TCSC Based Compensation with Genetic Algorithm Applied to the Optimal Reactive Power Flow Problem

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Abstract. In recent years, economic and environmental issues have shown the need to enhance the performance of power systems in order to postpone expansion investments. These issues have motivated research studies and technology developments to control the power flow, which allows better use of the current structure. One of these technologies is the Thyristor Controlled Series Compensation (TCSC), which permits a smooth control of the power flow throughout the transmission lines. This paper aims to analyze the performance of a TCSC device in power systems on the optimal reactive power flow point of view. The method uses a genetic algorithm to enhance the performance of power systems by adjusting the voltage of the control buses and the TCSC compensation. The method was tested in two standard IEEE 14-bus and IEEE 118-bus systems in the base case and under contingencies. The results showed that the method improved system performance by decreasing the reactive power loss and enhancing the voltage profile, both in the base case and under contingencies.

Keywords: Genetic Algorithm, Power System Planning, Reactive Power Flow Problem, Transmission Line Compensation, FACTS Devices.

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1 Introduction

In the last decades, the demand for electricity in Brazil and in the world has constantly increased, since the economic development and population growth [2]. In order to ensure a quality electricity supply, constant investments and proper operation are necessary to meet technical and economic needs. The overload of the system becomes impracticable due to the high cost of implementation, being necessary to optimize the existing installations so that investments in the electric sector are postponed as much as possible [6].

Several technologies have been studied and developed in order to make the power system more efficient and stable. For example, FACTS devices (Flexible AC Transmission Systems) are based on power electronics and allow better control of power flow, voltage stabilization, transmission capacity increasing, and others [3]. Among different types of FACTS devices, TCSC (Thyristor Controlled Series Compensation) allows better control of the power flow in the transmission lines, thus maximizing the transmission capacity [17].

Some performance indicators in power systems, such as voltage profile and energy losses, are directly related to the reactive power flow. FACTS devices, such as the aforementioned TCSC, have a significant influence on the reactive power flow, which directly affects the system performance. To improve a power system performance, some decision variables, such as the voltage of control buses and the TCSC, may be adjusted by using optimization methods. The genetic algorithm [8] shows promise for complex problems, such as the reactive power flow problem, since it is a global search method with efficient convergence [5].

This work aims to analyze the using of TCSC device in power systems from the point of view of the reactive power flow problem. The proposed solution provides to increase the reactive power flow reserve, thus enhancing the voltage stability. The proposed method uses a genetic algorithm as global optimization method in order to adjust the control bus voltage and the TCSC device. The proposed method is validated by an experimental study by using the IEEE 14 and IEEE 118 busbar systems. The results show that the proposed solution enhances the system stability, even without the TCSC device.

The rest of this word is organized as follows. Section 2 presents recent studies on the application of TCSC devices in power systems. Section 3 discourses the main concepts on FACTS devices, especially, in Section 3.1, on the TCSC and its advantages when installed in power systems. Section 4 presents the proposed method which uses a genetic algorithm to solve the reactive power problem. Section 5 shows the experiments and the results analyses. Finally, Section 6 presents the conclusions and suggestions to future works.

2 Related Works

In the last years, several works have used TCSC devices and other systems to increase the transmission capacity and to enhance the voltage stability in power systems [3, 6, 15]. Eladany et al. [6] developed an algorithm for optimal allocation of TCSC devices and improvement of the transient stability in electrical systems. The algorithm combined the particle swarm optimization, clustering techniques and catastrophe theory algorithm. Bruno et al. [3] explored the influence of TCSC in transmission systems through dynamic control of transmission line impedance. In results, the improvement of the tension profile and transient stability was evidenced.

Yadav and Bala [17] used a particle swarm optimization method to determine the optimal location of the TCSC device in the system, in order to increase the power transfer capacity. Mahapatra et al. [13] presented a proposal to improve voltage stability based on the combination of the IGSA (Improved Gravitational Search Algorithm) and FA (Firefly Algorithm) algorithms, together with the TCSC, through their optimal location and capacity.

