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RESEARCH ARTICLE OPEN ACCESS

IMPLEMENTATION OF GENETIC ALGORITHM ON A SINGLE-MACHINE INFINITE-BUS WITH TCSC

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ABSTRACT

This article presents the application and performance analysis of simulations performed in MATLAB/SIMULINK using the Genetic Algorithm (GA) in an infinite-bus machine power system installed with a thyristor-controlled series compensator (TCSC).

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INTRODUCTION

In article [PANDA, 2017] presents a modeling and simulation of a single-machine infinite-bus power system installed with a thyristor controlled series compensator (TCSC).Model 1.1 (IEEE) was used to represent the synchronous generator with field circuit and one equivalent damper winding on q-axis to more accurately to more accurately and realistically evaluate the effect of the machine infinite-bus with TCSC.

FACTS - *Flexible AC Transmission Systems*

The FACTS - Flexible AC Transmission Systems, it was created to let alternating current transmission systems more flexible.It is made up of more sophisticated equipment that adapts according to the application with capable of altering the natural parameters of a transmission system making them operate close to operational limits, neglecting investments in the expansion of these systems [Almeida, 2014].

The use of FACTS equipment allows [Silva, 2016]:

- Increase in the power transmission capacity of the network;
- Power flow control directing the flows to pre-defined routes;
- Enhancement of system security by preventing blackouts by increasing the speed of action during a failure;
- Increased transient stability limit limiting currents during short circuits and overload;
- Helps maintain system stability by damping electromechanical oscillations;
- Yield control and system expansion;

- Increase in the efficiency of transmission lines, reducing thermal losses and improving their flow.

Some of the existing FACTS devices are [SILVEIRA, 2016]:

- SVC - *Static VAR Compensator*;
- TCPST - *Thyristor Controlled Phase Shifting Transformer*;
- UPFC - *Unified Power Flow Controller*;
- STATCOM - *Static Synchronous Compensator*;
- SSSC - *Static Synchronous Series Compensator*;
- TSSC - *Thyristor Switched Series Capacitor*;
- TCSC - *Thyristor Controlled Series Capacitor*;

TCSC - *Thyristor Controlled Series Capacitor*

The TCSC is a series capacitor that belongs to the family of FACTS controllers, it is controlled by the firing angle of the thyristors and can have an equivalent inductive or capacitive reactance, according to its operation needs. It has been used to increase the power transfer capacity of transmission lines and improve system stability [PANDA, 2007] [Almeida, 2014]. In Fig. 1 we have a schematic of a basic model of TCSC which is composed of a thyristor controlled reactor in parallel with a capacitor bank.

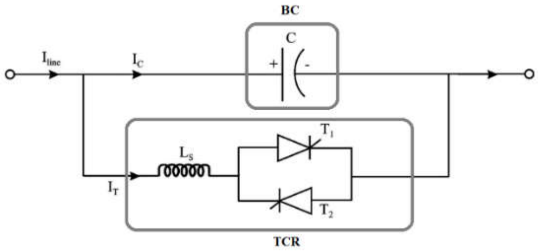


Figure 1. Basic module of a TCSC

where:

BC: capacitor banks:
C –capacitor;
TCR: Thyristor Controlled Reactor:
L-bypass inductor;
$T1$ e$T2$ -bidirectional thyristors.

Its purpose is to promote a continuously variable capacitance through the partial cancellation of capacitance through the TCR, which can be demonstrated by:

$$\frac{1}{X_{TCSC}} = \frac{1}{X_L(\alpha)} + \frac{1}{X_C}$$

$$X_{TCSC} = \frac{X_C X_L(\alpha)}{X_L(\alpha) + X_C} \quad (1)$$

There is:

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha}, X_L \le X_L(\alpha) \le \infty \quad (2)$$

where:
$X_L = \omega L$

$X_L(\alpha) = X_L \text{for} \alpha = 0$

$X_L(\alpha) \to \infty \text{for} \alpha \approx \frac{\pi}{2,8}$

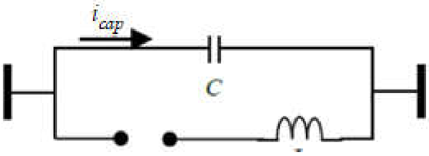
where:

X_C: capacitor bank reactance;
X_L: thyristor-controlled reactor reactance;
ω: system frequency;
α: delay angle.

