Simulation of the influence of STATCOM on power system losses

Simulación de la Influencia del STATCOM en las Pérdidas del Sistema de Potencia

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Artículo de investigación científica y tecnológica

***Abstract*—The supply of growing electricity demand is possible through continuous technological advances and the expansion of national and international electrical systems. This scenario could introduce voltage drops and consequent changes in the reactive power flow throughout the electrical network. In order to control these problems, various strategies have been developed as a solution to improve the transport and distribution of electrical energy. One of them is the Flexible Alternating Current Transmission System (FACTS), and more specifically the STATic synchronous COMpensator (STATCOM). This paper investigates the influence and effectiveness of STATCOM to mitigate the losses in the transmission lines and its impacts on bus voltage drops. The simulations are performed using the software DIgSILENT PowerFactory and the results showed that STATCOM reduces the power system losses in an interval of 23.86% until 32.86%, and in addition, the STATCOM decreases the annual energy cost by 7.82% in the implemented test case.**

***Index Terms*—Flexible AC transmission systems, power system modeling, power transmission, reactive power control, static VAr compensators.**

***Resumen*— El abastecimiento de la creciente demanda eléctrica es posible a través de los continuos avances tecnológicos y la expansión de los sistemas eléctricos nacionales e internacionales. Este escenario podría introducir caídas de tensión y los consiguientes cambios en el flujo de potencia reactiva en toda la red eléctrica. Para controlar estos problemas se han desarrollado diversas estrategias como solución para mejorar el transporte y distribución de energía eléctrica. Uno de ellos es el Sistema Flexible de Transmisión de Corriente Alterna (FACTS), y más concretamente el STATic synchronous COMpensator (STATCOM). Este artículo investiga la influencia y efectividad del STATCOM para mitigar las pérdidas en las líneas de transmisión y sus impactos en las caídas de tensión de las barras. Las simulaciones se realizan utilizando el software DIgSILENT PowerFactory y los resultados mostraron que el STATCOM reduce las pérdidas del sistema de potencia en un intervalo de 23,86% hasta 32,86%, y, además, el STATCOM disminuye el costo anual de energía en 7,82% en el caso de prueba implementado.**

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***Palabras claves*—Compensadores de VAr estáticos, control de potencia reactiva, modelado de sistemas de potencia, sistemas flexibles de transmisión de AC, transmisión de potencia.**

I. Introduction

ECONOMIC development depends significantly on the structure of the power systems since industrial development, productivity, and citizens' quality of life are strongly associated with a reliable, continuous, and high-quality supply of electrical energy. In this sense, the constantly increasing electrical load must be served with more robust, stressed, and interconnected power systems. This scenario requires the implementation of technical solutions to guarantee the correct operation of the power systems [1].

A. Motivation

One of the possible solutions is the implementation of FACTS, which are devices based on power electronic technologies. The FACTS systems have demonstrated to incorporate big benefits in the power systems, such as power factor control despite variable loads, flicker stabilization, voltage increase in the load bus, reduction of harmonics, increment in transmission capacity, minimal environmental impact, reduced project implementation time, lower investment cost, and improved stabilization of the power system [2], [3].

B. Literature Review.

The FACTS systems implementation has been previously analyzed by other authors with different study approaches. In [4]-[7], the FACTS have been used to alleviate congestion on transmission lines. In [8], the harmonic characteristics of a Static Var Compensator (SVC) are examined in small grid-connected power stations. In [9], the performance of SVC is shown as a mechanism to improve the voltage profile, power factor, and power loss in distribution substations. The authors in [10] use the SVC to enhance the power system stability. In addition, the Static Synchronous Series Compensator (SSSC) and Thyristor Controlled Series Compensator (TCSC) have also been employed to solve the problems named above in [11], [12].

With respect to the STATCOM, the authors in [13] show the optimal location of this device for safe loading margin and stability limits in power systems. Additionally, the STATCOM has been used for reducing low-frequency oscillations [14], improving voltage stability margin [15], and identifying sensitive buses [16].

C. Contribution

This document presents the simulation of the effects obtained by installing a STATCOM in an electrical substation. Specifically, the study is concentrated on changing the STATCOM loadability and checking the improvements in power system losses, voltage profiles and economic benefits.

