect energy storage devices as a DC battery and the SMES with the network. The SMES realize a high-power control during short-duration voltage sags and the battery provide power during low-power undervoltages [6].

2.3. Neutral Point Clamped

The NPC was proposed in 1981 as an inverter that produce three level output voltage [7]. Figure 5 presents the topology of the NPC connected to the distribution network. This converter have four fast switching elements for leg, governed by modulation signal that control the power injected to the network. A multilevel converter with the NPC topology was used to connect a SMES to the network through a DC-Chopper in [8].

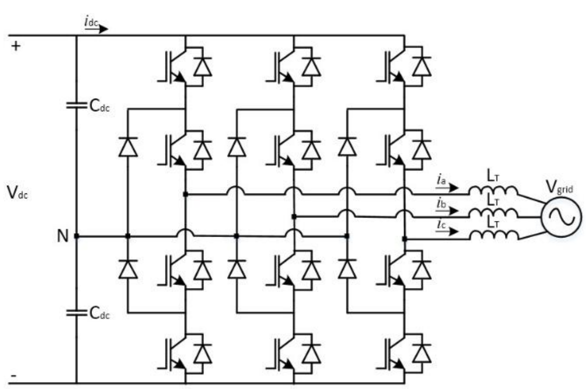


Fig 5. Circuit model of the NPC.

3. Control Design

This section presents the proposed strategy used to control an SMES, through a DC-Chopper and two different DC/AC converter and to describe the control and connection of a SMES with the network. The control use several integrated blocks in cascade such as a phase-locked loop (PLL), the Park transformation, active and reactive power control, inner loop and an SMES power control.

The most important blocks if this control are described in the next subsections.

3.1. Park Transformation

A power invariant Park transformation is used together with a conventional PLL to find the angle Θ of the grid and well as its frequency. This Park transformation is also used to calculate the voltage in the common coupling (PCC) and the current through DC/AC converter with the network in direct and quadrature reference frame. The power invariant Park transformation can be described as follows

$$[0dq] = [T_\theta][abc] \tag{1}$$

where,

$$T_\theta = \frac{\sqrt{2}}{\sqrt{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \tag{2}$$

In Figure 6, the PLL scheme to calculate the angle Θ of the grid is presented. The control proposed request the value of Θ to coupling the DC-Chopper with the network through the DC/AC converter.

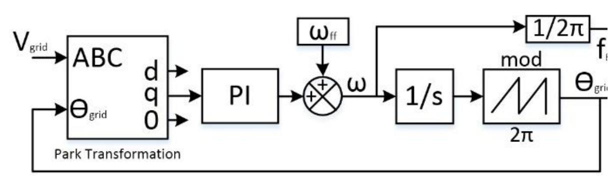


Fig 6. Scheme of the classic phase locked loop.

3.2. Active and Reactive Power Control

The active and reactive power, is controlled through the direct and quadrature reference current, using the Park transformation to find the direct and quadrature voltage at the PPC. The direct and quadrature current reference to control the active and reactive power, can be defined as is presented in as follows

$$i_{d_{ref}} = \frac{v_d P_{ref} - v_q Q_{ref}}{v_d^2 + v_q^2} \quad (3)$$

$$i_{q_{ref}} = \frac{v_q P_{ref} + v_d Q_{ref}}{v_d^2 + v_q^2} \quad (4)$$

3.3. Inner Loop

The inner loop, minimize the error between the direct and quadrature currents references with the direct and quadrature currents through the DC/AC converter and the network:

$$u_d = \left(k_p + \frac{k_i}{s}\right)\left(i_{d_{ref}} - i_d\right) \quad (5)$$

$$u_q = \left(k_p + \frac{k_i}{s}\right)\left(i_{q_{ref}} - i_q\right) \quad (6)$$

Using the Inner Loop control, the direct and quadrature voltage reference v_{ref} can be described as

$$v_{d_{ref}} = u_d - \omega L_T i_q + v_d \quad (7)$$

$$v_{q_{ref}} = u_q + \omega L_T i_d + v_q \quad (8)$$

With the inverse Park transformation, the reference voltage v_{ref} can be write as (9).

$$\left[v_{abc_{ref}}\right] = [T_\theta]^{-1}\left[v_{0dq_{ref}}\right] \quad (9)$$

3.4. SMES Power Control

The DC-Chopper use two signals to control the charging, freewheeling and discharging mode of the SMES, as is presented in table 1. In addition, the SMES have constrain due the construction, fabrication materials and the maximum current nominal through the SMES.

