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Research Article

A Fuzzy Inference-Based TCSC Control Technique to Improve Dynamic Power System Responses

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ABSTRACT

With the expansion of transmission systems, the devices that contribute to the overall power system performance must be adequate to the increasing modeling complexity and requirements. In this sense, the Flexible AC transmission system (FACTS) devices are often employed to improve stability and power quality, while the Thyristor-Controlled Series Compensator (TCSC) is a common example, able to change the equivalent transmission line impedance, improving power flow. This work discusses two established techniques for the control of TCSC devices based on the lead-lag model, whose parameters are defined through metaheuristic techniques, such as Genetic Algorithm and Particle Swarm Optimization. The results found in these publications are implemented in the Matlab/Simulink environment and confronted with the proposed Fuzzy logic application, written with linguistic inference, simplified rules, and simple membership functions. The two published models and the proposed Fuzzy logic performed satisfactorily with very similar results in all scenarios simulated considering a Single Machine Infinite Bus (SMIB) equivalent system model. The big advantage of the use of Fuzzy logic is its modeling simplicity, unlike the heuristic techniques that require much more modeling time and, sometimes, a large number of iterations to achieve acceptable parameters.

1. Introduction

Due to the intensification of the use of electric energy, new investments are necessary for expanding the electrical grid, whether as the construction of new power plants, transmission lines, or substations. However, the potential for regularization of large hydroelectric or thermoelectric plants, as well as large transmission lines, has been reduced as a result of the depletion of technical, social, environmental, and economically viable sites. It is no longer reasonable to accept constructions with massive socio-environmental impacts.

Consistently, electricity consumption has been growing over the years in Brazil, whether in the industrial, agricultural, commercial or residential sectors. According to the National Energy Balance 2022 in its summary report in 2021, electricity consumption was 4.2% higher when compared to 2020. Also, the historical electricity consumption in Brazil has increased its demand by 70% in the last 21 years, from 330 (GWh) to 570 (GWh) [1]. This shows us the irreversible path of constant expansion that electricity has been taking over other forms of energy. Compatible with the demand, the Brazilian national interconnected system also faced a great expansion in the past 10 years, from 75,000 (km) to 173,000 (km) [2].

As the electricity demand increases, the load over the transmission lines also increases. Consequently, in an overloaded system, problems like transient stability, power and frequency oscillations, unstable network voltage, and others start to appear. In this scenario, the Flexible AC Transmission System (FACTS) devices, based on power electronics, begin to be developed and applied in power networks aiming for power stability and control.

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FACTS devices are classified according to their connection to the electrical system. Their connection type can be series, shunt, shunt-series, or series-series. Each connection presents a different architecture in semiconductors placement and also presents different results in the system operation. Series devices can change the line impedance via adjustments in the series capacitor or inductor, thus improving the real power flow. Shunt devices, on the other hand, are in parallel with the grid and they inject current enhancing the voltage profile in the utility network. Shunt-series devices provide both compensations and work injecting current (shunt) and voltage (series) with a power exchange between this equipment through a DC-link capacitor. Lastly, the series-series architecture is made of two series branches in distinct power grids, enabling the power exchange among them and the optimization of power flow in both directions [3]. As part of one of the FACTS devices, TCSC improves voltage regulation and transient stability. Another important characteristic is the capacity to reduce the equivalent electric transmission line's distance. This paper will focus on the development of a simplified control based on Fuzzy logic for the Thyristor-Controlled Series Capacitor (TCSC), given its potential contributions in terms of power flow controllability and signal stability, and this control method is compared with other techniques simulated in a standard environment so that the methods can be adequately compared.

Just as there are many types of FACTS devices, also many control techniques were developed for their operation. Establishing effective means of system control and operation is one of the major areas of research and development in electrical engineering. In this sense, there are many different, published, and applied, control techniques to FACTS.

Given the exposed context, this manuscript provides a discussion on the potential for the use of Fuzzy logic in the control of TCSC devices in lieu of other techniques. The highlights can be summarized as follows: (i) an explanation of the physical concepts that involve the TCSC devices operation and how it contributes to the electrical system stability; (ii) the modeling of an equivalent system SMIB-type with the inclusion of a TCSC in its transmission line; (iii) presentation of two benchmark lead-lag metaheuristic control techniques, in addition to the proposed Fuzzy control system, and; (iv) SMIB fault simulations and comparisons between the presented control approaches.

The remainder of this paper is organized as follows. Section II provides an overview of the different TCSC devices and their applications for power system control. Section III presents the structure of two benchmark techniques and the proposed Fuzzy logic controller, while details regarding their implementation in the Matlab/Simulink environment and simulation results are portrayed in Section IV. Section V concludes the paper.

2. Thyristor Controlled Series Compensator

Certainly one of the main and best-known FACTS devices is the Thyristor-Controlled Series Compensator. Articles with TCSC control techniques are frequently published, each one presenting its relevance. [4] applies the H_∞ technique, aspiring for rotor angle stability employing the TCSC device. [5] develop a TCSC control based on the pole allocation technique and H_2 performance in order to improve the damping of oscillations between areas under multiple operating points. Stochastic techniques have also been applied to the control of TCSC as shown in the work done by [6] who proposed a Power System Stabilizer (PSS) control adopting the TCSC where the Particle Swarm Optimization (PSO) technique was used.