D. Paper Organization

This paper is organized as follows. Section II presents the STATCOM main characteristics and its respective modeling. The regional context associated with the FACTS systems is shown in III. Section IV describes the test system and the simulation scenarios. Section V exposes the analysis of the results and finally, section VI exposes the conclusions of this research.

II. STATCOM FRAMEWORK

Within the FACTS classification indicated in Fig. 1, the STATCOM is a second-generation thyristor control switch. The STATCOM behaves essentially as a synchronous compensator allowing continuous control of reactive power and offering a faster response speed and can provide capacitive and inductive compensation. The STATCOM has the ability to control the relative magnitude between the line voltage and the inverter output voltage. It is one of the most important FACTS controllers and uses a Voltage Source Converter (VSC) switching device to control the output voltage and the current injection [17].

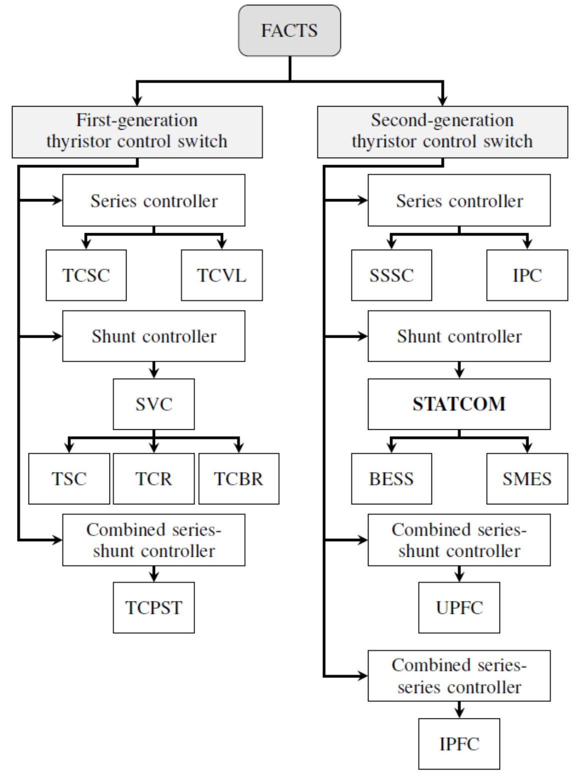


Fig. 1. FACTS classification.

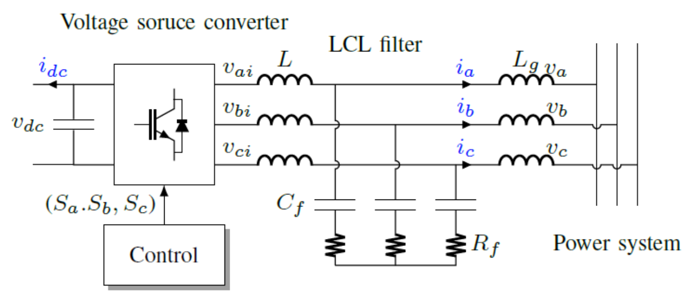


Fig. 2. STATCOM device diagram.

A. STATCOM Components

For the STATCOM, the voltage source controlled in amplitude and phase is implemented through inverters which are connected on their DC side to a capacitor and on their AC side to a transformer as indicated in Fig. 2. The functions of each STATCOM component are described below,

1) Inverter: The inverter is integrated with electronic devices, such as GTOs and IGBTs, which have cutting and conduction capacities. The inverter function is to generate the AC voltage from the DC voltage at the capacitor terminals of the DC side. The use of multiple inverters reduces harmonic distortion in the output voltage.

2) DC side capacitor: The main function of the DC side capacitor is to serve as a DC voltage source, making it possible to operate the inverter. In addition, the capacitor on the DC side serves as a temporary energy accumulator allowing the exchange between the electrical system and the STATCOM.

3) Transformer: The transformer is used for two main functions. The first is to serve as a coupling with the AC electrical system, adapting the operating voltages of the equipment and the voltage limits of the inverters with the network; in addition, with certain special configurations, the transformer eliminates some of the harmonics generated by the inverters, reducing the harmonic content inserted in the electrical network. The second consists of using the transformer to create zero-sequence blocking structures if one exists, and to serve as a damping element for transients [18].