Kalaivani and Dheebika [11] used an optimization method based on a genetic algorithm to improve voltage stability and decrease power losses and generation costs in the system. The optimal locations of FACTS devices are determined, such as TCSC, in addition to SVC (Static VAr Compensator) and UPFC (Unified Power Flow Controller). Kapetanaki et al. [12] have developed a probabilistic method to maximize the use of wind units. The study showed that the use of various reliability indicators and SVC and TCSC devices allow to integrate more wind units in the system. Nascimento et al. [15] developed a method for automatic allocation of FACTS devices in power systems with evolutionary algorithm. The method also seeks the optimal dispatch of reactive power of the generators having as a performance indicator three performance indicators, namely, the total loss of reactive power, the voltage deviation of the load bars and a stability indicator.

In general, recent studies have addressed the impacts of installing TCSC devices on the electrical system with a focus on optimizing the voltage profile and operating costs. This study goes further, analyzing the loss of total reactive power faced with two situations: i) optimization of voltage in the load buses; and ii) optimization in these buses added to the insertion of the TCSC device in the critical system bus. Considering that electrical systems have been increasingly overloaded, studies regarding stability became great relevance.

Elgebaly et al. applied a genetic algorithm to control Static Synchronous Series Compensators (SSSC) devices [7]. The authors propose an objective function to design and control SSSC devices by considering various technical and economical indices. The formulation of the objective function requires power flow analysis in the compensated transmission line under different loading conditions and compensation levels. The genetic algorithm and Self-adaptive Multi-population Elitist Jaya Algorithm (SAMPE-JAYA) are proposed as optimization techniques to obtain the minimized value of the multi-objective function. This paper proposes the installation of two SSSC devices in transmission line that leads to the improvement of the design and control indexes.

Zadehbagheri et al. [18] used a genetic algorithm to locate and achieve the optimal capacity of TCSC in transmission networks. The objective function is defined in order to reduce losses and increase network load ability. In the economic approach, the cost of installing the equipment in question was also included in the optimization problem. In this approach, the profit from installing TCSC is considered as the objective function of the problem and the best place and capacity of the equipment was determined in order to achieve the maximum amount of profit. In order to two-objective optimization in the technical approach, the genetic algorithm based on the Pareto front and the multi-objective HSA has been used. The model combines both TCSC and static VAR compensators (SVC). The results of numerical studies show that FACTS devices can have a significant effect in reducing losses and increasing network load ability.

3 FACTS Devices

Flexible AC Transmission Systems (FACTS) are power electronic devices which provide more controllability in power systems [6]. Several FACTS devices have been introduced for various applications in worldwide. A number of new types of devices are in the stage of being introduced in practice. FACTS devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. The basic applications of FACTS devices are [1]:

- power flow control;
- increase of transmission capability;
- voltage control;
- reactive power compensation;
- stability improvement;
- power quality improvement;
- power conditioning;
- flicker mitigation; and
- interconnection of renewable and distributed generation and storages.

There are several types of FACTS devices in which their applications depend on the objective, such as voltage, current or power control. Among several FACTS devices the following may be listed [9]:

- Static Voltage Controller (SVC): a shunt-connected static VAr generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the system. This is a thyristor-controlled thyristor-switched reactor, and/or thyristor-switched capacitor or combination;
- Static Synchronous Compensator (STATCOM): operates as a shunt-connected static VAr compensator whose capacitive and inductive output current can be controlled independent of the AC system voltage. this device can be based on a both voltage- or current-sourced converter;
- Thyristor Controlled Series Capacitor (TCSC): consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance. This is based on thyristors without the gate turn-off cabability;
- Static Synchronous Series Compensator (SSSC): operates without an external electric energy sources a series compensator whose output voltage is in quadrature with the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. This may include transiently rated energy storage or absorbing devices to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real voltage drop across the line;
- Unified Power Flow Controlled (UPFC): a combination of STATCOM and SSSC which are coupled with a common DC link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source; and
- Interphase Power Controller (IPC): a series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set independently by adjusting the phase shifts and/or the branch impedances, by using mechanical or electronic switches.

This work analyses the application of the TCSC device to control the reactive power flow in power systems.