TCSC operating model:

It has four modes of operation, which are:

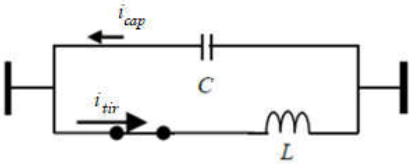
Block mode: Trigger pulses are blocked in the thyristor, so that there is no passage of current and the reactance of the capacitor is the equivalent impedance of the TCSC.This mode is often used when the TCSC operates at low impedance **$(\alpha = 180^\circ)$.**



Source: [7]

Figure 1. TCSC Block Mode

By-pass **Mode:** a constant trigger pulse is applied to the thyristor causing a good part of the line current to flow through the TCR - Thyristor-Controlled Reactor, so the TCSC has an inductive virtual reactance. $(\boldsymbol{\alpha = 90^{\circ}})$

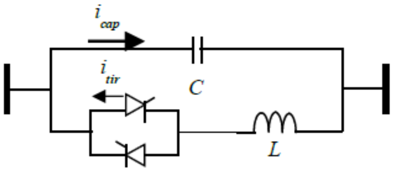


Source: [7]

Figure 2. TCSC By-pass Mode

Capacitive Vernier Mode: As the firing angle, the equivalent reactance of the compensator becomes capacitive, causing the TCSC to act as a variable capacitor. $(\boldsymbol{\alpha_{C_{LIM}} \leq \alpha < 180^{\circ}})$.

$\alpha_{C_{LIM}}$ limiting angle in the capacitive region;

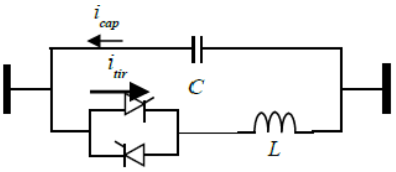


Source: [7]

Figure 3. TCSC Capacitive Vernier Mode

Inductive Vernier Mode: as the firing angle, the equivalent reactance of the compensator becomes inductive, causing the TCSC to act as a variable inductor. $(\boldsymbol{90^{\circ} < \alpha \leq \alpha_{L_{LIM}}})$**.**

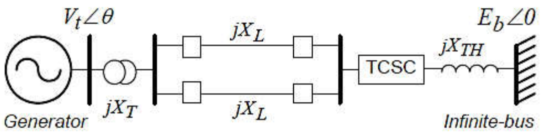
$\alpha_{L_{LIM}}$ limiting angle in the inductive region;



Source: [7]

Figure 4. TCSC Inductive Vernier Mode

SMIB model with TCSC for stability studies: In paper [PANDA, 2007], the proposed model for analyzing the SMIB system with TCSC is made using MATLAB/SIMULINK and using the Genetic Algorithm to improve the TCSC parameters. Fig. 6 shows the system considered in the study, where a synchronous generator is connected to the infinite bus through a double circuit of transmission lines and a TCSC.



Source: [PANDA, 2007]

Figure 4. Single-machine infinite-bus power system with TCSC

where,

V_t voltage at the generator terminal;
E_b voltage on the infinite bus respectively;
X_T transformer reactance;
X_L transmission line reactance per circuit;
X_{TH} reactance of the equivalent Thevenin impedance of the system at the connection point.

According to PANDA [PANDA, 2007], the synchronous generator is represented by model 1.1, with a field circuit and one equivalent damper winding on q-axis, so we have the following machine equations:

$$\frac{d\delta}{dt} = \omega_B(S_m - S_{mo}) \tag{3}$$

$$\frac{dS_m}{dt} = \frac{1}{2H}[-D(S_m - S_{mo}) + T_m - T_e] \tag{4}$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}\left[-E'_q + (x_d - x'_d)i_d + E_{fd}\right] \tag{5}$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{qo}}\left[-E'_d + \left(x_q - x'_q\right)i_q\right] \tag{6}$$

Where T_e is the electrical torque expressed in terms of the variables Ed' , Eq' , id andiqgiven by:

$$T_e = E'_d i_d + E'_q i_q + \left(x'_d - x'_q\right) i_d i_q \tag{7}$$

For a lossless network, the stator and network algebraic equations are expressed as:

$$E'_q + x'_d i_d = v_q \tag{8}$$

$$E'_d - x'_q i_q = v_d \tag{9}$$

$$v_q = -x_e i_d + E_b \cos\delta \tag{10}$$

$$v_d = x_e i_q - E_b \sin\delta \tag{11}$$

As per the equations above, the variables idandiqcan be obtained as:

$$i_d = \frac{E_b \cos\delta - E'_q}{x_e + x'_d} \tag{12}$$

$$i_q = \frac{E_b \sin\delta - E'_q}{x_e + x'_q} \tag{13}$$

Initial conditions: The considered system is nonlinear and must be operated in steady state with instant $\boldsymbol{t_0} = \mathbf{0}$and perturbation from instant$\boldsymbol{t_f} \geq \boldsymbol{t_0}$. Through the calculation of the power flow and from the operating point in steady state, we calculate the initial conditions of the machine at the instant$\boldsymbol{t_0}$: [9] e [10].