B. STATCOM Modelling

The mathematical model of a STATCOM device in the three-phase representation has the following form (1) and (2) [19],

$$v_{abc}^{\mathrm{T}} i_{abc} = v_{dc} C_b \frac{d}{dt} v_{dc} + v_{dc} i_{dc} \quad (1)$$

$$v_{abci} - v_{abc} = R_{eq} i_{abc} + L_{eq} \frac{d}{dt} i_{abc} \quad (2)$$

where v_{abc} is the voltage vector, i_{abc} is the current vector, v_{abci} is the inverter terminal voltage vector, C_b is DC bus capacitor, v_{dc} is its voltage, R_{eq} and L_{eq} are series equivalents of the resistances and inductances of the two LCL-filter coils, respectively, without considering the capacitor.

The first term of the system (1) corresponds to the calculation of the instantaneous three-phase power in the electrical network through the scalar product of the voltage and current vectors. To establish a simpler model of a grid-connected system, it is common practice to transform the electrical variables of the three-phase system abc to the system *dq0*-frame using Park's transformation, where, the position of the d-axis concerning phase a of the three-phase system, is taken as reference and representation indicated in (3) and (4),

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{2}{3}[P(\theta_e)] \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{3}$$

with

$$P(\theta_e) = \begin{bmatrix} \cos(\theta_e) & cos\left(\theta_e - \frac{2\pi}{3}\right) & cos\left(\theta_e + \frac{2\pi}{3}\right) \\ -\sin(\theta_e) & -sin\left(\theta_e - \frac{2\pi}{3}\right) & -sin\left(\theta_e + \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \tag{4}$$

The STATCOM device has no neutral line enabled and no connection to the ground system, so non-zero sequence signals are present. For this reason, the order of the compensator model is reduced, which is represented in the *dq0*-frame, as follows shown in $(5) - (7)$,

$$\frac{d}{dt}v_{dc} = \frac{2}{3C_b v_{dc}} v_d i_d - \frac{1}{C_b} i_{dc} \tag{5}$$

$$\frac{d}{dt}i_d = -\frac{R_{eq}}{L_{eq}} i_d + \omega_e i_q + \frac{1}{L_{eq}} v_d - \frac{1}{L_{eq}} v_{di} \tag{6}$$

$$\frac{d}{dt}i_q = -\frac{R_{eq}}{L_{eq}} i_q - \omega_e i_d + \frac{1}{L_{eq}} v_q \tag{7}$$

where v_{dq}, v_{dqi}, and $i_{dq}$are voltage, inverter terminal voltage, and current of the STATCOM device in the *dq*-frame. Refer to [19] for further details of the mathematical model.

III. FACTS INSTALLED IN COLOMBIA

The FACTS systems installed in the National Interconnected System in Colombia are indicated below and in addition, the last corresponds to the pilot of Flexible Distributed Alternating Current Transmission Systems (D-FACTS).

A. Chinú (500 kV)

ISA installed an SVC in the Chinú substation consisting of two banks of thyristor-switched capacitors (TSCs) and two banks of thyristor-controlled reactors (TCRs). The TSCs provide voltage support after large disturbances, damp power oscillations, control voltage, and balance the load. The SVC installed in the Chinú substation has the following features 500 kV +250, -150 MVAr. This project began to function at the end of 1999 [18].

B. Caño Limón (230 kV)

This project is similar to the FACTS in the Chinú substation with the difference that the SVC installed in this substation has the following features 230 kV +250, -150 MVAr.

C. Tunal

The Bogotá energy company commissioned in 2014 the SVC Static Reactive Power Compensator at the Tunal 230 kV substation to have the necessary reactive power for voltage support in Bogotá and the eastern area. The SVC installed in the Tunal substation has a control strategy that includes functions for reactive power control, overload capacity, and power oscillation damping control. The SVC is connected to the 230 kV network through three single-phase transformers connected in YN/d11, with a three-phase capacity of 240 MVA. In addition, it is composed of a TCR with a capacity of 140 MVAr, two TSC with a capacity of 80 MVAr each, and two filter banks tuned near the fifth and seventh harmonics [20].

