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Modeling and simulation of a static synchronous compensator for power distribution systems

Modelización y simulación de un compensador estático síncrono para sistemas de distribución de energía eléctrica

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Abstract: This paper deals with the modeling and simulation of a DSTATCOM (Distribution Synchronous Static Synchronous Compensator) in shunt connection to compensate an electrical power system. The simulation in the selected software will determine the performance, stability, power factor correction and voltage regulation in three-phase distribution systems. The behavior of the DSTATCOM will be tested in simulation under a condition that affects the power quality of the system.

Keywords: VSC, PWM, D-STATCOM, reactive power, active power, PCC.

Resumen: En este artículo se aborda la modelización y simulación de un DSTATCOM (Compensador Estático Síncrono de Distribución) en conexión shunt para compensar un sistema eléctrico de potencia. La simulación en el software seleccionado determinará el desempeño, la estabilidad, la corrección del factor de potencia y la regulación de tensión en sistemas de distribución trifásicos. El comportamiento del DSTATCOM será probado en simulación ante una condición que afecte la calidad de la energía del sistema

Palabras clave: VSC, PWM, D-STATCOM, potencia reactiva, potencia activa, PCC.

1. INTRODUCTION

In industry, commerce, and residential settings, there are numerous electrical and electronic equipment containing inductances and capacitances. Examples include electric motors, transformers, inductors in electronic power supplies, among others [9]. The above leads to power systems needing to provide not only useful energy, such as active power, but also increasingly contribute more reactive power. Reactive power reduces the capacity to transport useful energy. Additionally, it's important to highlight that connecting and disconnecting electronic devices and nonlinear loads causes "disturbances" in electrical systems,

which also degrade the sinusoidal waveform both in voltage and current [1].
The application of power electronic compensation systems has been carried out since the 1970s [2] with the introduction of the thyristor developed by General Electric and the application of the IGBT by Mitsubishi Electric in the same decade (see annexes for the nomenclature used), several power electronic devices were subsequently developed. One notable example is the Static Synchronous Compensator, STATCOM. [3].

The D-STATCOM is a Flexible Alternating Current Transmission System (FACTS) device, representing an application of STATCOM in the power distribution networks (SEP), aiming to compensate reactive power while maintaining grid voltage. This device can inject leading or lagging currents independently of the electrical system voltage [4]. Its connection is mainly done in shunt when connected to the point of common coupling (PCC), as shown in the figure 1.

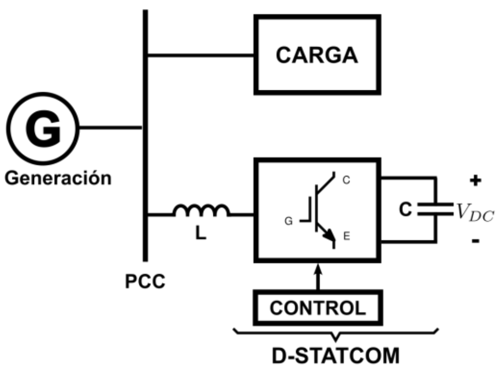

Fig. 1. *Block diagram of the D-STATCOM.*

2. OPERATION PRINCIPLE AND MODELING OF THE D-STATCOM

2.1. Operation principle

The D-STATCOM can mitigate voltage variations at the voltage bus, also known as the PCC (see figure 1), by compensating for the reactive power of the power distribution system as required. This is achieved by applying a higher voltage ($V_{D-STACOM}$) to the voltage of the bus or bar (V_{BUS}), Where reactive power is injected into the electrical grid, increasing the voltage value at the PCC, and vice versa, ($V_{D-STACOM}$) it is reduced with respect to V_BUS so that the compensator consumes reactive power, thus decreasing the voltage value at the PCC [5].

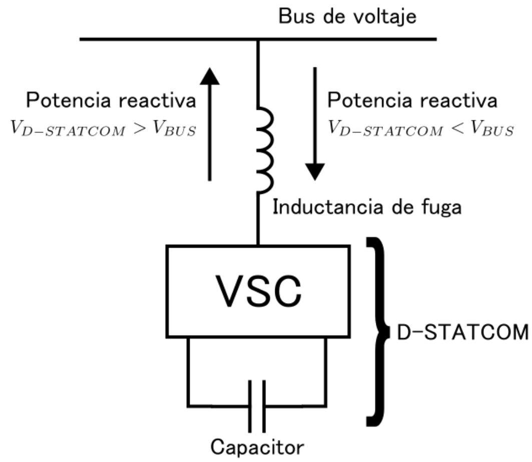

Fig. 2. *Operation principle of the D-STATCOM*

2.2. Modeling of the D-STATCOM

In figure 3, the connection of the D-STATCOM at the PCC point is shown in greater detail [6]. Although later on, a filter will be used in the simulation LCL, In the figure, only an inductance L is shown along with its internal resistance R. The resistance r_{on} corresponds to the internal resistance of each IGBT transistor.

