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Symmetrical Fault Analysis of Power Systems with the TCSC Operating in Active Power Flow Control Mode

José Miguel García Guzmán¹, Antonio Zacarías Martínez Delgado², Juan Pablo Razón González¹,
Miroslava Cano Lara³

Associate Professor, Department of Electromechanical Engineering, ITESI, Irapuato, México¹

Verification Engineer of Electrical Installations, VISA S.A. de C.V., México²

Associate Professor, Department of Mechatronic Engineering, ITESI, Irapuato, México³

ABSTRACT: FACTS devices are used to provide flexibility to power systems by controlling various electrical parameters, such as voltage magnitude, active and reactive power flow, among others. The Thyristor Controlled Series Compensator (TCSC) is one such device that is commonly used to control the flow of active power to a specified value. In active power flow control mode, the TCSC changes the impedance of the transmission line where it is connected, modifying the Thevenin equivalent impedance as seen from each substation of the power system. Thus, the short circuit capacity (SCC) and symmetrical fault current are also affected, therefore it is necessary to analyse the impact that TCSC has when operating in active power flow control mode on the SCC and symmetrical fault current, in order to ensure safe and reliable operation of power systems. This paper presents an analysis of symmetrical faults when the TCSC controls the active power flow in a transmission line to a specified value. To perform the analysis, first the active power flow control mode of the device is activated and then a computational algorithm is used to obtain the bus impedance matrix, whose main diagonal elements represent the Thevenin equivalent impedance as seen from each substation of the power system. Finally, with the elements of the main diagonal of the bus impedance matrix, which contain the TCSC reactance, the SCC and the symmetrical short-circuit current in each substation of the power system are calculated. Several test cases are conducted using the IEEE 5-node power system and the 39-node New England power system. The results of the test cases show that when the TCSC operates in the active power flow control mode the SCC and symmetrical short-circuit current increase at most nodes of the power system, with this increase being more significant at nodes close to the transmission line where the device is connected.

KEYWORDS: Power systems, TCSC, Short circuit capacity, Symmetrical short circuit current.

I. INTRODUCTION

In recent decades, there has been a constant growth in the number of electric power consumption centers, which has made it necessary for utilities to build new transmission lines and generation plants to increase the generation and transmission capacity of the power system. Recent environmental and economic regulations established by governments around the world limit the construction of new generation lines and power plants, and consequently, cannot keep pace with the growth in transmission capacity required by the power system [1]. This causes electric utilities to use existing transmission lines efficiently in order to meet power transmission requirements. One of the most common ways to increase the transmission capacity of existing lines is through the use of FACTS devices, as they allow delaying the construction of new lines. The Thyristor Controlled Series Compensator is one of the most widely used FACTS devices to improve the operation of power systems by reactive compensation of the series impedance of transmission lines, which allows controlling the active power flow through a line to a specified value [2, 3, 4]. The TCSC is a controller that can rapidly and continuously increase or decrease the series impedance of the transmission line by means of series reactive compensation over a wide range of operating conditions [7, 8]. This device consists of a Thyristor Controlled Reactor (TCR), which is a capacitor bank connected in parallel with a reactor [5, 6] and it can be represented by a controllable reactance model or a firing angle model.

The TCSC allows to reduce the symmetrical fault current in the first half of the cycle [9] and to respond quickly to transients occurring in the power system, since it can vary its equivalent impedance almost instantaneously. In addition to using the TCSC to control the active power flow, many theoretical studies have shown that the TCSC can be used as a short-circuit current limiting device [10, 11, 12, 12, 13, 14], but so far in the state-of-the-art review no use of this series controller has been reported in a dual-purpose operation, where the compensator controls the active power flow in a line and, in turn, limits the short-circuit current upon the occurrence of a fault in the system. It is important to mention that FACTS devices have several restrictions to be used in short-circuit current limiting applications, since sophisticated control devices and components that can respond quickly and at the same time withstand the fault current are required, which makes them have a high investment cost [15, 16]. Therefore, the application of these devices is generally restricted to the control of electrical parameters of the power system, using external devices for short-circuit current limitation purposes.