TCSC can be employed as subsynchronous oscillations controller as presented in [7]. The authors of [8] made a comparison between TCSC and the Unified Power Flow Controller (UPFC), where the TCSC was used as a flow controller. Other applications for TCSC are emerging, such as protecting the electrical grid against false data injection cyber-attacks, as shown in [9]. In the work developed by [10], the TCSC is coordinated with an energy storage system and works with a PID-Fuzzy control to optimize the power flow. As seen previously, there can be many applications for TCSC devices due to their versatility in controlling electrical parameters.

There are two TCSC architectures, namely the Thyristor-Controlled Series Reactor (TCSR) and Thyristor-Controlled Series Capacitor (TCSC). Both operate with a parallel Thyristor-Controlled Reactor (TCR), consisting of a reactance connected in series with a bidirectional thyristor valve. An overview of the TCSC circuit and its equivalent representation is depicted in Fig. 1.

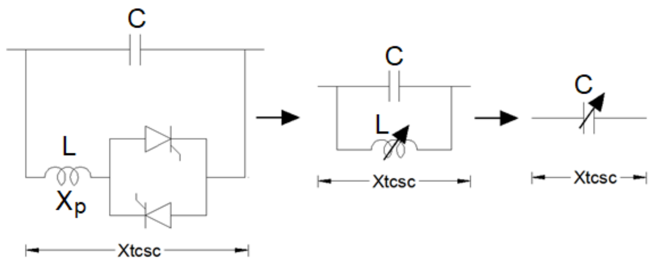


Figure 1. Equivalent TCSC circuit

The equivalent reactance X_P can be expressed as a function of the nominal reactance of inductor L and the firing angle of the thyristors α, as in (1):

$$X_P(\alpha) = X_p \frac{\pi}{\pi - 2\alpha - sen(2\alpha)} \quad (1)$$

It can be inferred that for α ϵ [0º, 90º], X_P starts from its nominal value until infinite. This controlled reactor is connected in parallel to the series capacitor of the bus, so it is possible to change the capacitive reactance by modifying the line impedance, as shown in Fig. 1. The TCSC control is then carried out according to the angle α, which adjusts the variable inductive reactance. Mathematically, the characteristic reactance X_{TCSC} can be expressed as [11]:

$$X_{TCSC}(\propto) = X_C - \frac{{X_C}^2}{(X_C - X_P)}\frac{\sigma + sen(\sigma)}{\pi} + \\ + \frac{4{X_C}^2}{(X_C - X_P)}\frac{cos^2(\sigma/2)}{(k^2 - 1)}\frac{(k\, tan(k\sigma/2) - \tan(\sigma/2))}{\pi} \qquad (2)$$

where:

X_P is the nominal reactance of inductor L;
X_C is the nominal reactance of capacitor C;
$\sigma = 2(\pi\text{-}\alpha)$ is the TCSC conduction angle; and
$k = \sqrt{X_C/X_P}$ is the compensation ratio.

As observed in (2), the TCSC reactance is a function of the thyristor firing angle, which will change the inductive reactance value, directly influencing the system compensation ratio. During the operation of the TCSC, care must be taken to prevent $X_P(\alpha)$ from being equal (or very close) to the value of X_C, otherwise, the system will become resonant, resulting in an infinite impedance on the bus -- which would be an undesirable operating condition [12]. The TCSC model can then be integrated into a Single Machine Infinite Bus (SMIB) equivalent system model to facilitate testing.

A SMIB is a synchronous machine connected to an infinite bus through a step-up transformer and at least one transmission line, as shown in Fig. 2. X_T and X_L correspond to the transformer and transmission line reactances, respectively, while V_T and V_B represent the voltages on the generator terminals and the infinite bus.

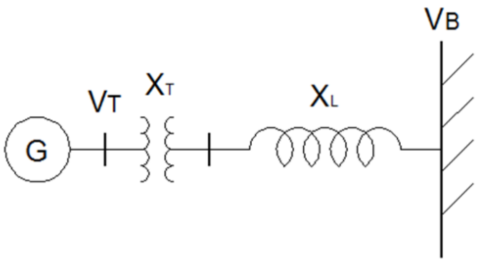


Figure 2. Simplified SMIB circuit

The current flow direction, and consequently the power, originates in the generator and pass through the transformer and the transmission, reaching the infinite bus. This model simplifies complex power system analyses. For example, when it is necessary to adjust the generator excitation parameters in a complex grid system, a SMIB -- with the equivalent impedance of the entire system --, can be proposed instead of placing all buses and loads at a given time.

In addition to the previously presented circuit, the TCSC device will be included so that stability analyzes can be conducted. The linear equation of an electromechanical stabilizer is normally used by applying parameter increments around the system operating point. The Phillips-Heffron model for a power system with a FACTS device is given by [13]:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \qquad (3)$$

$$\Delta\dot{\omega} = \left(-K_1\Delta\delta - K_2\Delta E_q' - K_p\Delta\sigma - D\Delta\omega\right)/M \qquad (4)$$

$$\Delta\dot{E_q}' = \left(-K_3\Delta E_q' - K_4\Delta\delta - K_q\Delta\sigma + \Delta E_{fd}\right)/T_{d0}' \qquad (5)$$

$$\Delta\dot{E_{fd}}' = \left[-K_A\left(K_5\Delta\delta + K_6\Delta E_q' + K_v\Delta\sigma\right) - \Delta E_{fd}\right]/T_A \qquad (6)$$

where:

$$K_1 = \partial P_e/\partial\delta\,, K_2 = \partial P_e/\partial {E_q}'\ e\ K_p = \partial P_e/\partial\sigma$$
$$K_3 = \partial E_q/\partial {E_q}'\,, K_4 = \partial E_q/\partial\delta\ e\ K_q = \partial E_q/\partial\sigma$$
$$K_5 = \partial V_T/\partial\delta\,, K_6 = \partial V_T/\partial {E_q}'\ e\ K_v = \partial V_T/\partial\sigma$$

This set of equations can be further represented by a Phillips-Heffron linearized equation model for a SMIB with the TCSC system. The corresponding block diagram for such a model is depicted in Fig. 3a.

