Effect of TCSR on Measured Impedance by Distance Protection in Presence Single Phase to Earth Fault

Mohamed Zellagui and Abdelaziz Chaghi

Abstract**—**This paper presents the impact study of apparent reactance injected by series Flexible AC Transmission System (FACTS) i.e. Thyristor Controlled Series Reactor (TCSR) on the measured impedance of a 400 kV single electrical transmission line in the presence of phase to earth fault with fault resistance. The study deals with an electrical transmission line of Eastern Algerian transmission networks at Group Sonelgaz (Algerian Company of Electrical and Gas) compensated by TCSR connected at midpoint of the line. This compensator used to inject active and reactive powers is controlled by three TCSR's. The simulations results investigate the impacts of the TCSR on the parameters of short circuit calculation and parameters of measured impedance by distance relay in the presence of earth fault for three cases study.

Keywords**—**TCSR, Transmission line, Apparent reactance, Earth fault, Symmetrical components, Distance protection, Measured impedance.

I. Introduction

ELECTRICAL power systems have to be planned, projected, constructed, commissioned and operated in such a way to enable a safe, reliable and economic supply of the load. The knowledge of the equipment loading at the time of commissioning, the prediction is necessary in the future for the design and determination of the rating of the individual equipment and of the power system as a whole. Faults, i.e., short-circuits in the power system cannot be avoided despite careful planning and design, good maintenance and thorough operation of the system. This implies influences from outside the system, such as faults following lightning strokes into phase-conductors of overhead lines and damages of cables due to earth construction works as well as internal faults due to ageing of insulation materials [1]. Fault currents therefore have an important influence on the design and operation of power systems equipment. More than 83% of the occurred faults on the 220 and 400 kV overhead transmission networks in Algerian Company of Electrical and Gas [2], are single phase to ground type. Distance protection relays have been widely applied as the primary protection in HV transmission lines due to their simple operating principle and capability to work independently under most circumstances [3-4].

M. Zellagui is with LSP-IE Research Laboratory, Department of Electrical Engineering, University of Batna, Campus CUB, 05000 Algeria (phone: 213-670-098-403; fax: 213-33-815-123; e-mail: m.zellagui@ymail.com).
A. Chaghi is with LSP-IE Research Laboratory, Department of Electrical Engineering, University of Batna, Campus CUB, 05000 Algeria (phone: 213-556-557-102; fax: 213-33-815-123 (e-mail: az_chaghi@univ-batna.dz).

The basic operation principle of distance relay is based on the fact that the line impedance is fairly constant with respect to the line length. However, the implementation of FACTS controllers in power system transmission for enhancing the power system controllability and stability have introduced new power system issues in the field of power system protection that must be considered and analyzed [5-7].

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems [8]. The presence of the FACTS devices in the faulted loop introduces changes to the line parameters seen by the distance relay. The impact of FACTS device would affect both the steady state and transient trajectory of the apparent impedance seen by distance relays due to the fast response time of FACTS controllers with respect to that of the protective devices. The impact of FACTS devices on distance protection varies depending on the type of FACTS device used, the application for which it is applied and the location of the FACTS device in the power system.

The impact of Thyristor Controlled Series Capacitor (TCSC) on distance protection has been reported for general research on the influence of TCSC on the transmission lines protection in [9] while the impact on communication-aided distance protection schemes and its mitigation is reported in [10]. In reference [11] the impedance measured (Z_{seen}) by distance relay for inter phase faults with TCSC on a double transmission line high voltage is being studied and in reference [12] the variation of Z_{seen} by distance relay for inter phase faults in presence of TCSC on adjacent transmission line by considering MOV Operation is investigated. The effects of voltage transformers connection point on Z_{seen} at relaying point for inter phase faults is also reported in reference [13]. Comparing TCSC placements on double circuit line at mid-point and at ends from measured impedance point of view is mentioned in [14], and impact of TCSC on Z_{seen} by MHO distance relay on 400 kV Algerian transmission line in presence of phase to earth fault with fault resistance is reported in reference [15].

The impact of GTO Controlled Series Capacitor (GCSC) on

Z_{seen} by MHO distance protection single phase to earth fault with fault resistance varied in presence GCSC on 220 kV line in [16] and on 400 kV line in [17].