The TCSC controller has wide applications in power systems, but among the most common are to increase: a) the active power flow through a line, b) the static stability limits of the lines and c) the power transmission capacity. In the above applications, the device must operate capacitively to lower the series impedance of the line where it is connected. With the decrease of this impedance the topology of the power system changes, which causes the values of the Thevenin equivalent impedance, as seen from the network nodes, to also decrease, causing an increase, in many occasions significant, of the short-circuit capacity (SCC) and the short-circuit current (I_{Fk}) of the power system. It has been shown that the integration of the TCSC into the power system can lead to problems in the protection system, especially in distance protection [17,18, 19]. It is clear that with the increases in I_{Fk} and S_{CC} , a resizing of the primary equipment of the substations, a recalibration and readjustment of the overcurrent relays, as well as a new protection coordination study must be carried out. For this reason, it is necessary to carry out a fault study to know the values of the SCC and I_{Fk} in the substations of the power system, as well as the currents flowing in the transmission elements during the fault.

In the above-mentioned context and taking into account the increasing safety and reliability constraints of power systems around the world, in this work a symmetrical fault analysis of power systems with the TCSC operating in active power flow control mode is carried out. The structure of the paper is as follows: Section II presents the modeling of the TCSC device. The general formulation for the symmetrical fault analysis and the short-circuit capacity, without considering and taking into account the TCSC, are described in Section III and IV, respectively, while in Section V the results of the test cases are presented. Finally, Section VI shows the conclusions obtained from this work.

II. MODELLING OF THYRISTOR-CONTROLLED SERIES COMPENSATOR

The TCSC adjusts the value of its equivalent reactance to control the flow of active power through a transmission line to a specified value. In this sense and from a circuit theory perspective, the TCSC device can be represented by a firing angle model and a controllable reactance model. The latter model is the one used in this work to carry out the study of symmetrical faults considering the operation of the series compensator.

A. EQUIVALENT CIRCUIT OF TCSC

A schematic representation of the equivalent circuit of TCSC is presented in Fig. 1.

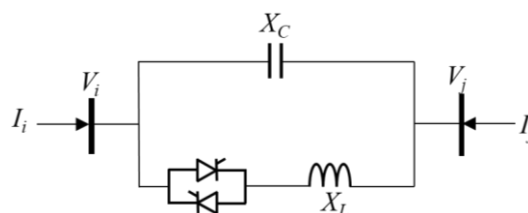


Fig. 1. Equivalent circuit of TCSC.

The figure shows that this device consists of a capacitor bank in parallel with a Controlled Reactor, which consists of a reactor connected in series with two thyristors in anti-parallel. The thyristors are the control elements of the TCSC [3, 20].

B. VARIABLE REACTANCE MODEL OF TCSC

As mentioned, the controllable reactance model is the one used in this work. The reason for this is due to the resonance region of the device presented with the firing angle model, in which it is not possible to obtain results due to convergence problems, hence the variable reactance model, since it does not present a resonance region [21], is more suitable to carry out the analysis proposed in this work.

The state variable of this TCSC model is the variable reactance X_{TCSC} , which is set to a certain value, such that it allows varying the line series impedance and controlling the active power flow to a specified value [2]. The injected power equations of the TCSC at node k for this model are given by Eq. (1) and (2) as follows,

$$P_i = \frac{V_i V_j}{X_{TCSC}} \sin(\theta_i - \theta_j) \tag{1}$$

$$Q_i = \frac{V_i^2}{X_{TCSC}} - \frac{V_i V_j}{X_{TCSC}} \cos(\theta_i - \theta_j) \tag{2}$$

The equations for power injection at node m are obtained by exchanging the subscripts k for m in the above equations.

C. ACTIVE POWER FLOW CONTROL EQUATION OF TCSC

The purpose of the TCSC device is to control at a specified value P_{sh} the active power flow P_{ij} through the transmission line connected between nodes $i-j$. The TCSC is connected between nodes $k-m$, as shown in Fig. 2, in order to carry the active power control action given by Eq. (3).

$$P_{ij} - P_{sh} = 0 \tag{3}$$

Where the power flow P_{ij} corresponds to the power injected by the TCSC, given by Eq. (1), which depends on the reactance of the X_{TCSC} .