D. Bacatá

The Bacatá substation at 500 kV, located in the eastern area of Colombia, has a STATCOM with a reactive power supply capacity of 200 MVAr. This element allows a constant supply of reactive power, regardless of voltage drops in the system, and it needs little space for its operation.

E. Envigado

Pilot D-FACTS of the company EPM (Empresas Públicas de Medellín), is a regional pioneer project with international recognition by the World Economic Forum in 2020, within the Critical Infrastructure category, as one of the three technologies that have played a fundamental role in the energy transformation in the last decade due to its environmental, social and property benefits, by facilitating the connection of renewable energy generation and infrastructure optimization [21].

IV. TEST SYSTEM AND SIMULATION SCENARIOS

The test system has a single-sectioned bus substation and is illustrated in Fig. 3. A 28 kV STATCOM device with a reactive power supply capacity of 200 MVAr (two 100 MVAr in parallel), which is connected on the high side of the electrical substation via a step-up transformer (28 kV/500 kV) as illustrated in Fig. 4.

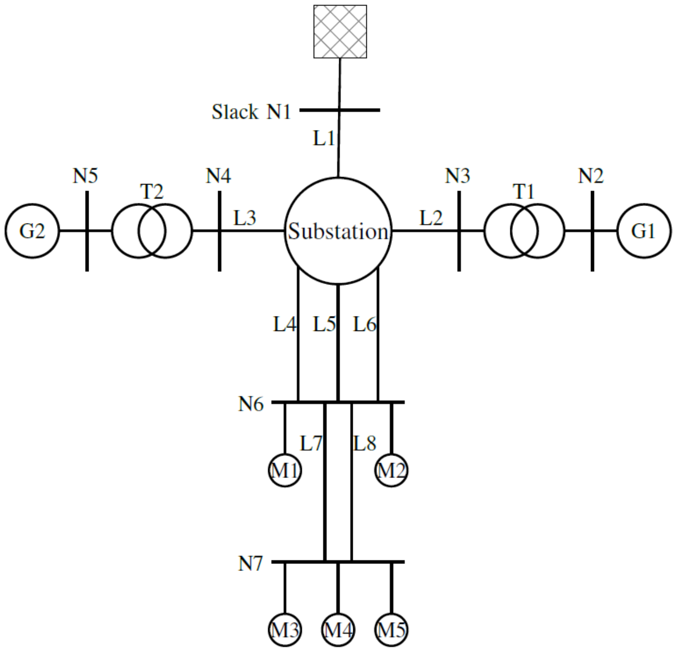


Fig. 3. Power test system with an electrical substation 500 kV/110 kV.

The test system parameters are listed in Appendix A, in tables I, II, III and IV, and this system consists of the following elements: electrical substation, STATCOM device, 8 Transmission lines (L), 10 system nodes (N), 4 Transformers (T), 2 Generators (G), 5 Engines (M), 1 Slack infinite bus.

For simulation purposes, two scenarios are suggested to analyze the impact of the STATCOM device in a power system. The first scenario simulates the test system without the STATCOM device by varying the system loadability from 50% to 150% using intervals of 10%. In this scenario, it is also considered that generators always provide the same active power and maintain the voltage constant at the nodes they are connected. The second scenario considers a STATCOM device installed in the electrical substation, which regulates the voltage at the high side voltage of the electrical substation.

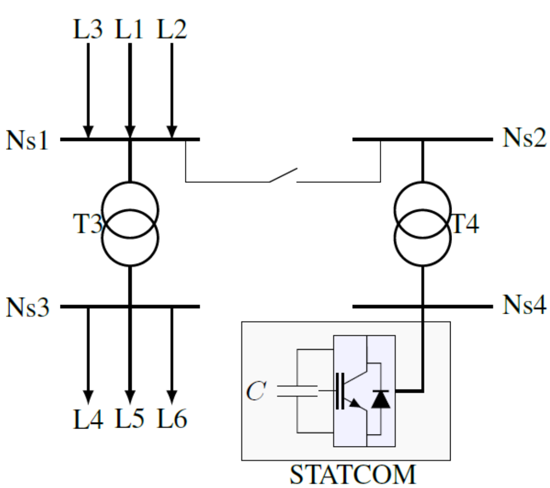


Fig. 4. Electrical substation 500 kV/110 kV.