3.1 Thyristor Controlled Series Capacitor

Thyristor Controlled Series Capacitor (TCSC) consists of the series compensating capacitor shunted by a thyristor-controlled reactor, as shown in Figure 1. The basic idea of the TCSC is to provide a continuously variable capacitor [14]. The steady-state impedance of the TCSC is from a parallel L_C circuit, by consisting of a fixed capacitive impedance, X_C, and a variable inductive impedance, $X_L(\alpha)$, such that

$$X_{TCSC}(\alpha) = \frac{X_C \, X_L(\alpha)}{X_L(\alpha) - X_C} \qquad (1)$$

where α is the delay angle measured from the crest of the capacitor voltage.

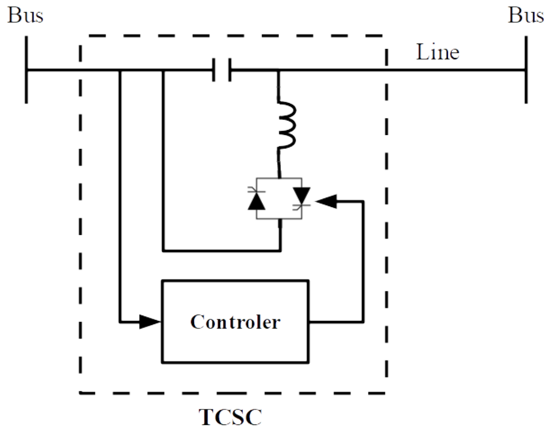

Figure 1: Schematic diagram of a TCSC device

Among the advantages to use TCSC device in power systems, the following can be highlighted not limited to [9, 14]:

- fast and continuous control of the series compensation in the transmission lines;
- dynamic control may ensure optimum power flow through both normal and emergency conditions;
- increase the loading capability of lines to their thermal capabilities, thus including short term and seasonal;
- Damp the electromechanical oscillations of power systems and machines;
- increase the system security through raising the transient stability limit;
- provide flexibility in siting new generations;
- reduce reactive power flows, thus allowing the lines to carry more active power;
- support the voltage regulation, since this generates reactive power proportional to the loading;
- control the line capacitance and reactance, thus limiting short-circuit currents and overload; and
- increase utilization of lowest cost generation.

Since the increasing of the transmission capacity and the power flow control, TCSC presents technical and economic advantages, which are the reason this technology is being applied in power systems worldwide [12].

4 Genetic Algorithm for Optimal Reactive Power Flow

This section presents the proposed method based on genetic algorithm for handling the reactive power flow problem. Genetic algorithm is a method based on population which uses Darwin's theory of evolution as mechanism of search [10, 4]. Theoretically, a genetic algorithm (GA) may be applied to any optimization problem. GA is a probabilistic global search and optimization method that achieves the global optimum with a probability of 1 [16].

The proposed method uses a GA to adjust the decision variables of the problem, i.e., the voltages of the control buses and the reactances of the TCSC devices. The method based on GA aims to minimize the total reactive power loss or simply reactive power loss.

Figure 2 shows the block diagram of the genetic algorithm applied to the reactive power flow problem. A population in an AG is composed of individuals or candidates for solutions of the problem. An individual is formed by genes, i.e., the decision variables of the problem. The solution proposed by an individual is evaluated by a fitness function. The solution quality is the individual fitness.

From N individuals of the population, $P(k)$, at k-th generation, a pool of individuals is selected, $Q(k)$. These individuals are combined with each other and generate the offsprings, $F(k)$, which are mutated according to a probability, p_m, thus generating $F(k)$. Then, from the current population and the offsprings, $P(k) + F(k)$, N individuals are selected to form a new population, $P(k+1)$, for the next generation, $k+1$. Thus, the evolutionary process continues until a stopping criterion is satisfied.

As a biological population, a GA population evolves after generations through variation and selection operators. Therefore, GA tends to produce a population with a better mean fitness than the initial one. The next sections present the solution model (individual) and the operators that compose the search mechanism of the genetic algorithm.