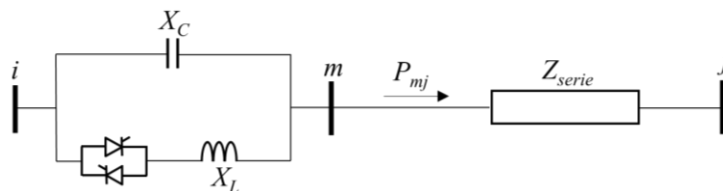


Fig. 2. Compensated transmission line by TCSC.

III. SYMMETRICAL FAULT MODELING

Fault analysis consists of determining the bus voltages to subsequently calculate the nodal short-circuit level and the currents of the transmission lines during the fault, as well as the short-circuit capacity of the system. The information obtained from these studies is used to adjust the protection system relays and perform the protection coordination study.

A. SYMMETRICAL FAULT ANALYSIS USING BUS IMPEDANCE MATRIX

Fault analysis is performed relatively simply with the use of the bus impedance matrix. Consider an n -node power system as shown in Fig. 3 [22]. Each generator is represented by a constant voltage source with its appropriate reactances, which may be X_d'' , X_d' or X_d . Transmission lines are represented by their equivalent circuit π and all impedances are expressed in per unit on a common MVA basis.

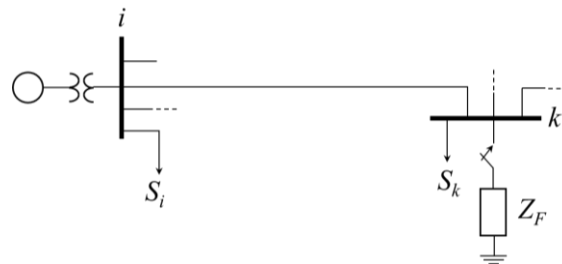


Fig. 3. Application of a symmetrical fault in an n -node power system.

From the previous power system, it is possible to obtain Eq. (4) by means of which the nodal voltages during the fault are calculated.

$$V_{F,bus} = V_{0,bus} + Z_{bus} I_{F,bus} \tag{4}$$

Where $V_{F,bus}$ and $V_{0,bus}$ are the vector of nodal voltages during the fault and pre-fault, respectively. Z_{bus} is the bus impedance matrix containing the power system topology and $I_{F,bus}$ corresponds to the vector of fault currents at each node. In matrix form Eq. (4) is written as follows,

$$\begin{bmatrix} V_{F1} \\ \vdots \\ V_{Fk} \\ \vdots \\ V_{Fn} \end{bmatrix} = \begin{bmatrix} V_{01} \\ \vdots \\ V_{0k} \\ \vdots \\ V_{0n} \end{bmatrix} + \begin{bmatrix} Z_{11} & \cdots & Z_{1k} & \cdots & Z_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{k1} & \cdots & Z_{kk} & \cdots & Z_{kn} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{n1} & \cdots & Z_{nk} & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ -I_{Fk} \\ \vdots \\ 0 \end{bmatrix} \tag{5}$$

In Eq. (5) n is the total number of buses in the system. It is important to note that in the vector $I_{F,bus}$ all values are zero, except at the faulted node and for a solid fault the $V_{Fk}=0$. Thus, it is possible to express the short-circuit current at node k by Eq. (6).

$$I_F = \frac{V_{0k}}{Z_{kk} + Z_F} \quad k = 1, 2, \dots, n \tag{6}$$

Once the short-circuit level is known, it is possible to calculate the remaining values of the vector $V_{F,bus}$, which contains the nodal voltages of the power system during the fault. Knowing the nodal voltages during the fault, the current flowing through the I_{Fij} transmission elements can be calculated using Eq. (7).

$$I_{Fij} = \frac{V_{Fi} - V_{Fj}}{Z_{ij}} \quad \begin{matrix} i = 1, 2, \dots, n \\ j = 1, 2, \dots, n \\ i \neq j \end{matrix} \tag{7}$$

In Eq. (7) the term Z_{ij} represents the series impedance of the transmission elements.