Table 1. DC-Chopper Control

Mode	S_1	S_2
Charging	1	1
Freewheeling	1	0
Discharging	0	0

The SMES constrain can be defined in current terms, as is given in (10).

$$if: (i_{smes} > 0.95 * i_{dc}), then \text{ Freewheeling Mode} \quad (10)$$

4. Tests and Results

This section presents the tests and results obtained with the proposed design to control a SMES, using a DC-Chopper to realize charge and discharge to the SMES, and compare the performance of two scenarios with different DC/AC converters to realize the coupling with the network. Both scenarios presents three operation mode to realize the charging, freewheeling and discharge to the SMES. First, the control proposed is used to charge the SMES. Then, a freewheeling mode is performance and finally the SMES is discharging in small power packs to valid the control proposed.

4.1. System Parameters

Table 2 presents the parameters of the system proposed. This parameters are used in two converters DC/AC studied.

Table 2. Parameters of the system proposed

Parameter	Value
P_{nom} [MW]	1
V_{ac} [kV]	2.5
Frequency	60
V_{dc} [kV]	5
I_{dc} [A]	350
E_{smes} [kJ]	612.5
L_{smes} [H]	10
L_T [mH]	4
C_{dc} [uF]	10000

4.2. Active Power

The figure 7, performance the active power control evaluated in three operation states with the 2LC and the NPC respectively.

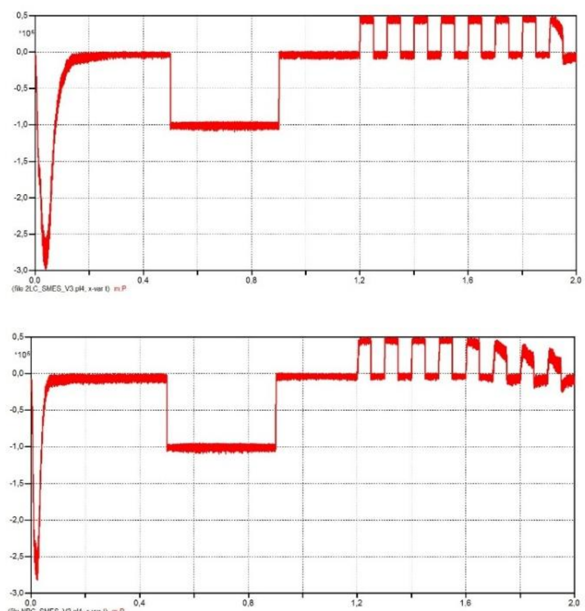


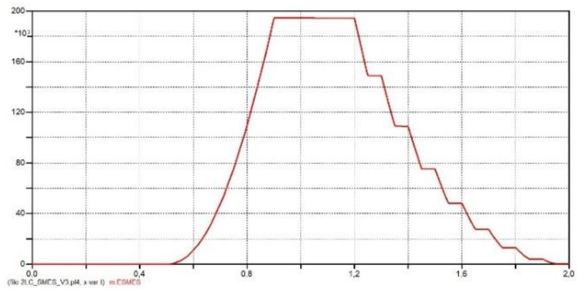
Fig 7. Comparison for the 2LC and the NPC.

The 2LC present better stability performance that the NPC.

4.3. SMES Energy

Figure 8 shows the performance the energy obtained in the SMES in three operation states with the 2LC and the NPC respectively.

The first topology require less energy than the second topology to the same operations states.



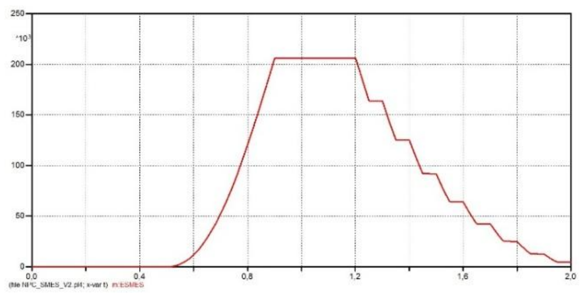


Fig 8. SMES Energy with the NPC.

5. CONCLUSIONS

The VSC use two bidirectional converters and a DC-Link capacitor to integrate the SMES with the power network was presented. This integration permitted a power control with low harmonics at the AC side, beside it performed a control of charge, freewheeling and discharging, using a current constraint in the SMES. In addition, two DC/AC converters are compared to couple the proposed system. The control constants are find by the metaheuristic algorithm "Simplex Annealing" presented in tools of the software ATP/EMPT. This algorithm minimize the error between the power reference and the power injected with the proposed system.

The DC/AC converters performance has been compared with the same operating conditions and proposed control. The 2LC request less energy in the SMES and this performance is better with low energy stored than the NPC, because the second topology need four fast switching elements by leg producing higher conduction and switching losses compared with the first topology that only require two fast switching elements by leg. The energy stored in the SMES can be injected to the network in small power packs as is presented in this paper, or injected in a big power pack according tho the application.

6. ACKNOWLEDGMENT

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