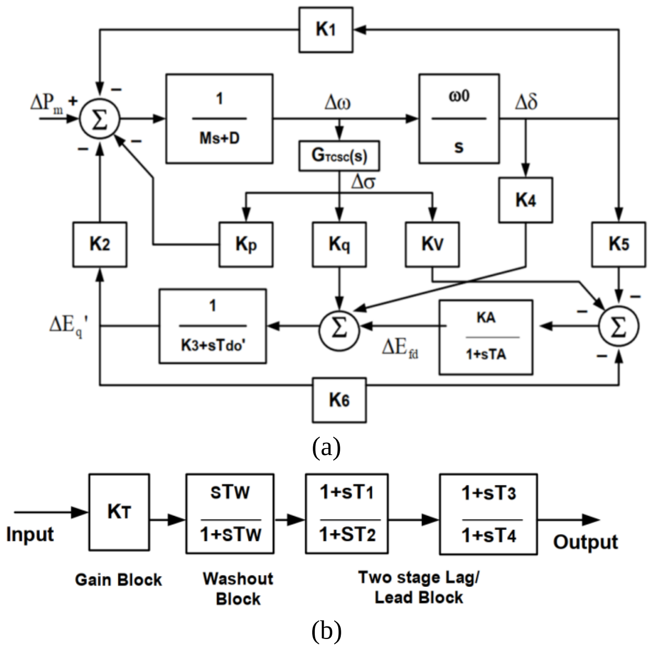


Figure 3. The structures for the a) Phillips-Heffron model of SMIB with TCSC, and; b) TCSC lead-lag [13]

Once the SMIB/TCSC model has been equated, the next step is to define the TCSC control structure and the base simulation scenarios models to be applied in the Matlab/Simulink environment.

3. Proposed Controls and Benchmark Models

With the understanding of the operation, the equations of the TCSC device, the modeling of the SMIB system, and the union of the two concepts in order to improve the power flow and the stability of the system, the proposed TCSC control technique along with some benchmark models. The Electric Power System (EPS) modeled as SMIB with TCSC form will follow the model proposed by [14].

In the next subsections, two lead-lag control techniques will be shown, where their parameters were adjusted using metaheuristic techniques. A lead-lag control structure consists of a K_T gain block, a washout filter block, and a two-stage phase compensation block, as seen in Fig. 3b.

For the lead-lag control structure, it is necessary to define the parameters K_T, T_W, T_1, T_2, T_3, and T_4. The determination of these parameters is considered a tuning problem in the multi-modal space, where some combinations of these parameters can bring good results and a single solution is optimal. Testing each of these combinations individually until finding the optimal answer is computationally infeasible, resembling the Traveling Salesman Problem, where the Salesman needs to define the best route to travel through different cities, visiting each one just once. A characteristic that makes it more difficult to parameterize these variables in the EPS is the system mutability during its stable operation or even in the face of a disturbance.

3.1. Multi-Objective Genetic Algorithm

Genetic Algorithm (GA) is a heuristic technique that performs an improved search process towards the best parameters. It is important to highlight that the answer presented by the GA, most of the time, will not be the ideal answer, but a response with a minimum acceptable quality. Finding an adequate answer through GA depends on probabilistic factors and a guided random technique to start the simulations.

Every GA needs to satisfy an objective function. In the case of controlling TCSC devices, the focus is on minimizing system oscillations in the face of a disturbance, seeking to improve stability. However, meeting the stability of the system is not a matter of a single objective once stability is related to multiple parameters, among them we have the generator rotor angle, angular velocity, and electrical power. When a GA meets more than one objective function it is said to be a Multiobjective Genetic Algorithm (MOGA). Certainly, the greatest difficulty found is meeting the different objectives, for example, when improving the response in speed and angle, the power can be out of control.

The definition of the variables K_T, T_W, T_1, T_2, T_3, and T_4 (as presented in Fig. 4) will have as objective function the stability parameters of rotor angle, angular velocity, and electrical power. The first step in MOGA is to translate the problem to the computer, where each variable is a gene and the set of six variables will be an individual or also called a chromosome. The set of individuals is the population. Individuals from this population will be crossed, and the genes of the parents (generation 1) will be passed on to the children (generation 2), and these will be analyzed in the objective function. If the objective function is met, the generational cycle ends; if not met, a new generation is started with the children.

In the work taken as reference for the MOGA control parameters, [13] made some considerations regarding the TCSC control transfer function, as shown below:

$$u = K_T\left(\frac{sT_W}{1+sT_W}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)y \qquad (7)$$

From the function shown in (7), $\boldsymbol{u}$ and $\boldsymbol{y}$ are the output and input signals respectively. The system input variable is the speed variation, and the output is α, the thyristor firing angle. In steady state, it is expected $\sigma = 0$. The T_W value is previously defined as 10 seconds, and for this reason, this gene will be removed from the problem chromosome. In order, not to make long generational iterations, parameter limits (maximum and minimum) are given on each variable. For this reason, in the genetic algorithm, the gain K_T and the time constants T_1, T_2, T_3, and T_4 limits must be defined by the user. The referred author assumed that the gain K_T should vary from 30 to 80 and, as the time constants have closer values, their simulation limits will be equal $T_1 = T_2 = T_3 = T_4$ between 0.1 and 0.6.