$$i_{a0}\angle\varphi_0 = \frac{(P_{t0} - jQ_{t0})}{\widehat{V_{t0}^*}} \tag{14}$$

$$E_{q0}\angle\delta_0 = V_{t0}\angle\theta_0 + jx_q I_{a0}\angle\varphi_0 \tag{15}$$

$$i_{d0} = -I_{a0}\sin(\delta_0 - \varphi_0) \tag{16}$$

$$i_{q0} = I_{a0}\cos(\delta_0 - \varphi_0) \tag{17}$$

$$v_{d0} = -V_{t0}\sin(\delta_0 - \varphi_0) \tag{18}$$

$$v_{q0} = V_{t0}\cos(\delta_0 - \varphi_0) \tag{19}$$

$$E_{fd0} = E_{q0} - \left(x_d - x_q\right)i_{d0} \tag{20}$$

$$E'_{q0} = E_{fd0} + (x_d - x'_d)i_{d0} \tag{21}$$

$$E'_{d0} = -\left(x_q - x'_q\right)i_{q0} \tag{22}$$

$$T_{e0} = E'_{q0} i_{q0} + E'_{d0} i_{d0} + \left(x'_d - x'_q\right) i_{d0} i_{q0} \tag{23}$$

$$V_{ref} = V_{t0} + \frac{E_{fd0}}{k_a} \tag{24}$$

Modeling the Thyristor Controlled Series Compensator (TCSC): The thyristor firing angles (α), or conduction angle (σ), are programmed to adjust the reactance of the TCSC according to a system control algorithm, normally in response to some variations in system parameters. With the variation of (α) or (σ), this process can be modeled as a quick exchange between the corresponding reactances offered to the power system.As the total current passing through the TCSC is sinusoidal; the equivalent reactance at the fundamental frequency can be represented as a variable reactanceX_{TCSC}. Therefore, in steady state, the relationship betweenα and$X_{TCSC}$is described by the following equation:[PANDA, 2007]

$$X_{TCSC}(\alpha) = X_C - \frac{X_C^2}{(X_C - X_P)}\frac{(\sigma + \sin\sigma)}{\pi} + \frac{4X_C^2}{(X_C - X_P)}\frac{\cos^2(\sigma/2)}{(k^2-1)}\frac{[k\tan(k\sigma/2) - \tan(\sigma/2)]}{\pi} \tag{25}$$

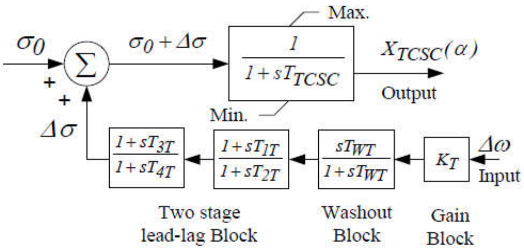
The TCSC is modeled as a variable capacitive reactance within the operating region defined by the limits imposed by α, so the relationship between α and the equivalent fundamental frequency reactance offered by the TCSC, $X_{TCSC}(\alpha)$is a single-valued function. Therefore:

$$X_{TCSC_{min}} \le X_{TCSC} \le X_{TCSC_{max}}$$
$$X_{TCSC_{max}} = X_{TCSC}(\alpha_{min})$$
$$X_{TCSC_{min}} = X_{TCSC}(180^\circ) = X_C$$

In this case the controller will operate only in the capacitive region.