The D-STATCOM is controlled using a dq reference frame system, for which the phase currents delivered by the VSC must be measured in order to calculate the quadrature currents i_d e i_q. The PLL estimates the angle ρ and the phase voltages of the VSC are operated to calculate the quadrature voltages V_{sd} y V_{sq}. These measurements feed the controllers using a dq reference frame system which is used to provide modulation m_d y m_q, necessary to transform into an abc system and be compared with the PWM carrier.

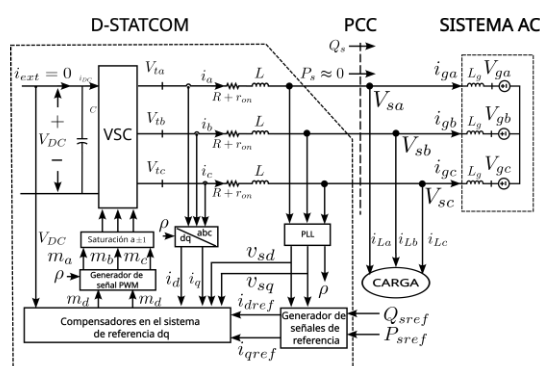

Fig. 3. *Complete D-STATCOM system, load, and three-phase source.*

Applying Kirchhoff's current and voltage laws, expressions at the PCC are obtained.

$$V_{sa} = L_g \frac{di_{ga}}{dt} + V_{ga} + V_{null} \tag{1}$$

$$V_{sb} = L_g \frac{di_{gb}}{dt} + V_{gb} + V_{null} \tag{2}$$

$$V_{sc} = L_g \frac{di_{gc}}{dt} + V_{gc} + V_{null} \tag{3}$$

$$i_{ga} = i_a - i_{La} \tag{4}$$

$$i_{gb} = i_b - i_{Lb} \tag{5}$$

$$i_{gc} = i_c - i_{Lc} \tag{6}$$

The voltageV_{null} corresponds to the voltage at the center of the reference generator connection to 0V.

Using the spatial vector transformation, i.e., transforming from the abc three-phase reference system to the Park or dq0 reference system as explained in the annex Spatial Vector Representation, it is fulfilled:
:

$$\vec{V_s} = L_g \frac{d\vec{i_g}}{dt} + \vec{V_g} \tag{7}$$

$$\vec{i_g} = i - \vec{i_L} \tag{8}$$

$$\vec{V_g} = \widehat{V_g} e^{j(\omega_0 t + \theta_0)} \tag{9}$$

The D-STATCOM is controlled in the dq0 reference system and will be synchronized to a rotation angle ρ.
Substituting the following vector representation into (7):

$$\vec{V_s} = V_{sdq} e^{j\rho} \tag{10}$$

$$\vec{i_g} = i_{gdq} e^{j\rho} \tag{11}$$

$$\vec{V_g} = \widehat{V_g} e^{j(\omega_0 t + \theta_0)} \tag{12}$$

You get

$$V_{sdq} e^{j\rho} = L_g \frac{d}{dt}\left(i_{gdq} e^{j\rho}\right) + \widehat{V_g} e^{j(\omega_0 t + \theta_0)} \tag{13}$$

$$\mathrm{V_{sa}} = \mathrm{L_g} \frac{\mathrm{di_{ga}}}{\mathrm{dt}} + \mathrm{V_{ga}} + \mathrm{V_{null}} \tag{14}$$

$$\mathrm{V_{sdq}} e^{j\rho} = \mathrm{L_g} \frac{\mathrm{d}}{\mathrm{dt}} \mathrm{i_{gdq}} e^{j\rho} + \widehat{\mathrm{V_g}} e^{j(\omega_0 + \theta_0)} \tag{15}$$

$$L \frac{di_d}{dt} = L\omega_0 i_q - (R + r_{on}) i_d + V_d - V_{sd} \tag{16}$$

$$L \frac{di_q}{dt} = L\omega_0 i_d - (R + r_{on}) i_q + V_d - V_{sq} \tag{17}$$

Where the active and reactive power at the PCC in the dq reference frame are [7]:

$$P_s = \frac{3}{2}\left[V_{sd}(t) i_d(t) + V_{sq}(t) i_q(t)\right] \tag{18}$$

$$Q_s = \frac{3}{2}\left[-V_{sd}(t) i_q(t) + V_{sq}(t) i_d(t)\right] \tag{19}$$

The D-STATCOM uses current control because voltage control would not respond correctly to a short circuit fault [8]. That's why the dq controller uses the current control variables i_d e i_q so the system follows the current reference without error i_{dref} and i_{qref} which are calculated using equations (18) y (19).