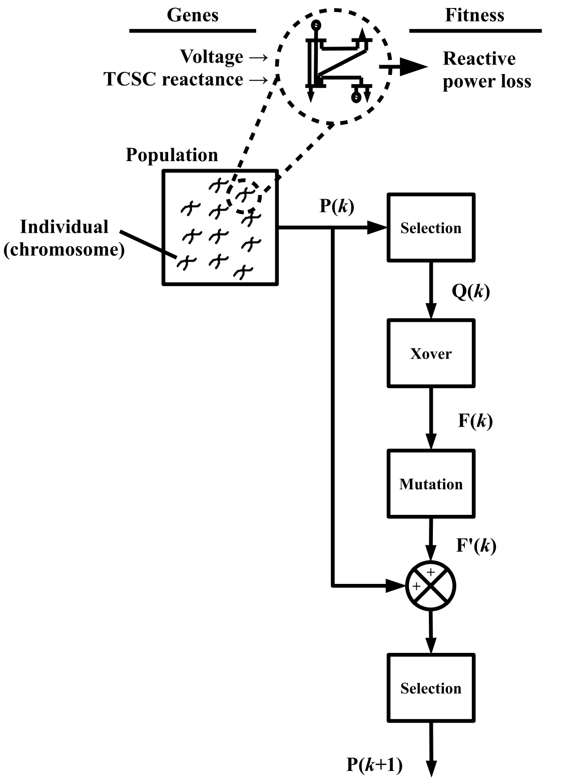

Figure 2: Block diagram of GA for reactive power flow problem

4.1 Encoding the Decision Variables

In this approach, an individual of the population that encodes the decision variables, **U**, is a vector composed of the voltages of the control buses and the reactances of the TCSC devices. Figure 3 shows the m-th individual of the population. The first genes are the voltages of the control buses, $V_i^{(m)} \in [V_{\min}, V_{\max}]$, and the next genes are the reactances of the TCSC devices, $X_j^{(m)} \in [X_C, X_L]$, where X_C and X_L are capacitive and inductive TCSC reactances, respectively.

$V_1^{(m)}$	...	$V_i^{(m)}$	...	$X_1^{(m)}$	...	$X_j^{(m)}$

Figure 3: Encode of the decision variables

4.2 Selection Operator

This operator selects a pool of individuals from the population. The selection is probabilistic as a function of the individual fitness. Thus, the individual, from fitness point of view, has higher probability to be selected than other ones of the population [8].

In this work, as shown in Figure 4, the tournament selection is used. This operator selects G individuals ($G \leq N$) at random. Then, from the pool of G individuals, the individual with best fitness is selected. The larger G, the higher the selection pressure, since the probability of the best individuals be selected increases. For example, if $G = N$, the selection is elitist, maximum selection pressure, since the best individual will be selected.

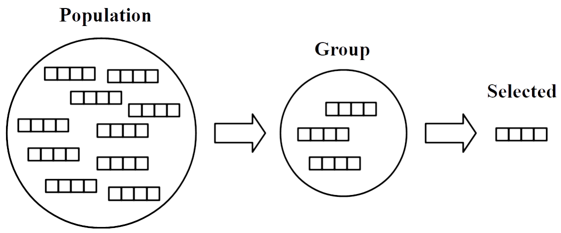

Figure 4: Selection by tournament

4.3 Variation Operators

The variation operators modify the offsprings, $F(k)$, i.e., the individuals created from genetic material (decision variable) of the two parents in current population, $P(k)$. There are two variation operators, crossover and mutation.

In crossover, there is one random cut point in the two parents, P_1 and P_2, which defines how the offsprings are formed, as shown in Figure 5. The offsprings, D_1 and D_2, are created from segments of the two parents, P_1 and P_2, according to the cut point. This process produces a local search on the solutions space, since the new individuals are created around the parents.