For the impact of Static Synchronous Series Compensator (SSSC) on Z_{seen} by distance relay on 400 kV transmission line without fault is investigated in [18, 19] while in the presence of single phase to ground fault on 220 kV transmission line is reported in [20] and for inter phase faults on 400 kV transmission line is reported in [21]. The impact of Static Synchronous Compensator (STATCOM) on the performance of distance relay on electrical transmission system is studied in [22, 23].

In this research paper, the impact of apparent reactance injected by TCSR on short-circuit parameters of single phase to earth fault with resistance fault (R_F) is presented. The impact on the resistance and the reactance measured by relay in case of earth fault at the end of transmission line in the presence of TCSR installed on 400 kV midline single transmission line protected by distance relay is being studied.

II. Apparent Reactance Injected by TCSR on Transmission Line

The compensator TCSR mounted on Fig. 1 consists of variable inductance (L_1) connected in series with the transmission line controlled by thyristors mounted in anti-parallel and controlled by an firing angle (α) which varies between 90° and 180°, and a fixed value inductance (L_2) connected in shunt [8, 24].

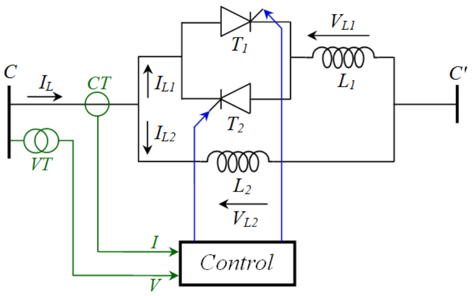


Fig. 1 Principal operation of TCSR

This compensator can be modeled as a variable reactance (X_{TCSR}) as shows in Fig. 2.

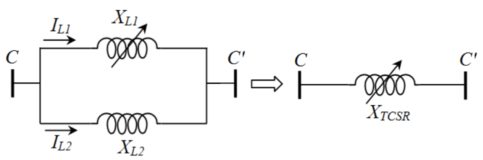


Fig. 2 Apparent reactance injected by TCSR

From Fig. 2, the apparent reactance of the TCSR injected on transmission line is defined by the following equation [8], [24, 25]:

$$X_{TCSR}(\alpha) = X_{L1}(\alpha) // X_{L2} = \frac{X_{L1}(\alpha).X_{L2}}{X_L(\alpha) + X_{L2}} \quad (1)$$

The reactance of the first inductance X_{L1} (α) controlled by thyristors is defined by equation:

$$X_{L1}(\alpha) = X_{L1-\max}\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right] \quad (2)$$

where,

$$X_{L1-\max} = L_1.\omega \quad (3)$$

And the second reactance of inductance (X_{L2}) is defined by formula:

$$X_{L2} = L_2.\omega \quad (4)$$

From equations (2) and (4), the final equation (1) becomes:

$$X_{TCSR}(\alpha) = \frac{L_2 L_1 \omega^2 \left(\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right)}{\omega\left(L_2 + L_1\left(\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right)\right)} \quad (5)$$

The active and reactive powers on transmission line with TCSR are defined by following equations:

$$P(\delta) = \frac{V_A.V_B}{Z_{AB} + X_{TCSR}(\alpha)}\sin(\delta) \quad (6)$$

$$Q(\delta) = \frac{V_B^2}{Z_{AB} + X_{TCSR}} - \frac{V_A.V_B}{Z_{AB} + X_{TCSR}(\alpha)}\cos(\delta) \quad (7)$$

where, Z_{AB} is impedance of transmission line, δ is line angle, V_A and V_B voltage on extremity of transmission line

III. Single Phase to Earth Fault Calculation in Presence of TCSR

Fig. 3 shows transmission line in case of a single phase (phase A) to ground fault at busbar B with fault resistance (R_F) in the presence of a series compensator TCSR inserted on midline, while Fig. 4 shows the equivalent circuit.