$$i_{dref}(t) = \frac{2}{3} V_{sd} P_{sref}(t) \tag{20}$$

$$i_{qref}(t) = \frac{2}{3} V_{sd} Q_{sref}(t) \tag{21}$$

Using equations (20) and (21), reference values for desired active power, P, and reactive power, Q, are calculated. However, in the case of the D-STATCOM, only the required active power is controlled to compensate for device losses.
In section 5 of the simulation, these references are shown using the voltage of the DC link V_{DC} to calculate the necessary value of active power along with the voltage value V_D needed to achieve the required reactive power, as shown in figure 3.

3. SIMULATION

The core of the D-STATCOM is the VSC, where on the DC side, a capacitor C is connected [10]. This device is coupled to the SEP through a filtering inductance. The VSC consists of a three-phase bridge of IGBTs, each with a diode in anti-parallel acting as a rectifier.

Figure 4 shows the block diagram integrating the simulation with Matlab's Simulink software.

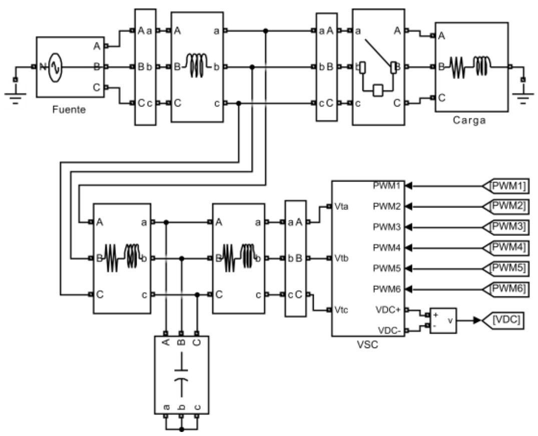

Fig. 4. *D-STATCOM connected to PCC in a multi-wire circuit in Matlab*

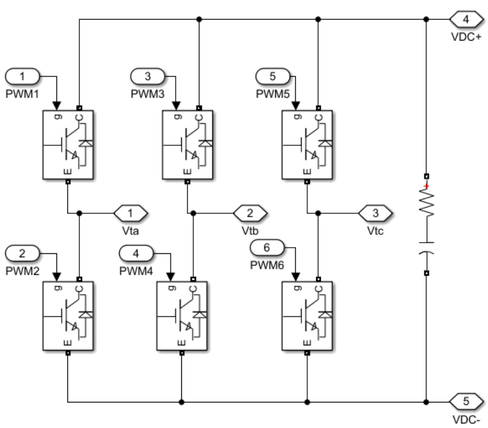

Fig. 5. *Three-phase IGBT bridge*

In this module, PWM modulation is used for triggering each IGBT switch (see figure 5), by comparing the modulating signal calculated by the control circuit with a carrier signal of higher frequency than the modulating one (see figure 3).

Figure 6 shows the logic used for generating the PWM signals. The control circuit calculates the voltages in the dq reference system which are then transformed into the abc reference system.

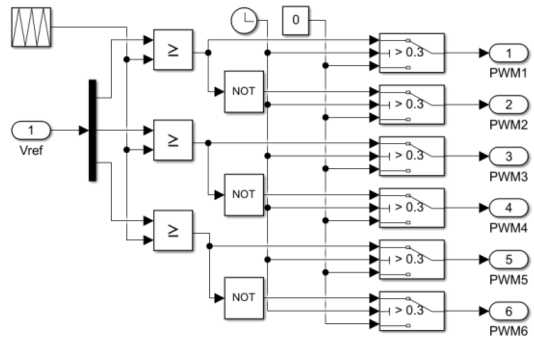

Fig. 6. *Subsystem for PWM signal generation*

Figure 7, proposed by [11], calculates the current signal i_d e i_q starting from the reference V_{DC} y V_d, respectively, and this is compared with the measured value at the DC bus and the voltage V_d measured at the PCC.