B. SHORT CIRCUIT CAPACITY OF POWER SYSTEM

The short-circuit capacity is used to size primary substation equipment and to define the interrupting capacity of circuit breakers. The short-circuit capacity at a bus k is a common measure of bus robustness, it is measured in MVA and is determined as the product of the magnitudes of the rated voltage and the fault current, as shown in Eq. (8) [22].

$$SCC = \sqrt{3} V_{Lk} I_{Fk} \times 10^{-3} \text{ MVA} \quad (8)$$

Where the line-to-line voltage V_{Lk} is expressed in kV and the short-circuit current I_{Fk} in amperes. In terms of the bus reactance X_{kk} , the short-circuit capacity is determined in a simpler way by Eq. (9).

$$SCC = \frac{S_B}{X_{kk}} \text{ MVA} \quad (9)$$

Where $X_{kk} = \text{re}\{Z_{bus, kk}\}$ is the vector containing the imaginary part of the elements of the main diagonal of the bus impedance matrix.

IV. SYMMETRICAL FAULT ANALYSIS CONSIDERING THE TCSC MODEL

When the TCSC model is integrated into the power system the network topology is modified as shown in Fig. 4. Node m is a "fictitious" node that is added to the system and the equivalent impedance of the line where the device is connected changes, since the compensator must modify its reactance in order to control the active power flow. This results in a change in the fault current and short-circuit capacity at the nodes, as well as in the current flowing during the fault in the transmission elements.

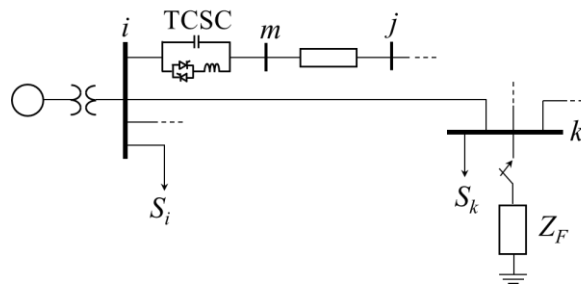


Fig. 4. Application of a symmetrical fault in an n-node power system considering the integration of the TCSC device.

A symmetrical fault is applied at node k through the fault impedance Z_F . With the integration of the TCSC, the nodal voltages during the fault are determined as follows,

$$\begin{bmatrix} V_{F1} \\ \vdots \\ V_{Fk} \\ \vdots \\ V_{Fn} \\ V_{Fm} \end{bmatrix} = \begin{bmatrix} V_{01} \\ \vdots \\ V_{0k} \\ \vdots \\ V_{0n} \\ V_{0m} \end{bmatrix} + \begin{bmatrix} Z_{11} & \cdots & Z_{1k} & \cdots & Z_{1n} & Z_{1m} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\ Z_{k1} & \cdots & Z_{kk} & \cdots & Z_{kn} & Z_{km} \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\ Z_{n1} & \cdots & Z_{nk} & \cdots & Z_{nn} & Z_{nm} \\ Z_{m1} & \cdots & Z_{mk} & \cdots & Z_{mn} & Z_{mm} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ -I_{Fk} \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad (10)$$

In Eq. (10) the subscript m represents the fictitious node where the TCSC controller is connected to the compensated transmission line. It is important to mention that in the Z_{bus} matrix the elements Z_{im} and Z_{mj} do not represent, respectively, the mutual impedances between the nodes $i-m$ and $m-j$, nor does the element Z_{mm} represent the impedance

of node m itself. These elements represent the impedance that results from adding a new node to the power system and that causes the bus impedance matrix to increase its size to $(n+1) \times (n+1)$. In this regard it is worth mentioning that, in order to carry out the analysis presented in this work, a computational algorithm was implemented to form the Z_{bus} considering the power system topology, which is modified by the addition of a new node and by the line impedance compensated by the TCSC. The fault parameters I_{Fk} , I_{Fij} and SCC are calculated using Eq. (6), (7) and (9), respectively, since the calculation of these at the "fictitious" node, denoted by m , where the TCSC is connected is not considered.