Problem Formulation

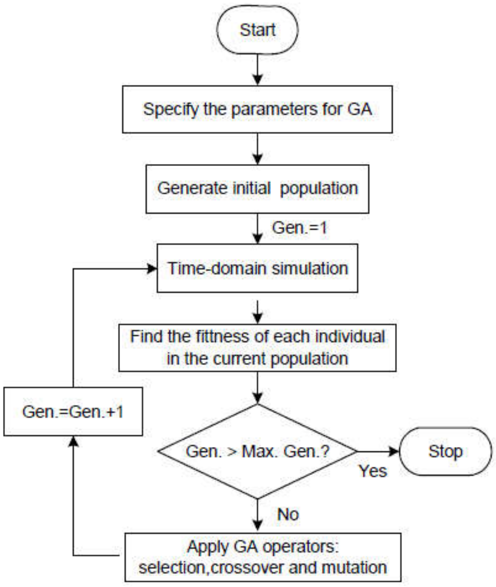
TCSC controller structure: In Fig. 7, we have the structure of damping controller that modulates the reactance offered by the TCSC, $\boldsymbol{X_{TCSC}(\alpha)}$. Where the input signal of the controllers is the variation of the angular speed of the synchronous machine ($\boldsymbol{\Delta\omega}$)and the output signal is the reactance$\left(\boldsymbol{X_{TCSC}(\alpha)}\right)$offered by the TCSC.The controller structure is formed by a gain block with gain $\boldsymbol{K_T}$, two-stage phase compensation blocks and a signal washout block which serves as a high-pass filter, with the time constant $\boldsymbol{T_{WT}}$ which high enough to allow signals associated with oscillations in input signal to pass unchanged.The time constant blocks$\boldsymbol{T_{1T}, T_{2T}, T_{3T}}$ and $\boldsymbol{T_{4T}}$provide the phase-lead characteristic to compensate for the phase lag between input and the output signals.conduction angle$\boldsymbol{\sigma_0}$, which remains constant throughout the disturbance analysis period, as the steady-state power flow is slow acting.[PANDA, 2007]



Source:[PANDA, 2007]

Figure 5. Structure of TCSC-based controller

Application of the Genetic Algorithm: PANDA, propose to optimize the parameters of the TCSC controller, the use of a Genetic Algorithm (GA).GA is based on the mechanisms of natural selection and genetics.They keep a group of random individuals that will be tested, where the fittest are kept and the others are discarded.Those that are kept have their characteristics modified through the crossover so that they multiply until they find an optimal solution for a given problem. In Fig. 8, we have the computational flowchart of the GA optimization approach.



Source: [PANDA, 2007]

Figure 8. Flowchart of the genetic algorithm

The results obtained through the optimization are shown in Table 1.

Table 1.

OPTIMIZED TCSC CONTROLLER PARAMETERS USING GENETIC ALGORITHM				
Gain	Time constants			
K_T	T_{1T}	T_{2T}	T_{3T}	T_{4T}
32.6247	0.1464	0.1402	0.1235	0.1524

Source:[PANDA, 2007]

The relevant parameters are given below: [PANDA, 2007]

- Generator: $H = 3,542$, $D = 0$, $X_d = 1,7572$, $X_q = 1,5845$, $X_d^{'} = 0,4245$, $X_q^{'} = 1,04$, $T_{do}^{'} = 6,66$, $T_{q0}^{'} = 0,44$, $R_a = 0$, $P_e = 0,6$, $Q_e = 0,02224$, $\delta_0 = 44,37^0$.
- Exciter: $K_A = 400$, $T_A = 0,025\ s$.
- Transmission line: $R = 0$, $X_L = 0,8125$, $X_T = 0,1364$, $X_{TH} = 0,13636$, $G = 0$, $B = 0$.
- TCSC Controller: $T_{TCCSC} = 15\ ms$, $\alpha_0 = 142^0$, $X_{TCSC0} = 0,62629$, $k = 2$, $T_W = 10\ s$, $X_{MAX} = 0,8\ X_L$, $X_{MIN} = 0$.