V. Results Analysis

Fig. 5 shows the behavior of the voltages with different percentages of loadability at the nodes N6, Ns1, and Ns3. These nodes are selected given that these are the nodes where the effects of the STATCOM on the electrical system are best evidenced. Node Ns1 is the node where the STATCOM device will keep the voltage constant. The voltage of Ns1 with the implementation of the STATCOM device remains constant at 1.00 pu. However, without the STATCOM devices, the voltage changes from 1.02 pu and decreases to 0.99 pu observing a voltage reduction as the system loadability increases.

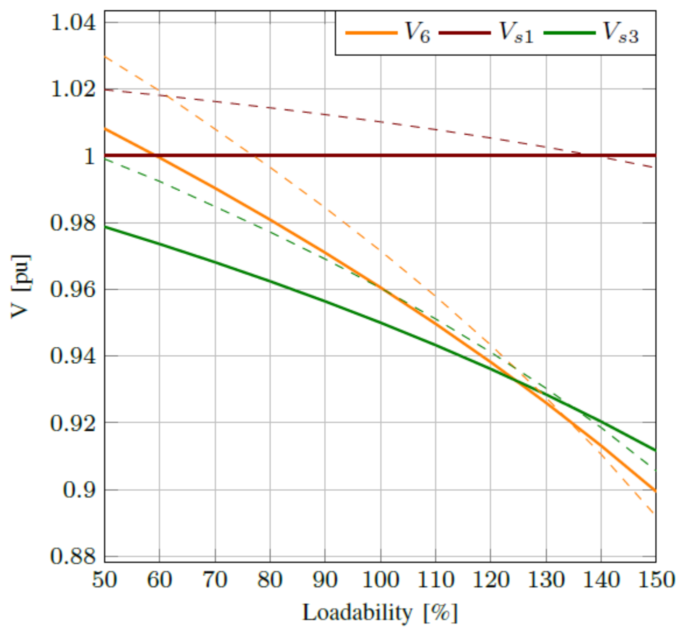


Fig. 5. Voltages of the representative nodes (—with STATCOM; ---without STATCOM).

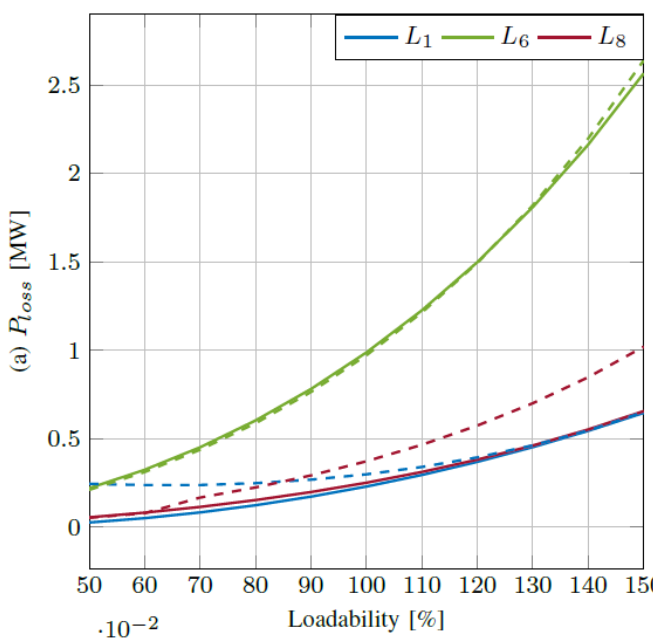
The Ns3 node with the STATCOM implementation starts with a voltage of 0.98 pu and decreases to 0.91 pu; analyzing the graph without the STATCOM implementation, the voltage starts at 1.00 pu and drops to 0.90 pu. It can be observed that the total change in voltage without the STATCOM is higher than with the STATCOM implementation.

Additionally, in Fig. 5 is presented the voltage V_6 with the STATCOM device connected to the system starts at 1.00 pu and decreases to 0.90 pu; while when the STATCOM device is not considered, the voltage at this same node N6 starts at 1.03 pu and as the load increases it decreases to 0.89 pu. It can be noted that the voltage drop is more drastic when the STATCOM device is not considered in the system.