V. TEST CASES

In this section, several test cases are presented to analyze the effect of TCSC integration in the study of symmetrical faults. The test cases are carried out using the 5-node power system and the 39-node New England system where the fault current at the nodes and transmission elements, as well as the short-circuit capacity at each node of the power system are calculated.

A. TEST CASE WITH 5 NODE POWER SYSTEM

The 5-node power system consists of two generators and seven transmission lines [23]. The reactances considered in generators 1 and 2 are $j0.2$ pu and $j0.4$ pu, respectively. The initial condition of the X_{TCSC} is 0.002 pu and the convergence tolerance used is 1×10^{-9} . In this test case, line 4-3 is chosen to be compensated, since it is the transmission line that transmits the least amount of active power. The TCSC is used to increase the active power flow from 6.6 MW to 8 MW. To perform this control action the TCSC modifies its reactance from 0.002 pu to -0.0860 pu. Clearly, the negative sign indicates that the device performs a capacitive type of compensation, which causes the equivalent reactance of the compensated line to decrease. Once the transmission line is compensated, the bus impedance matrix is calculated and Z_{kk} and X_{kk} are extracted to calculate the system short-circuit level and capacity. A comparison of the nodal I_{Fk} current with and without TCSC device compensation is presented in Table I, while a comparison of the SCC with and without reactive series compensation is presented in Table II.

Tabla I. Comparison of short circuit current I_{Fk} with and without TCSC.

Node	I_{Fk} without TCSC	I_{Fk} with TCSC
1	7.653 pu	7.653 pu
2	6.491 pu	6.492 pu
3	4.099 pu	4.292 pu
4	4.768 pu	4.835 pu
5	4.881 pu	4.921 pu

Tabla II. Comparison of SCC short-circuit capacity with and without TCSC.

Node	I_{Fk} without TCSC (MVA)	I_{Fk} with TCSC (MVA)
1	721.940	721.983
2	649.088	649.227
3	421.823	438.554
4	484.509	491.271
5	494.355	498.457

According to the results shown it is possible to observe that compensating line 4-3 causes an increase in the SCC of each SEP node. It is also clear that there is an increase in the nodal current I_{Fk} . The most notorious increase of the mentioned parameters is presented in node 3, due to the fact that it is the most susceptible to a fault.

B. TEST CASE WITH 39 NODE POWER SYSTEM

The New England power system consists of 39 nodes, 10 generators and 34 transmission lines [24]. Same as the previous test case, in this case the initial condition of the X_{TCSC} is 0.002 pu and the convergence tolerance used in the simulations is 1×10^{-9} . In this case study, the line connected between nodes 17-18 is chosen to increase its active power flow from 213.25 MW to 250 MW and 280 MW. It is decided to select an increase of the active power flow in the lines, since the TCSC is normally used for this purpose and not the opposite. The final reactance that the device has to control the power flow in the line at 250 MW and 280 MW is -0.0090 pu and -0.0147 pu, respectively. Both reactances are negative, so the TCSC performs a capacitive compensation, however, it should be noted that there is a higher capacitive reactance when the device controls the active power flow at the higher value. Fig. 5 and Fig. 6 show a graphical

comparison of the short-circuit capacity and fault current at the system nodes when the power flow is controlled at 250 MW and 280 MW, respectively. Two increments of active power flow control are chosen to clearly visualize the trend in the SCC and I_{Fk} values in the system when active power flow control is carried out.