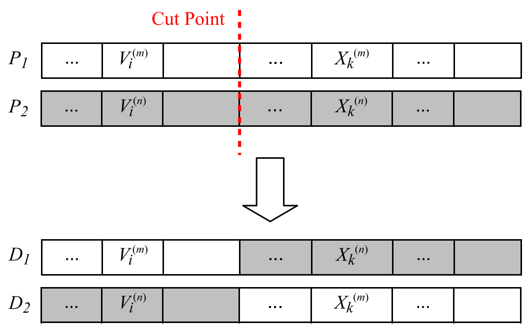

Figure 5: 1-point crossover operator

The mutation, performed after crossover, is a random change in the individual genes, $F(k)$, according to a probability $p_m \in [0, 1]$. Figure 6 shows the mutation in the reactance $X_j^{(1)}$ of the TCSC device, which is changed to $X_j^{(1)}$ if $r \leq p_m$, where $r \in [0, 1]$ is a random variable with uniform distribution.

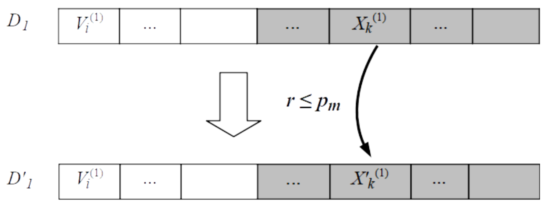

Figure 6: Uniform mutation

5 Experimental Study

In order to validate the proposed method, several experiments were performed by using the power flow package Matpower [19]. Two power systems were used, the IEEE 14 and IEEE 118 busbar. In both systems, the proposed method was applied with and without the TCSC device. Two performance indicators were used, the reactive power loss and the voltage deviation of the load buses calculated as follows

$$D_m = \frac{1}{N_C} \sum_{V_i \in \mathbf{C}} |1 - V_i| \tag{2}$$

where V_i is the voltage magnitude of i-th load bus, $\mathbf{C}$ is the set of load buses, and N_C is the number of load buses.

The method was tested in both the base case and three type of contingencies with the $N-1$ criterion. Table 1 shows the parameters used by genetic algorithm. The TCSC device was installed in only one transmission line, and its reactance was set relative to the transmission line reactance (pu).

Parameter	Value
Population size	100
Crossover rate	0.8
Mutation rate	0.1
Selection rate	Tournament
Number of parents	80
Number of offspring	50
Selection pressure	0.8
Number of generations	100
Control bus voltage (pu)	[0.96, 1.04]
TCSC reactance (pu)	[– 0.3, 0.3]

Table 1: Genetic algorithm parameters

In the experiments, the performance of the proposed method was analyzed with and without the TCSC device in both cases by using the genetic algorithm. These cases were performed in both the base case and contingencies. Thus, the systems in normal operation and critical ones were tested and analyzed.

5.1 Base Case Analysis

This section presents the experiment results of both IEEE 14 and IEEE 118 busbar systems for the base case, i.e., the intact system.

5.1.1 IEEE 14-bus System

The standard IEEE 14-bus system has 5 generators, 17 transmission lines, 3 transformers (substations) with a power rating of 100 MVA, and 11 load buses. This is a small system; however, it is useful for evaluating the application of TCSC devices in isolated systems. The system demand totals 259 MW of real power and 73.5 MVAr of reactive power, with an installed capacity of 772.4 MW.

In experiments with the IEEE 14-bus system, the reactive power loss decreased with the TCSC device installed and the adjustment of the decision variables by the genetic algorithm, as shown in Figure 7. The reactive power loss was 18.6% smaller than that in the initial state without TCSC device. With TCSC, the reactive power loss was 21.5% smaller than that in the initial state. The line compensation by TCSC improved the system performance by reducing the reactive power loss by about 3%.

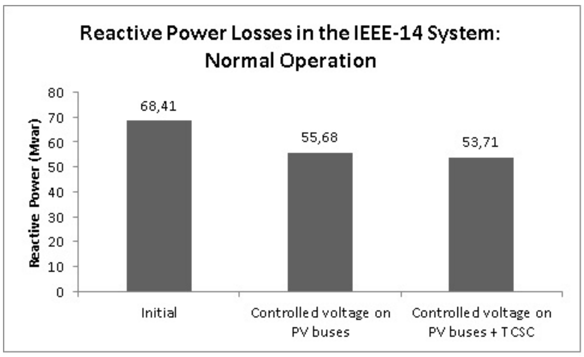

Figure 7: Reactive power loss in IEEE 14-bus system – base case

Table 2 shows the voltage deviation of the load buses with respect to the nominal voltage (1 pu). The proposed method also decreased this performance indicator, thus approaching the load bus voltages to the nominal value. In this performance indicator, the both versions with and without TCSC device achieved similar results; however, GA with TCSC reached about 6% less deviation than that without TCSC.