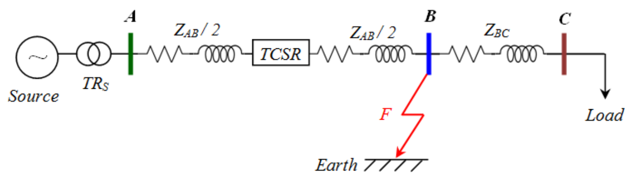


Fig. 3 Transmission line with TCSR

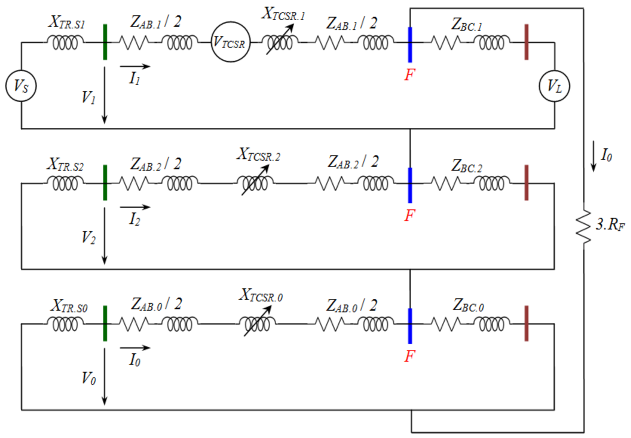


Fig. 4 Earth fault equivalent circuit with TCSR

With TCSR inserted in midline, the new impedance of transmission line ($Z_{AB\text{-}TCSR}$) is:

$$Z_{AB-TCSR} = R_{AB} + j\left[X_{AB} + X_{TCSR}(\alpha)\right] \tag{8}$$

The basic equations for this type of fault [15],[26, 27] are:

$$I_b = I_c = 0 \tag{9}$$

$$V_a = V_1 + V_2 + V_0 = R_F . I_a \neq 0 \tag{10}$$

The symmetrical components of currents are:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{11}$$

From equation (9) and matrix (11), the symmetrical components of currents become:

$$I_1 + I_2 + I_0 = \frac{I_A}{3} \tag{12}$$

The symmetrical components of voltages are:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{13}$$

From equation (10) and matrix (13), the direct components of voltage become:

$$V_1 = -\left(V_0 + V_2\right) + R_F . I_A \tag{14}$$

and,

$$V_s + V_{TCSR} - I_1 \left[\frac{Z_{AB.1}}{2} + X_{TCSR.1} + \frac{Z_{AB.1}}{2}\right] = A + B + C \tag{15}$$

where, the coefficients A, B and C are defined as:

$$A = -\frac{1}{3}\left[-\left(\frac{Z_{AB.0}}{2} + X_{TCSR.0} + \frac{Z_{AB.0}}{2}\right).I_0\right] \tag{16}$$

$$B = -\frac{1}{3}\left[-\left(\frac{Z_{AB.2}}{2} + X_{TCSR.2} + \frac{Z_{AB.2}}{2}\right)I_2\right] \tag{17}$$

$$C = R_F . I_A \tag{18}$$

The coefficients $Z_{AB\text{-}T}$ and $Z_{TCSR\text{-}T}$ are defined for simplicity as:

$$Z_{AB-T} = Z_{AB.1} + Z_{AB.2} + Z_{AB.0} \tag{19}$$

$$X_{TCSR-T} = X_{TCSR.1} + X_{TCSR.2} + X_{TCSR.0} \tag{20}$$

$$V_s + V_{TCSR} = \frac{I_A}{3}\left[\frac{Z_{AB-T}}{2} + X_{TCSR-T} + \frac{Z_{AB-T}}{2}\right] + R_F . I_A \tag{21}$$

From equations (19), (20) and (21), the current at phase (A) currents in presence TCSR on midline is given by:

$$I_A = \frac{3.\left(V_S + V_{TCSR}\right)}{\left(\frac{Z_{AB-T}}{2}\right) + X_{TCSR-T} + \left(\frac{Z_{AB-T}}{2}\right) + 3.R_F} \tag{22}$$

From equation (12), the symmetrical components of currents in presence TCSR on midline are:

$$I_1 = I_2 = I_0 = \frac{V_S + V_{TCSR}}{\left(\frac{Z_{AB-T}}{2}\right) + X_{TCSR-T} + \left(\frac{Z_{AB-T}}{2}\right) + 3.R_F} \tag{23}$$