All data are in pu unless specified otherwise

Simulação MATLAB/SIMULINK

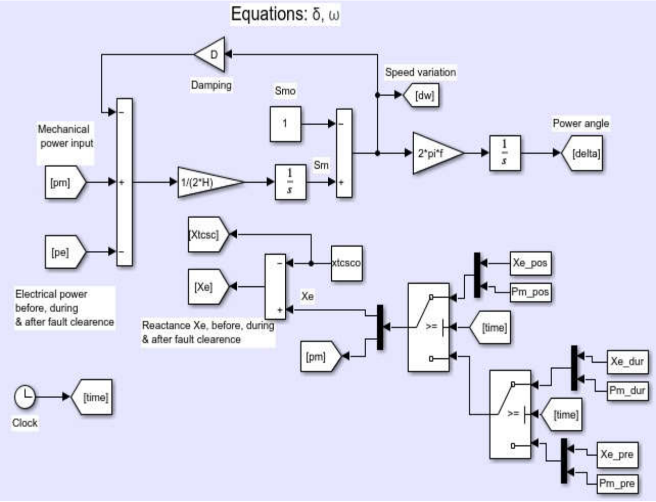


Figure 6. SMIB - Model 1.1 - Without TCSC

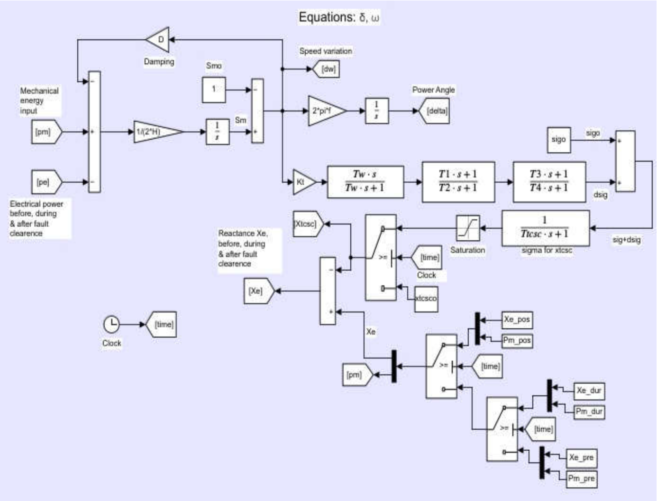


Figure 7. SMIB - Model 1.1 - With TCSC

RESULTS

The simulation was performed for Case 3 of the paper [PANDA, 2007], with a reduction of 1 pu in the mechanical power, with the following result:

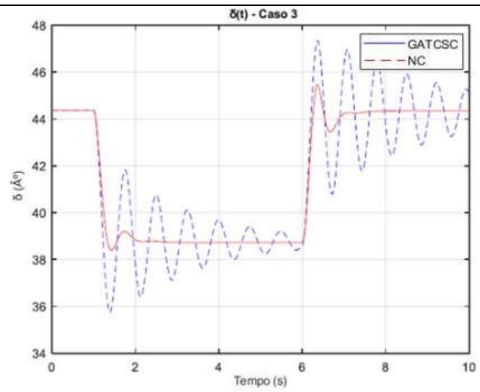
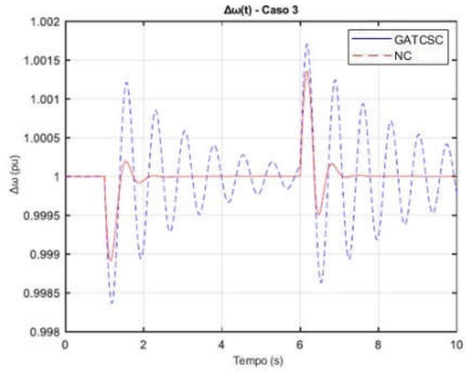
	

Figure 8 - Variation of the power angle δ	**Figure 9 - Variation of speed deviation $\Delta\omega$**