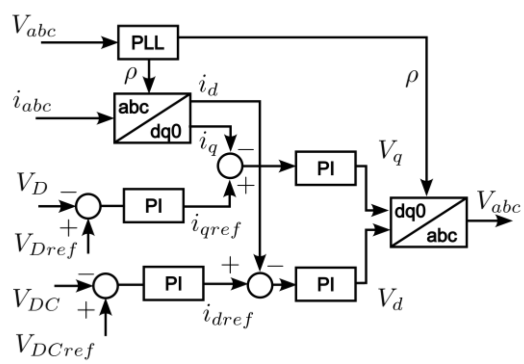

Fig. 7. *D-STATCOM connected to PCC in a multi-wire circuit*

Tabla 1: *Values of the circuit elements*

Element or device	Value	Remarks
VDC	2500 V	DC bus voltage
C	1000 uF	VSC capacitance
Carga	80 kW	Load active power
	40 kVAR	Load reactive power
Generador	2.7 mH	Ls Generator inductance
	480 V	Line-to-line voltage
Filtro LCL	623 uH	Li VSC side inductance
	374 mH	Lg generator side inductance
	46 uF	LCL filter capacitance Cf

Running the simulation it is observed in Figure 8 that from 0 seconds to 0.2 seconds the voltage at the VSC terminals is provided by the diodes connected to the IGBTs operating as a three-phase rectifier. At time 0.2 the load is connected to the power circuit and note a drop in the VSC terminal voltage. Subsequently, at 0.3 seconds the control signals are enabled in the IGBTs where a diffuse signal is observed in the graph, which corresponds to the three-phase PWM modulation.

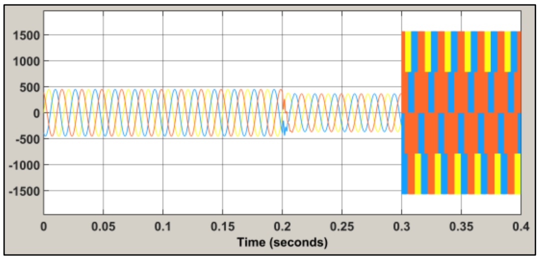

Fig. 8. *Voltage on the D-STATCOM terminals.*

Figure 9 details a zoom between time 0.297 seconds to time 0.309 approximately and shows the PWM modulation which when averaged follows an approximately sinusoidal signal.

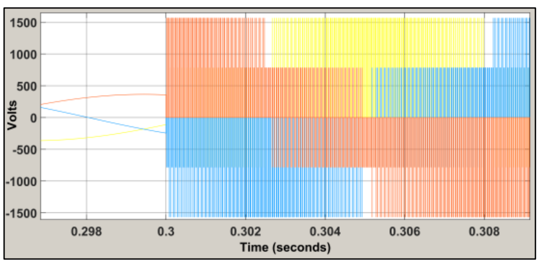

Fig. 9. *Zoom in time of the voltage on the D-STATCOM terminals*

In this simulation, the modulating signal has a frequency of 60 Hz and the carrier signal of 10 kHz. The circuit in figure 5 shows the three-phase source and on the right side the load. Connected to the PCC through a LCL filter where the modulations that have been calculated individually are shown and the STATCOM block, which is available in the Matlab toolbox, has not been used.

The LCL filter achieves coupling and also current and voltage filtering for the purpose of improving the measurements going to the controller.

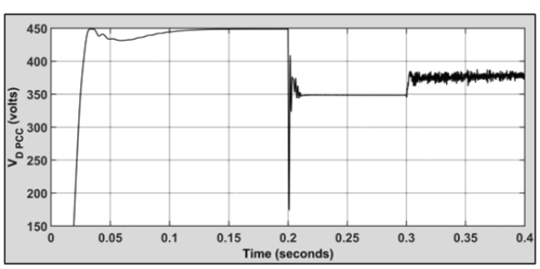

Fig. 10. *D-STATCOM response to voltage change.*

Figure 10 shows the response to voltage variation at the PCC. The graph is detailed from 0 seconds and reaching 0.15 seconds the measurement stabilizes. The voltage shown is V_d which corresponds to the amplitude of the peak voltage of the phase voltage, ie:

$$V_{LL} = 480\ V$$

$$V_{fase} = \frac{480}{\sqrt{3}} = 277.13\ Vrms$$

$$V_{fase\ pico} = 391.91V$$

In Figure 11 the PCC with the generator at no load reaches a voltage of 450 V peak. In 0.2s the circuit breaker is closed and the transient of the load connection is shown, lowering the PCC voltage to 350 V peak. In 0.3s the VSC IGBT bridge is enabled and a recovery of the PCC voltage is noticed. Note that the device reaches a peak voltage of 392 V in approximately 0.9s.