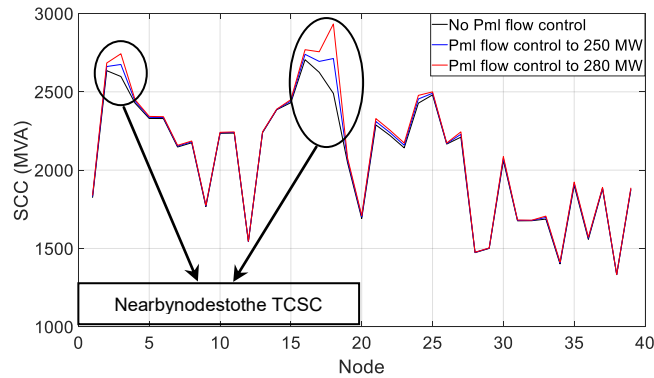


Fig. 5. Short-circuit capacity profile of the 39-node system buses with and without TCSC compensation.

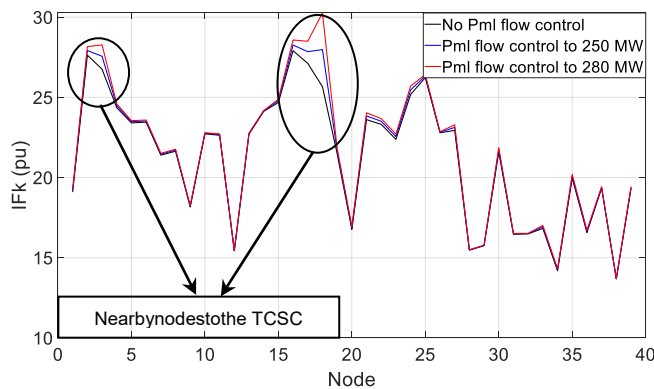


Fig. 6. Short-circuit current profile at the 39-node system buses with and without TCSC compensation.

The figures show that when the TCSC performs its control action, there is an increase in both the short circuit capacity and the fault current in the system nodes. This increase is very slight in most of the nodes; however, it is very significant in the nearby nodes where the transmission line is connected to the TCSC. Something similar occurs with the fault current flowing through the transmission elements, since an increase of such current also occurs in the elements near the faulted node and the line where the controller is connected. For example, for a fault at node 27, the fault current on line 17-18 without compensation is 3.9879 pu, while for 250 MW and 280 MW compensation it is 4.9077 pu and 5.6001 pu, respectively.

The above results show that the TCSC has a direct impact on the safe operation of the electrical system, since in the electrical areas near the line where the FACTS device is connected there is a significant increase in the SCC and I_{Fk} of the system. The increase in SCC makes it necessary to resize and replace the buses and primary equipment of the electrical substations, while with the change in I_{Fk} it will be necessary to renew the circuit breakers for those whose interrupting capacity is commensurate with the calculated fault current level. In addition, with the increase of the fault current in the transmission elements, it will be necessary to readjust the distance protection in all the lines of the system and to carry out a new protection coordination scheme, with the intention of guaranteeing the correct operation of the protection system zones. Although the TCSC can be used to limit the short-circuit current, it is not feasible to use it, since it would be very costly to have a device based on power electronics capable of withstanding the enormous levels of short-circuit current that occur during a fault.

The results suggest that the replacement of the primary and protection equipment should be carried out only in the nodes close to the line where the TCSC is connected, since it would be expected that the oversizing of the equipment

would be fulfilled in those nodes where small increases in the capacity and short circuit level occur. In spite of this, the investment required to replace the equipment to guarantee the safe and reliable operation of the power system will be considerable.

VI. CONCLUSIONS

An analysis of symmetrical fault of power systems with the TCSC operating in active power flow control mode has been presented. The results of the test cases show that when the TCSC carries out the control of the active power flow, at a higher value than the one in the line where it is connected, there is a significant increase in the capacity and short-circuit current in the nodes near the compensated line. Likewise, there is an increase in the fault current in the transmission elements, mainly in those elements close to the faulted node and the compensated line. The above suggests a resizing of the primary equipment of the power substations, as well as a readjustment of the protection relays and a new protection coordination study.

Thus, it can be concluded that the integration of the TCSC brings with it considerable effects on the safety of the power system, so that the electric power supply companies, in addition to the investment associated with the TCSC, will have to invest in an adaptation of the protection system to ensure the safe operation of the system with the operation of the FACTS device. This situation is not only present with the device considered in this work, but in all equipment that manipulates power system parameters.

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