On the other hand, Fig. 6 shows that the transmission line L_1 without the implementation of STATCOM device starts with line power losses of 0.24 MW and increases up to 0.65 MW. In the case of the implementation of STATCOM, the line power losses start from 0.02 MW, increasing in a parabolic way until reaching 0.64 MW. The line power losses L_1 for the entire loadability range are reduced by 23.86%. The power losses in transmission line L_6 show no major differences in losses with the implementation of STATCOM, and without it, as can be seen in the power losses starting at 0.21 MW and reaching up to 2.64 MW. Transmission line L8 is the one that presents the most significant difference between the implementation of STATCOM and without it, as can be seen in Fig. 6 until reaching 65% of system loadability. Transmission line L_8 has losses of almost 0.08 MW with the implementation of STATCOM and without it, but from this point onwards, it begins to vary. Without the implementation of the STATCOM device, it begins to increase losses up to 1.02 MW. On the other hand, with the implementation of STATCOM, they increase up to 0.65 MW because L_8 is the line that connects node 6 with node 7 where motors M3, M4, and M5 are located, being the farthest line of the system and with higher loadability. In this case, the reduction of losses with implementing STATCOM considering all loadability cases is 32.86%. It is important to note that this loss reduction is for each line L_7 and L_8.

Line L_2 has constant losses of 0.01 MW, and L_3 has constant power losses of 0.02 MW with the STATCOM implementation. These losses constantly behave for two reasons: first, the generators in all load cases always generate the same power, and second, the substation voltage is constant in all load cases due to STATCOM. At the same time, without implementing the STATCOM device, the line power losses L_2 start from almost 0 MW and increase to 0.01 MW, and the line power losses L_3 start from 0.01 MW and increase to 0.02 MW. The losses in these lines behave as a parabola since the substation voltage varies according to the power system loadability.

Transformers T1 and T2 present changes in their reactive power with the implementation of STATCOM, and without it, reactive power starts from -25 MVAr to 0 MVArs. With the implementation of the STATCOM device, the two transformers present a constant reactive power of -5 MVArs.



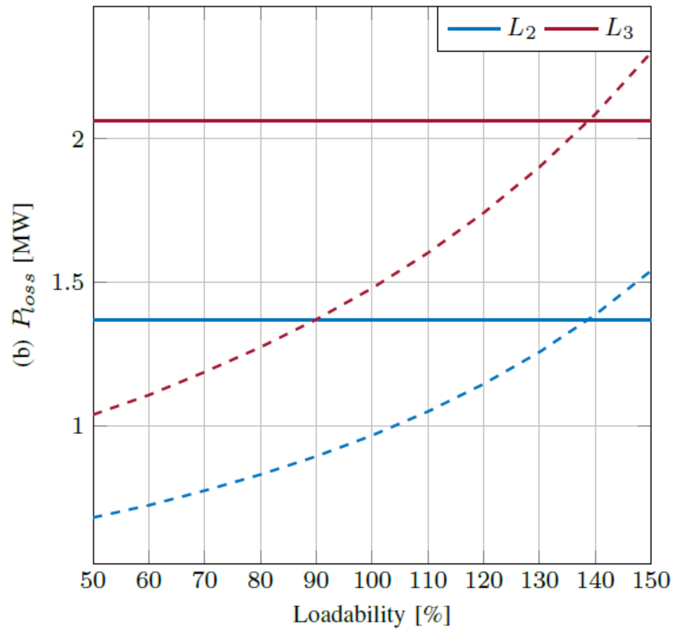


Fig. 6. Transmission lines power losses (—with STATCOM; ---without STATCOM).

It can be seen that the STATCOM device compensates for the reactive power required by the system as shown in Fig. 7. While in transformer T3 the reactive power does not have any significant change, and this is due to the load requirements and considering that the STATCOM does not compensate downstream of it.