The direct components of voltages in presence TCSR are:

$$V_1 = V_S + V_{TCSR} - \left(\frac{Z_{AB.1}}{2} + X_{TCSR.1} + \frac{Z_{AB.1}}{2}\right).I_1$$
$$\Rightarrow V_1 = \frac{\left(V_S + V_{TCSR}\right).\left[Z_{AB}' + X_{TCSR}' + 3.R_F\right]}{\frac{Z_{AB-T}}{2} + X_{TCSR-T} + \frac{Z_{AB-T}}{2} + 3.R_F} \tag{24}$$

where, the coefficients Z_{AB}' and X_{GCSC}' are defined as:

$$Z_{AB}' = Z_{AB.2} + Z_{AB.0} - 2.Z_{AB.1} \tag{25}$$

$$X_{TCSR}' = X_{TCSR.2} + X_{TCSR.0} - 2.X_{TCSR.1} \quad (26)$$

The inverse components of voltages in presence TCSR are:

$$V_2 = -\left(\frac{Z_{AB.2}}{2} + X_{TCSR.2} + \frac{Z_{AB.2}}{2}\right).I_2$$
$$\Rightarrow V_2 = -\frac{(V_S + V_{TCSR}).[Z_{AB.2} + X_{TCSR.2}]}{\left(\frac{Z_{AB-T}}{2}\right) + X_{TCSR-T} + \left(\frac{Z_{AB-T}}{2}\right) + 3.R_F} \quad (27)$$

The zero components of voltages in presence TCSR are:

$$V_0 = -\left(\frac{Z_{AB.0}}{2} + X_{TCSR.0} + \frac{Z_{AB.0}}{2}\right).I_0 - R_F.I_0$$
$$\Rightarrow V_0 = -\frac{(V_S + V_{TCSR}).[Z_{AB.0} + X_{TCSR.0} + R_F]}{\left(\frac{Z_{AB-T}}{2}\right) + X_{TCSR-T} + \left(\frac{Z_{AB-T}}{2}\right) + 3.R_F} \quad (28)$$

The coefficients Z_{AB}' and X_{TCSR}' are defined as:

$$Z_2' = Z_{AB.2} + X_{TCSR.2} \quad (29)$$
$$Z_0' = Z_{AB.0} + X_{TCSR.0} \quad (30)$$
$$S_a = 3.a^2 - 1 \quad (31)$$
$$S_b = 3.a - 1 \quad (32)$$

From equations (24), (27) and (28), the three phase voltages on transmission line in presence of TCSR are:

$$V_A = \frac{3.R_F.(V_S + V_{TCSR})}{\left(\frac{Z_{AB-T}}{2}\right) + X_{TCSR-T} + \left(\frac{Z_{AB-T}}{2}\right) + 3.R_F} \quad (33)$$

$$V_B = \frac{(V_S + V_{TCSR}).\left[\left(a^2 - a\right)Z_2' + \left(a^2 - 1\right)Z_0' + S_a R_F\right)\right]}{\left(\frac{Z_{AB-T}}{2}\right) + X_{TCSR-T} + \left(\frac{Z_{AB-T}}{2}\right) + 3.R_F} \quad (34)$$

$$V_C = \frac{(V_S + V_{TCSR}).\left[\left(a - a^2\right)Z_2' + \left(a - 1\right)Z_0' + S_b R_F\right)\right]}{\left(\frac{Z_{AB-T}}{2}\right) + X_{TCSR-T} + \left(\frac{Z_{AB-T}}{2}\right) + 3.R_F} \quad (35)$$

IV. Impedance Measured by Distance Relay

The basic principle of distance protection involves the division of the voltage at the relaying point by the measured current. The apparent impedance so calculated is compared with the reach point impedance. If the measured impedance is less than the reach point impedance, it is assumed that a fault exists on the line between the relay and the reach point.

The reach point of a relay is the point along the line impedance locus that is intersected by the boundary characteristic of the relay. Distance relay has been widely used in the protection of transmission lines. The basic principle of operation of distance protection is shown in Fig. 5 [3, 4]. The input to the distance relay point is the phase voltages and line currents transformed with the help of voltage transformer (VT) and current transformers (CT).