Table 2: Voltage deviation in IEEE 14-bus system – base case

Initial State	No TCSC	TCSC
0.0096	0.0033	0.0031

5.1.2 IEEE 118-bus System

The IEEE 118 busbar system has 19 generators, 35 synchronous compensators, 186 transmission lines, 9 transformers (substations), and 91 load buses. This is a large and highly connected system, useful to analyze the application of TCSC devices in large systems. The system demand totals 4,242 MW of real power and 1,438 MVAr of reactive power, with an installed capacity of 9,962 MW.

In this system, only the adjusting of the control bus voltages reduced about 30% of the reactive power loss with respect to the initial state. The installation of the TCSC device decreased the reactive power loss by about 10 MVAr compared to the system without TCSC, as shown Figure 8. This difference represents about 1% less loss.

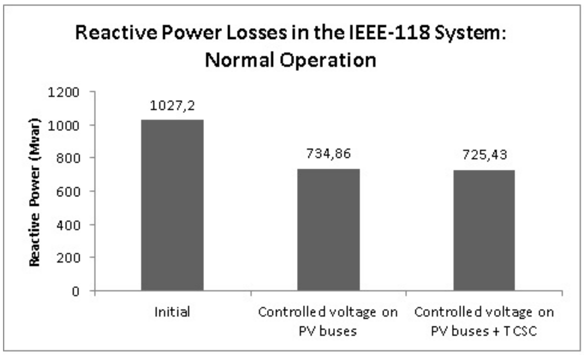

Figure 8: Reactive power loss in IEEE 118-bus system – base case

Table 3 shows the voltage deviation of the load buses with respect to the nominal value (1 pu). After the installation of the TCSC device, the voltage deviation increased since the objective of the genetic algorithm is to decrease the reactive power loss. Thus, to reduce the loss, GA with TCSC caused a voltage deviation increase of about 0.001 pu.

Table 3: Voltage deviation in IEEE 118-bus system – base case

Initial State	No TCSC	TCSC
0.0047	0.0011	0.0021

5.2 Contingency Analysis

In normal operation, the power system operates with all variables into the normal limits and no equipment is being overload. The system operates without violation constraints even in a contingency. This section presents a performance analysis of the proposed method in contingencies in both IEEE 14 and IEEE 118 busbar systems.

5.2.1 IEEE 14-bus System

In all cases, each contingency increases the reactive power loss in this system with respect to the base case, as shown in Figure 9. However, the control actions, after the contingency, decreased the loss.

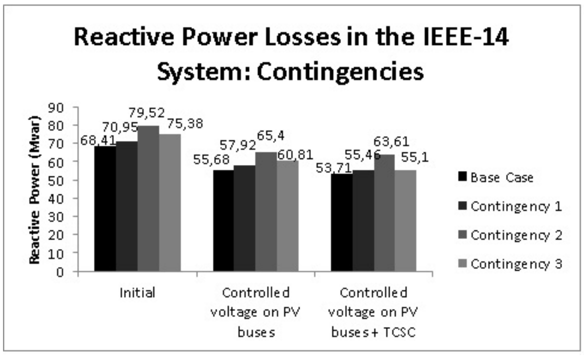

Figure 9: Reactive power loss in IEEE 14-bus system – contingencies

In contingency 1, where the transmission line from bus 6 to 13 outages, the reactive power loss increased in 2 MVAr. In contingency 2, where the transmission line from bus 4 to 7 outages, it was the worst case, thus increasing about 10 MVAr of reactive power loss. In contingency 3, where the generator of the bus 3 outages, the reactive power loss increased 7 MVAr; however, this performance indicator increased only 2 MVAr when the TCSC device was used. In all contingencies, GA with TCSC outperformed the version without this device. On average, GA with TCSC achieved a reactive power loss 5% smaller than that without TCSC, and in contingency 3, the reactive power loss was 9% smaller than that without TCSC.