The simulation parameters were defined with an initial population of 50 individuals (chromosomes), a maximum of 100 generations (iterations), and a maximum mutation degree of 0.3 between generations. Values achieved in this work, as the given variables uncertainty limits are shown in Table 1 [13].

Table 1. MOGA-Enhanced Control Parameters

Param.	K_T	T_1	T_2	T_3	T_4
Min.	30	0.1	0.1	0.1	0.1
Max.	80	0.6	0.6	0.6	0.6
MOGA	32.6247	0.1464	0.1402	0.1235	0.1524

Simulations were performed with the values presented in Table 1, and the authors concluded that the presented solution delivers control for angle deviation, angular velocity, and electrical power.

3.2. Particle Swarm Optimization

In the same vein as other population-based stochastic techniques, the Particle Swarm Optimization (PSO) algorithm can also be used for parameter fitting. The origin of this method was the observation of animals that opt for collectivism, taking advantage of social sharing, rather than individuality, which results in competition. The main examples to be cited are the fish that group together in shoals and the grouping of birds when they are moving.

This technique shares some similarities with the Genetic Algorithm, such as the definition of an initial population, which has a guided solution. However, unlike GA, PSO does not have evolution operators such as crossover and mutation. With these differences, this method has fewer parameters and therefore becomes more attractive to implement.

Potential solutions to the improvement problem are called particles and they "fly" through the problem space in search of the best answer. Particle displacement can occur based on two principles. The first is related to the particle experience and the second is the experience acquired by the group following the best results particles (solutions). In the first case, the particle has a memory so it can return to the previous point if the new point is less favorable. In the PSO algorithm, the particle position memory referring to its best answer is called position best (p_{best}) while the best of all particles in the population (group) is called group best (g_{best}). The particle displacement speed is variable and its calculation takes into account the parameters "p_{best}" and "g_{best}" according to the equations present in (8).

$$v_{j,g}^{(t+1)} = w.v_{j,g}^{(t)} + c_1.r_1.\left(pbest_{j,g} - x_{j,g}^{(t)}\right) + \\ +c_2.r_2.\left(gbest_g - x_{j,g}^{(t)}\right) \quad (8)$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)} \quad (9)$$

The interested reader may refer to [15] for further details and discussion regarding this modeling approach. Analyzing the velocity equation in (8), there are two random variables r_1 and r_2 that give an unpredictable velocity behavior for each particle. As the speed is variable and the position is speed-dependent (9), the position also is variable and interdependent on the group.

Likewise the previous subsection, a published article will be taken as a reference for the PSO control parameters. [16] also made some considerations regarding the TCSC control using the PSO technique. In the same way as the MOGA algorithm, the PSO technique will aim to define the variables K_T, T_W, T_1, T_2, T_3, and T_4 (as shown in Fig. 3b), however, in this case, the author, this time, chose to make $T_1 = T_3$, $T_2 = T_4$, and $T_W = 10$, keeping the same stability multi-objective of rotor angle, angular velocity, and electrical power. Parameter limits were given to K_T, and the time constants T_1 and T_2. The author assumed that the gain K_T should vary from 5 to 70 and the time constants, T_1 and T_2, between 0.1 and 1.0.

The results achieved after the simulation, as well as the limits established for each variable, are shown in Table 2 [16].

Table 2. PSO-Enhanced Control Parameters

Param.	K_T	T_1	T_2
Min.	5	0.1	0.1
Max.	70	1.0	1.0
MOGA	35.2107	0.80904	0.75106

In the end, the author carried out Matlab/Simulink simulations with the PSO-optimized values and obtained control in the TCSC response due to oscillations. In addition, it was reported that this PSO-based parameter improvement process consumed approximately 3,207 seconds of computational time [16].

3.3. Fuzzy Logic

Nowadays, many of the controls employed in FACTS devices are PI-type and are focused on regulating the deviation of active and reactive power. PI controls are simple and easy to develop, however, their performance is compromised when large amplitude oscillations occur in the system. To work around this problem a simple fuzzy logic control can be used. It is known that fuzzy logic has been successfully applied for many years in the excitation control of machines [17] and in the reactors switching control [18].

Differing from the line of stochastic computational techniques, where a good solution is sought in the tangle of answers, Fuzzy logic is based on the observation of how human beings make decisions based on linguistic information rather than numerical information. When compared to the previous alternatives with stochastic methods presented in 3.1 (MOGA) and 3.2 (PSO), it is noticed a greater simplicity in the elaboration of the control model using Fuzzy logic. It is not necessary, for example, to define a set of partially satisfactory responses (populations) and also not necessary to define operation limits for variables that, in some cases, require operator expertise.

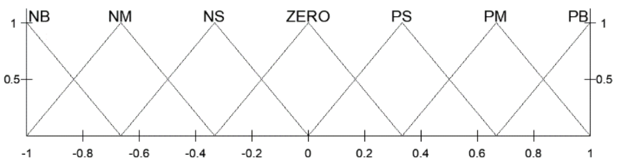
Then, the proposed model consists of replacing the lead-lag-type control structure with a non-adaptive Fuzzy Logic Controller (FLC) with linguistic inference (Mamdani). This choice was made because it is expected gain in terms of problem modeling time, the possibility of using linguistic parameters, and, especially, the absence of an increased number of iterations to reach improved answers.