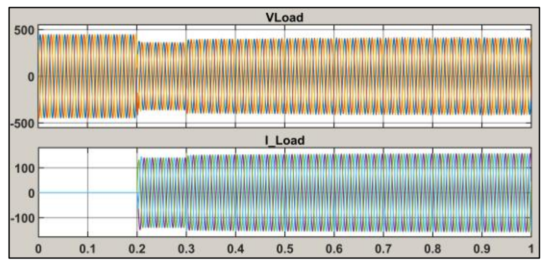

Fig. 11. *Voltage and current in the load.*

Figures 12 and 13 show the voltage and current at the three-phase source and at the VSC respectively.

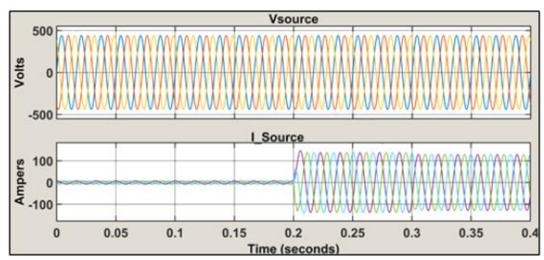

Fig. 12. *Alternator voltage and current*

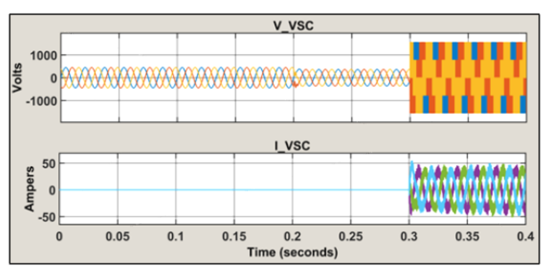

Fig. 13. *Alternator voltage and current*

4. CONCLUSIONS

Applying physical laws such as Kirchhoff's laws, the dynamic equations describing the behavior of the AC system under load and coupled to a VSC were developed.

Using Matlab Simulink, the simulation of the SEP and the VSC control system for voltage compensation in the PCC was carried out.

The D-STATCOM presents a fast response to disturbances being effective in maintaining voltage levels in acceptable ranges.

The D-STATCOM improves the stability of the SEP, preventing voltage sags and swings due to its fast compensation response.

Since the D-STATCOM compensates reactive power, it improves the power factor of the SEP and contributes to better power quality for end users.

The D-STATCOM, being a DC to AC converter like the inverters of renewable energy systems, would allow the latter to be integrated as compensators in the SEP, modifying the control system of the VSC.

The D-STATCOM, by improving the power factor with its reactive power contribution in the SEP, increases the useful energy transport capacity in the distribution network, making the SEP more efficient.

It is important that the current and voltage measurement systems in the PCC, VSC and loads are the best, since incorrect measurements can cause the D-STATCOM to provide incorrect reactive power values and ultimately cause instability in the SEP.

It is important to review and adjust the protection schemes of the D-STATCOM to the SEP as a wrong setting can impair the coordination of SEP protections.

The gain values of the PI controllers in loop i_d e i_q depend on the values of the internal resistance of the leakage inductance, the IGBT turn-on resistance, r_on nd the leakage inductances which in this article were L_i y L_g.

When simulating the D-STATCOM it was found that there must be a procedure to enable each of the different components that make up the D-STATCOM. It is preferable to start with the capacitors charged before the IGBTs are unlocked for operation.

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ANNEXES

Annex A: Nomenclature

FACTS *Flexible Alternating Current Transmission System*
STATCOM *Static Synchronous Compensator*
D-STATCOM *Distribution Static Synchronous Compensator*
DC *Direct current*
AC *Alternating current*
VSC *Voltage Source Converter*
VA *Voltage-Ampere*
IGBT *Insulated Gate Bipolar Transistor*
SEP *Electrical power system*
P *Active Power*
PLL *Phase Locked Loop*
Q *Reactive Power*
PWM *Pulse Width Modulation*
LCL *Inductor capacitor inductor filter*

Annex B: Spatial phasor representation

The author[7] in his work Voltage-sourced converters in power systems modeling control and applications performs the transformation from abc frame to dq0 frame using Space Phasor representation. The conversion is performed for three-phase systems using the following equations:
:

$$f_a(t) = \hat{f}\cos(\omega t + \theta_o)$$

$$f_b(t) = \hat{f}\cos\left(\omega t + \theta_o - \frac{2\pi}{3}\right)$$

$$f_c(t) = \hat{f}\cos\left(\omega t + \theta_o - \frac{4\pi}{3}\right)$$

Where $\hat{f}$, θ_0 and ω are the amplitude, initial phase angle and angular velocity of the phasor.

$$\vec{f}(t) = \frac{2}{3}\left[e^{j0} f_a(t) + e^{j\frac{2\pi}{3}} f_b(t) + e^{j\frac{4\pi}{3}} f_c(t)\right]$$