The voltage adjustment and TCSC compensation by using a genetic algorithm allowed maintaining the voltage of the load buses close to the nominal values even in contingencies, as shown in Table 4. The results with and without TCSC compensation were approximately equal; however, in contingency 1, the TCSC compensation increased the voltage deviation compared to GA without TCSC.

Table 4: Voltage deviation in IEEE 14-bus system – contingencies

Contingency	TCSC	No TCSC
1	0.0055	0.0040
2	0.0017	0.0016
3	0.0018	0.0021

Table 5: Voltage deviation in IEEE 118-bus system – contingencies

Contingency	TCSC	No TCSC
1	0.00058	0.0014
2	0.00014	0.0017
3	0.00081	0.0024

5.2.2 IEEE 118-bus System

The IEEE 118-bus system is a large and robust power system, thus providing more tolerance to faults. Therefore, the contingencies did not increase the reactive power loss, as shown in Figure 10. After the application of the proposed method, this indicator reduced about 30%, similar to the base case.

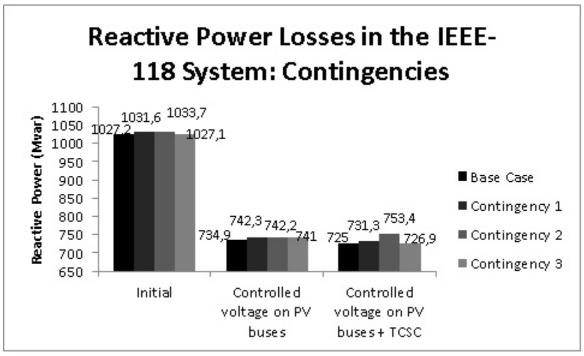

Figure 10: Reactive power loss in IEEE 118-bus system – contingencies

In contingency 1, where the transmission line from bus 2 to 12 outages, the reactive power loss increased by about 5 MVAr compared to the base case. In contingency 2, where the transmission line from bus 25 to 26 outages, an unusual case occurred: the reactive power loss increased when using the TCSC device. This situation occurred due to the type of contingency and the location where it took place. In contingency 3, where the generator at bus 46 outages, there was no significant change in the reactive power loss. On average, GA with TCSC achieved a reactive power loss 0.6% smaller than that without TCSC, and in contingency 3, the reactive power loss was about 2% smaller than that without TCSC.

In all contingencies, TCSC compensation provided low voltage deviation compared to GA without TCSC, as shown in Table 5. In this large system, TCSC compensation proves to be important for better performance in contingencies.

6 Conclusion

The use of technologies that allow for maximum exploration of existing power systems has been widely discussed, since investments in this sector entail high costs. Thus, FACTS devices, such as TCSC, have been an important option, since they enable better system control to increase transmission capacity and voltage stability.

The installation of TCSC devices in transmission lines permits better control of the power flow, thus decreasing the reactive power loss and enhancing the voltage stability. The application of TCSC devices in power systems faces technical and economic challenges. From a technical point of view, there are phenomena that can be caused by the installation of these devices in the system, e.g., ferroresonance. From an economical perspective, the purchasing costs of these devices are high, necessitating a cost-benefit assessment.

This paper conducted a study to analyze the optimal reactive power flow by using a genetic algorithm. In the proposed method, a TCSC device is installed on a transmission line, and the genetic algorithm adjusts the voltage in control buses and the TCSC compensation. The method was tested and analyzed in two standard power systems – IEEE 14 and IEEE 118 busbar systems. The experiments were conducted in the base case and contingencies.

The experiments showed that installing a TCSC device on a transmission line and adjusting the control bus voltages and TCSC compensation were effective. The total reactive power loss decreased in both power systems, in the base case and under all contingencies. Moreover, the method also decreased the voltage deviation of the load buses, especially during contingencies in the IEEE 118-bus system.

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