As per the previously proposed methods, it is necessary to define an input and output. In order to maintain equality between the methods, the input to be fuzzified will be the angular velocity, while the defuzzified output is the thyristor firing angle control.

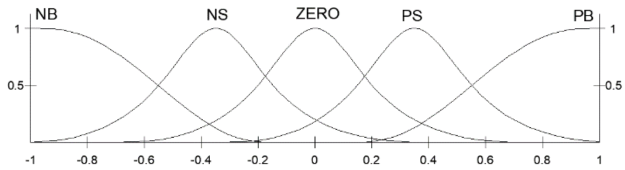
Additionally, is necessary to define the Membership Functions (MF) and the rules that will govern the Mamdani inference method. For the MF definition, the work carried out by [19] was taken as a reference. In this article, the authors proposed a PI-Fuzzy system with reduced rules for the control of a TCSC.

At this point, it is important to highlight that the work developed by [19] is different from the current proposal of this work. The authors of [19] and [20] propose the implementation of an adaptive PI-Fuzzy system to control the TCSC triggering. The characteristics that govern the adaptive Fuzzy (MF and rules) are adjusted in real time. Another difference is that the FLC inputs are different, in the models discussed in previous articles there are two inputs, one is measurement error around a defined setpoint and the other one is the variation of this error between samples. Furthermore as the system has two inputs and each input has seven MF, it results in 49 system rules, being much larger to the proposal of this work.

Focusing on simplicity and modeling timing reduction and taking into account previous experiences in [19] and [20], different Membership Functions size of input (angular velocity) and output (firing angle) were tested, among them 3, 5, 7 and 9. The results achieved with 7 and 9 MF were the best, and the choice to use 7 was made based on rule reduction, the less Membership Functions fewer rules will be used. Angular Velocity (W) was set as input and their membership functions were sectioned into seven equally spaced triangular functions as detailed earlier. However the firing angle, set as output, is composed of three central Gaussian functions, a Z-shape function on the negative side and an S-shape function on the positive side. Both, input and output, are detailed on Fig. 4a and Fig. 4b respectively where N, P, B, M, S means negative, positive, big, medium and small.



(a)



(b)

Figure 4. Fuzzy membership functions a) input and b) output

Finally, the linguistic inference rules must be set in order to allow the system to operate correctly. This work will apply a direct proportionality relationship between input and output, where severe angle corrections are applied when the velocity is far from its steady state, all rules are shown in Table 3.

Table 3. Mamdani Inference Rules

Speed (W)	Firing Angle (α)
NB	NB
NM	NB
NS	NS
ZERO	ZERO
PS	PS
PM	PB
PB	PB

The proposed fuzzy logic will replace the time constants T_W, T_1, T_2, T_3, and T_4 of the lead-lag model, however, the K_T gain is still missing. Based on the simulations carried out using MOGA and PSO, the authors set values for the uncertainty of K_T between 5 and 80. With the Fuzzy logic implemented in the Simulink block diagram, quick simulations were performed with some integer values of K_T starting from 0 to 100 with a step between simulations of 10. An acceptable response result was observed when K_T equals 50.

4. Results and Discussion

All the controllers discussed in the previous section are implemented and tested in a SMIB-type power system, similar to the one shown in Fig. 2, with the inclusion of a parallel transmission line, as presented in Fig. 5.

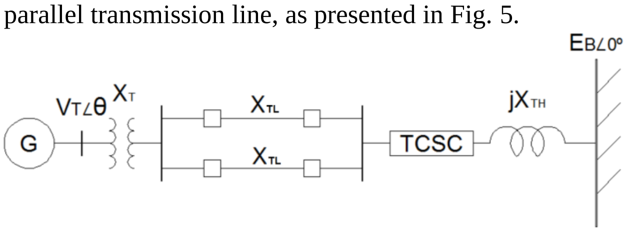


Figure 5. SMIB with TCSC and parallel transmission line

The simulations consider two different scenarios. First, the generator operates a little over its nominal capacity when a three-phase short occurs on the generator bus. The second scenario occurs with the generator at nominal load when a three-phase short circuit occurs in one of the lines. After the short, the line with the fault will be removed from the system.

In both cases, the fault type will be a symmetrical three-phase short circuit and will occur at instant 1 (s), being successfully extinguished after 100 (ms). The circuit returns to its original characteristics in scenario 1, however, in scenario 2, the removal of one of the system's transmission lines results in an increase of the SMIB equivalent impedance. The program used to calculate the initial parameters was developed and executed in Matlab R2020a, with all parameters listed in Appendix. The

Simulink diagram was made based on the model shown in Fig. 3, referring to the work published by [14].