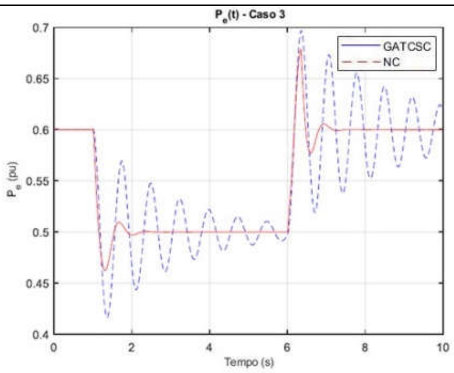


Figure 10 - Variation of electrical power P_e

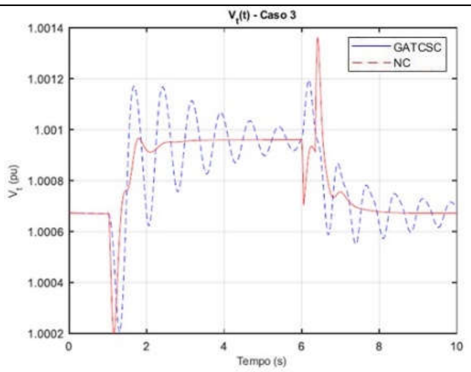


Figure 11 - Terminal voltage variation V_t

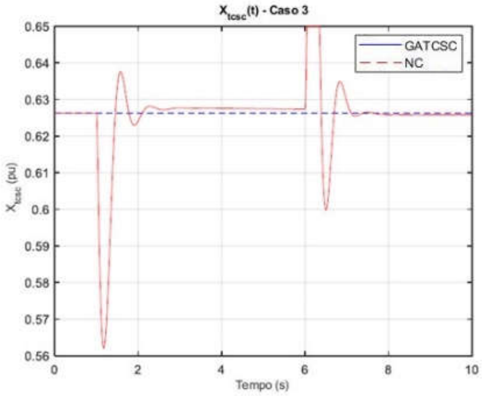


Figure 12 - X_{TCSC} variation

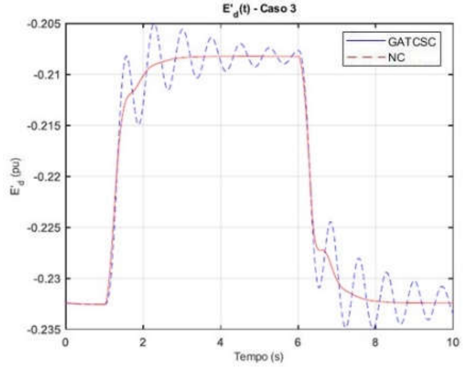


Figure 13 - Voltage variation E'_d

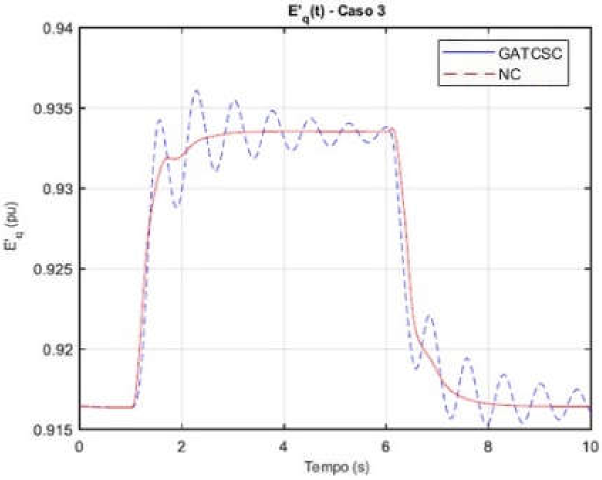


Figure 14 - Voltage variationE'_q

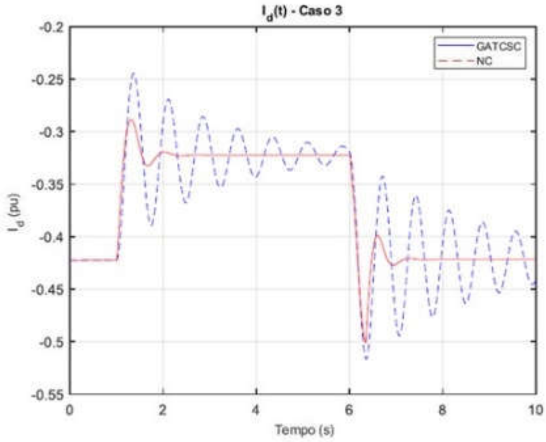


Figure 15 - Current variation I_d

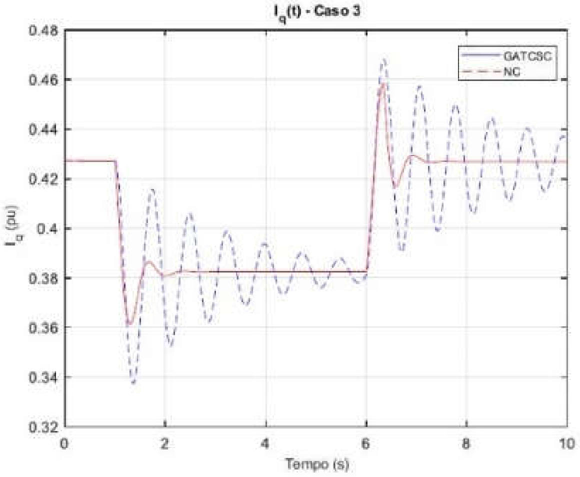


Figure 16 - Current variationI_q

Analysis of Results: Analyzing the data provided, it is possible to reproduce all the cases presented by PANDA [PANDA, 2007]. The case chosen in this article for reproduction was Case 03. Its reproduction allows us to observe that there was a performance gain in transient stability for the system by applying the TCSC for small perturbations**.**

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