A. *Complementary analysis*

This part shows the annual energy cost due to the total energy losses in the transmission lines of the power system. These power losses are computed as average power losses in loadability scenarios. The annual costs are calculated as (8).

$$C_{anual} = C_{STN} P_{loss} H_d D_{anual} \quad (8)$$

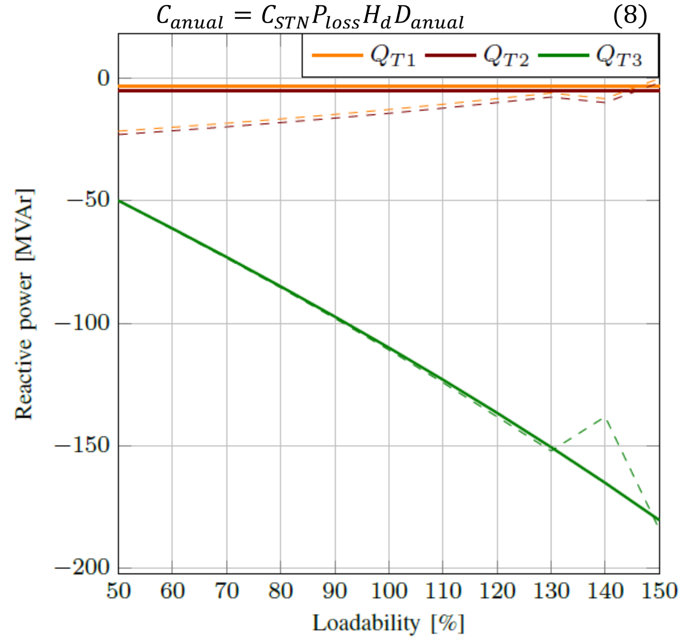


Fig. 7. Transformers reactive power (—with STATCOM; ---without STATCOM).

where C_{anual} represents the annual energy cost in COP, C_{STN} is the cost of the energy transport of the National interconnected system in COP/kWh, P_{loss} is power system losses, H_d corresponds to the hours in a day, and D_{anual} denotes the days of the year.

The C_{STN} in September of 2022 was 50.8461 COP/kWh, which is used to compute the C_{anual}. The total power losses with and without STATCOM devices in the power system are 5.96 MW and 6.47 MW, respectively. The annual cost of energy with and without STATCOM devices are 2.654.858 COP and 2.882.035 COP, respectively. Thus, based on this study case, the STATCOM device reduces the energy cost in the power system by 7.82%.

VI. Conclusions

The implementation of the STATCOM device greatly reduced the losses of the power system analyzed and improves the system performance. The effectiveness of the STATCOM device is remarkable both in its decrease in losses in the electrical system and the decrease in operating costs. Therefore, the implementation of this device is linked to the budget or the level of investment available to the utility to improve its service.

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APPENDIX A. TEST SYSTEM PARAMETERS [22].

TABLE I.
TRANSMISSION LINES DATA.

Line	Node k	Node m	Length [km]	Rated voltage [kV]	Resistance [Ω/km]	Reactance [Ω/km]	Susceptance [μs/km]	Rated current [kA]
L1	N1	Ns1	100	500	0.02336	0.33103	483.133	1.905
L2	N3	Ns1	70	500	0.02336	0.33103	483.133	1.905
L3	N4	Ns1	85	500	0.02336	0.33103	483.133	1.905
L4	NS3	N6	15	110	0.1318	0.4787	34.793	0.467
L5	NS3	N6	15	110	0.1318	0.4787	34.794	0.468
L6	NS3	N6	15	110	0.1318	0.4787	34.795	0.469
L7	N6	N7	7	110	0.1318	0.4787	34.796	0.470
L8	N6	N7	7	110	0.1318	0.4787	34.797	0.471

TABLE II.
TRANSFORMERS DATA.

Transformer	Node k	Node m	V_H/V_L [kV]	Rated power [MVA]	Reactance [%]	Connection
T1	N3	N2	13.8/500	40	4	Y_N/D
T2	N4	N5	13.8/500	40	4	Y_N/D
T3	Ns1	Ns3	500/110	200	4	Y_N/Y_N
T4	Ns2	Ns4	500/28	200	14.85	Y_N/D

TABLE III.
LOADS DATA.

Motor	Node	Rated voltage [kV]	Active power [MW]	Reactive power [MVAr]
M1	N6	110	40	20
M2	N6	110	40	20
M3	N7	110	40	20
M4	N7	110	40	20
M5	N7	110	40	20

TABLE IV.
GENERATORS DATA.

Generator	Node	Rated voltage [kV]	Rated power [MVA]	Power factor	Connection	Operating power [MW]
G1	N2	13.8	40	0.8	Y_N	25
G2	N5	13.8	41	0.9	Y_N	22