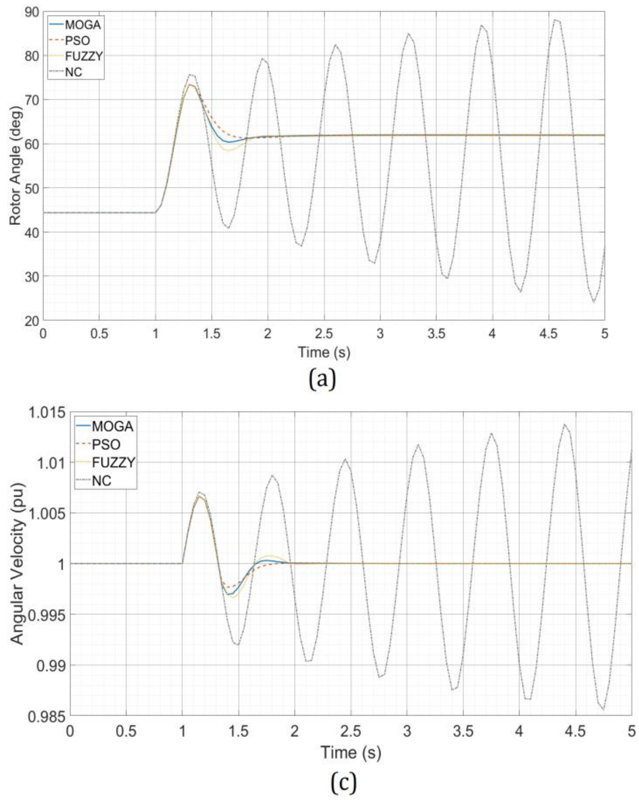


Figure 6. Three Phase Fault Results: a) Rotor Angle; b) Electrical Power; c) Angular Velocity, and; d) Equivalent Reactance

The gain and time constants used in the Genetic Algorithm (MOGA) are shown in Table 1. The parameters used in the Particle Swarm (PSO) are shown in Table 2. Finally, the Fuzzy logic will follow the input, output, member functions, and the rules described in subsection 3.3.

4.1. Three Phase Fault Unchanged System

In this scenario, the generator is operating with a mechanical load of 1.1 (pu) when in 1 (s) a three-phase fault occurs on the machine bus, lasting 100 (ms). After this period, the fault is eliminated and the system will return to its nominal impedance parameters. The TCSC responses with the MOGA, PSO, and Fuzzy logic techniques for the variables of rotor angle, electrical power delivered to the infinite bus, angular velocity, and the circuit equivalent reactance, are present in Fig. 6a, 6b, 6c, and 6d respectively. Along with the controlled curves, the not-controlled (NC) system response is also present, for comparison purposes.

Analyzing Figure 6a, the speed remains nominal until the instant of 1 (s) when the disturbance occurs. After 1.1 (s) the uncontrolled signal assumes an increasing sinusoidal shape, indicating a long-term instability behavior if no control measures are applied. For this reason, the use of control techniques is indispensable.

The TCSC responses with the MOGA, PSO, and Fuzzy logic techniques for the variables of rotor angle, electrical power, angular velocity, and the circuit equivalent reactance are very similar in reaction to the disturbance that occurred on the generator bus. This is a clear indication that lead-lag control methods as well as the proposed Fuzzy logic are well-designed, and can handle this type of disruption.

4.2. Three Phase Fault and Line Removal

In the second scenario, the generating machine is operating at its nominal load of 1.0 (pu) when in 1 (s) a three-phase fault occurs in one of the transmission lines with a duration of 100 (ms). After this period, the line is removed from the system by changing the initial pre-fault parameters of the SMIB. As in the previous case, the TCSC responses with the MOGA, PSO, and Fuzzy logic techniques for the variables of rotor angle, electrical power delivered to the infinite bus, angular velocity, and the circuit equivalent reactance, are present in Fig. 7a, 7b, 7c and 7d, respectively. It is important to note that in Fig. 7a and 7c the Not Controlled (NC) curve was removed due its high values.

In this type of failure, the Fuzzy logic presented slightly inferior results, having a longer time to stabilize the system after the line removal. When the results are compared, more oscillations and a longer recovery to the new stable state are observed in the Fuzzy controller. Steady state time for the MOGA and PSO techniques was slightly higher than 1.5 (s) while stability in the Fuzzy control is reached 2.5 (s) after fault.

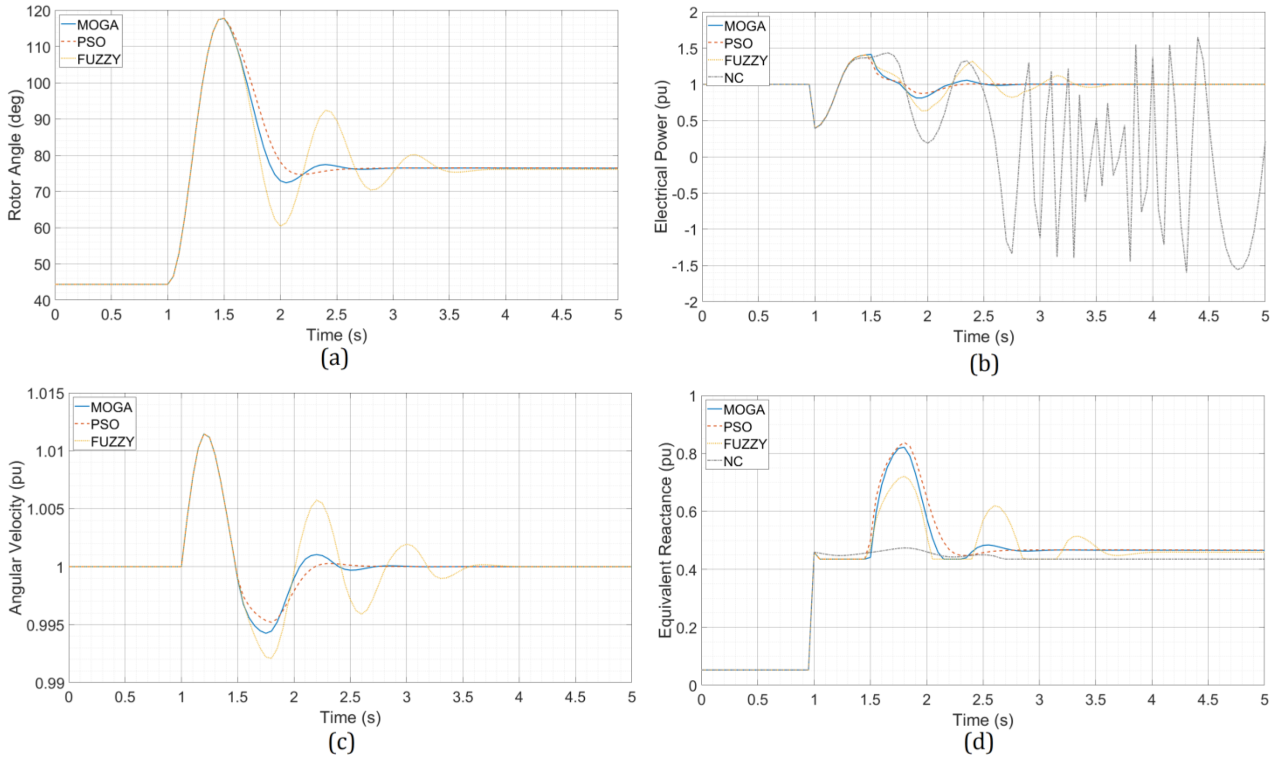


Figure 7. Three Phase Fault with Line Removal Results: (a) Rotor Angle; (b) Electrical Power; (c) Angular Velocity, and; (d) Equivalent Reactance.

When the equivalent reactance curves are compared in Fig. 7d, the Fuzzy logic presents a less aggressive response and, for this reason, the steady state is reached more slowly. This result does not discredit the Fuzzy logic because, 1.5 (S) after the fault, the Fuzzy curve signals are already with reduced amplitude and tending to stability.

After carrying out the simulations and observing the results, it is interesting to establish comparisons between the control techniques. In Table 4 there is a comparison between the characteristics of each technique presented in this work in addition to the post-fault signal stabilization time in both scenarios.

Table 4. Comparison of control techniques and their operation times

Ref.	Control	Guided solutions	Itera-tions	MF	Time to stabilize (s)	
					Scenario #1	Scenario #2
[13]	MOGA	Yes	Yes	No	1.0	1.5
[16]	PSO	Yes	Yes	No	1.0	1.5
Paper	FLC	No	No	Yes	1.0	2.5

Analyzing the data in Table 4, it can be seen that there is a lot of similarity, in terms of time, between the control techniques. It is seen that the FLC achieves stability in all simulated cases with values often equal to those of lead-lag techniques. In scenario 2, the FLC response is one second higher than the other techniques. This result does not discredit Fuzzy logic, especially because it presents a simpler modeling when compared to heuristic techniques.

5. Conclusion

To solve the multi-objective problem of the TCSC firing angle, two stochastic lead-lag control structures were presented in this work, requiring a considerable time to model and perform iterations aiming for a reasonable solution. Both the Genetic Algorithm (MOGA) and the Particle Swarm (PSO) initially need a set of possible solutions for the system and, from this initial set, new solutions begin to be tested. The answers (chromosomes in MOGA or particles in PSO) are then compared with an objective function that presents minimum parameters to be met.

The greatest disadvantage of these models relates to the mutability of the EPS, which is common to occur over the years. In certain circumstances, the addition of new system nodes, a new generator, or a transmission line will invalidate the modeling carried out so far, making it necessary to recompile all the parameters, model the new system, and carry out new iterations. For this reason, this work endeavored to propose the use of Fuzzy logic, with rules and simple member functions, in a summarized system (equivalent) and even so, it presented such reliable results, and in some cases, even better than the stochastic methods used in the lead-lag control system.

Fuzzy logic showed to be more versatile when compared to the cited techniques. Its modeling was much faster, there was no need to present pre-defined solutions for the control, as well as the non-performance of iterations to meet the minimum acceptable criteria. For example, as stated at the end of subsection 3.2, the PSO parameters were improved with a computational time of approximately 50 minutes, without considering all the time used in the initial modeling of the problem. On the other hand, the Fuzzy technique used in the simulations was made using one input, one output, seven triangular MF, and finally seven simple rules. To apply the fuzzy logic, an average time of 10 minutes is estimated to compose the system control, from the modeling of the input and output parameters to the linguistic rules.

For this reason, when an equivalent SMIB-type system is presented, so that the thyristors firing control is modeled, it is advisable to first use the Fuzzy logic as a solution and, if this is not enough, other techniques can then be applied. Another advantage, in this case, is the use of linguistic norms, that allow the same idealized model in this work to be used in other SMIB systems, with different variables and initial parameters, such as reactances, time constants, and bus voltages.

The main objective of the work is not to invalidate the use of other control techniques, but rather to propose the use of a simpler system before moving on to more complex alternatives. This proposal can save a lot of effort and time in researching control solutions, especially when TCSC is considered to improve the operation of a system. This work is not definitive and does not mean that the use of fuzzy logic will be successful in all existent possible network configurations. For this reason, new simulations must be carried out both in equivalent SMIB systems and in multiple bus systems so that more detailed conclusions can be presented.

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Appendix

Parameters values used in simulations. All information is in pu, unless specified.

Generator:

f = 60 Hz, H = 3.542, D = 0,
X_d = 1.7572, X_q = 1.5845, X_d' = 0.4245, X_q' = 1.0400,
T'_{d0} = 6.6600, T'_{q0}=0.4400,
R_a=0, P_e=1.1, Q_e=0.0222, δ_0=44.37º.

IEEE ST1 Exciter:

K_a = 400, T_a = 0.0255.

System:

S_{base} = 100 MVA, R = 0,
X_{TL} = 0.8125, X_T = 0.1364, X_{TH} = 0.1363.

TCSC:

X_{TCSC} = 0.6262, α_0 = 142º,
X_{MIN} = 0, X_{MAX} = 0.8X_{TL}.

References

[1] E. P. E. Brazilian Energy Research Company, “Balanço energético nacional Relatório Síntese 2022: ano base 2021,” Ministério de Minas e Energia - Brasil, Rio de Janeiro, 2022.

[2] O. N. S. Brazilian National System Operator, “Operation Network Transmission Lines,” Ministério de Minas e Energia - ONS, [Online]. Available: https://dados.ons.org.br/dataset/linha-transmissao. [Acesso em 20 August 2022].

[3] G. S. Chawda, A. G. Shaik, O. P. Mahela, S. Padmanaban e J. B. Holm-Nielsen, “Comprehensive review of distributed FACTS control algorithms for power quality enhancement in utility grid with renewable energy penetration,” *IEEE Access,* vol. 8, pp. 107614--107634, 2020.

[4] L. Chang, Y. Liu, Y. Jing, X. Chen e J. Qiu, “Semi-Globally Practical Finite-Time Hinf Control of TCSC Model of Power Systems Based on Dynamic Surface Control,” *IEEE Access,* vol. 8, pp. 10061--10069, 2020.

[5] J. Deng e X.-P. Zhang, “Robust Damping Control of Power Systems With TCSC: A Multi-Model BMI Approach With H $_{2}$ Performance,” *IEEE Transactions on Power Systems,* vol. 29, pp. 1512--1521, 2014.

[6] M. M. de Menezes, P. B. de Araujo e D. B. do Valle, “Design of PSS and TCSC damping controller using particle swarm optimization,” *Journal of Control, Automation and Electrical Systems,* vol. 27, pp. 554--561, 2016.

[7] L. A. Pilotto, A. Bianco, W. F. Long e A. Edris, “Impact of TCSC control methodologies on subsynchronous oscillations,” *IEEE transactions on Power Delivery,* vol. 18, n. 1, pp. 243 -- 252, 2003.

[8] S. E. Mubeen, R. Nema e G. Agnihotri, “Comparison of Power flow control: TCSC versus UPFC,” *2008 Joint International Conference on Power System Technology and IEEE Power India Conference,* pp. 1 -- 5, 2008.

[9] E. Naderi, S. Pazouki e A. Asrari, “A remedial action scheme against false data injection cyberattacks in smart transmission systems: application of thyristor-controlled series capacitor (TCSC),” *IEEE Transactions on Industrial Informatics,* pp. 2297--2309, 2021.

[10] B. Dekaraja e L. C. Saikia, “Impact of energy storage and flexible alternating current transmission devices in combined voltage and frequency regulation of multiarea Multisource Interconnected Power System,” *Energy Storage,* vol. 4, n. 3, pp. 2578 -- 4862, 2022.

[11] R. M. Mathur e R. K. Varma, Thyristor-based FACTS controllers for electrical transmission systems, John Wiley \& Sons, 2002.

[12] S. Meikandasivam, R. K. Nema e S. K. Jain, “Behavioral Study of TCSC Device -- A MATLAB/Simulink Implementation,” *International Journal of Electrical and Computer Engineering,* vol. 8, 2008.

[13] S. Panda, R. Patel e N. Padhy, “Power system stability improvement by TCSC controller employing a multi-objective genetic algorithm approach,” *International Journal of Electrical and Computer Engineering,* vol. 1, pp. 553--560, 2006.

[14] S. Panda e N. P. Padhy, “MATLAB/SIMULINK based model of single-machine infinite-bus with TCSC for stability studies and tuning employing GA,” *International Journal of Energy and Power Engineering,* vol. 1, pp. 560--569, 2007.

[15] A. T. Al-Awami, Y. Abdel-Magid e M. Abido, “A particle-swarm-based approach of power system stability enhancement with unified power flow controller,” *International Journal of Electrical Power \& Energy Systems,*

vol. 29, pp. 251--259, 2007.

[16] S. Panda, R. Patel e N. Padhy, "Robust Coordinated Design of PSS and TCSC using PSO Technique for Power System Stability Enhancement," *Journal of Electrical Systems,* vol. 3, pp. 109--123, 2007.

[17] M. A. M. Hassan, O. Malik e G. Hope, "A fuzzy logic based stabilizer for a synchronous machine," *IEEE Transactions on Energy conversion,* vol. 6, pp. 407--413, 1991.

[18] M. Noroozian, G. Andersson e K. Tomsovic, "Robust, near time-optimal control of power system oscillations with fuzzy logic," *IEEE transactions on power delivery,* vol. 11, pp. 393--400, 1996.

[19] S. Hameed, B. Das e V. Pant, "Reduced rule base self-tuning fuzzy PI controller for TCSC," *International Journal of Electrical Power & Energy Systems,* vol. 32, pp. 1005--1013, 2010.

[20] R. Navabi, R. Etemad e H. A. Shayanfar, "Self tuning fuzzy PI controller for UPFC to improve power system stability optimized by ant colony method," *2010 Asia-Pacific Power and Energy Engineering Conference,* pp. 1--5, 2010.