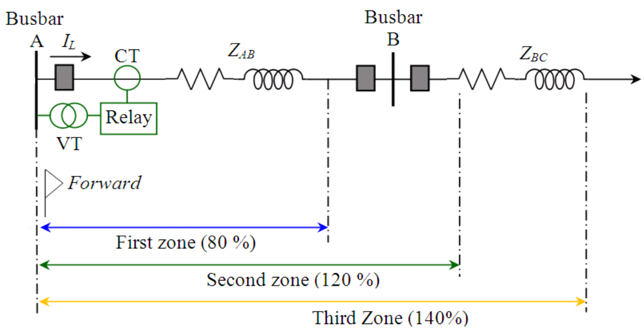


Fig. 5 Principal and setting zones for distance protection

The total impedance of electrical transmission line AB measured by distance relay without fault is [15-17], [28]:

$$Z_{seen} = K_Z.Z_{AB} = \left(K_{VT}/K_{CT}\right).Z_{AB} \quad (36)$$

$$\text{where,} \quad K_{VT} = V_{prim}/V_{sec} \quad (37)$$

$$\text{and,} \quad K_{CT} = I_{prim}/I_{sec} \quad (38)$$

The impedance Z_{AB} is real total impedance of protected transmission line AB, and K_{VT} and K_{CT} is ratio of voltage to current transformers respectively. The presence of TCSR, the apparent reactance injected (X_{TCSR}) has a direct influence on the total impedance of the protected line (Z_{AB}). This effect especially on the reactance X_{AB} and no influence on the resistance R_{AB}, it is represented in Fig. 6.

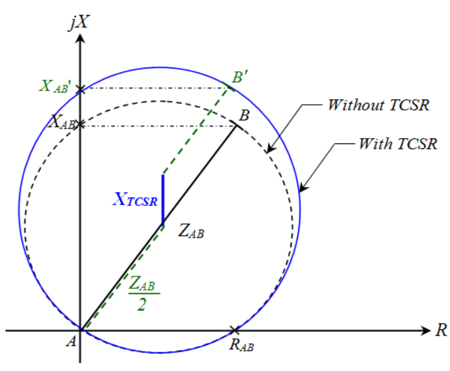


Fig. 6 Impact of the TCSR on total impedance

The voltage would fall towards zero at the point of the fault. In case of earth fault in phase (A), the impedance measured is calculated by flowing equation [4], [15], [27]:

$$Z_{seen} = \frac{V_{Relay}}{I_{Relay}} = \frac{V_A / (I_A + K_o . I_o)}{K_Z} = R_{seen} + j.X_{seen} \qquad (39)$$

where,

$$K_o = \frac{Z_o - Z_1}{3.Z_1} \qquad (40)$$

$$K_Z = \frac{K_{CT}}{K_{VT}} \qquad (41)$$

The coefficient K_Z is ratio of impedance transformers.

V. Case Study, Results and Interpretations

The power system studied in this paper is the 400 kV Algerian electrical transmission networks at Algerian Company of Electrical and Gas (group Sonelgaz) which is shows in Fig. 7 [29]. The distance relay protection is located in the busbar at Ramdane Djamel substation to protect transmission line between busbar A and busbar B respectively at Ramdane Djamel and Oued El Athmania substation in Mila. The busbar C is located at Salah Bay substation in Sétif. The series compensator TCSR is installed in midline.

The parameters of TCSC, transmission line and fault condition are summarized in the appendix.

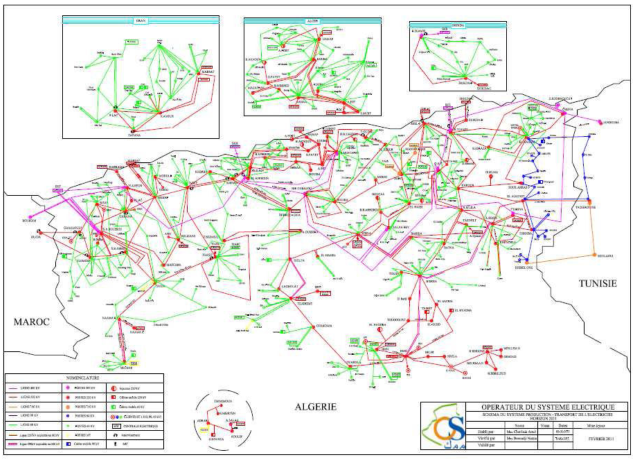
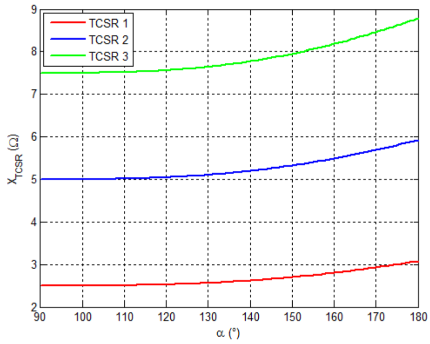
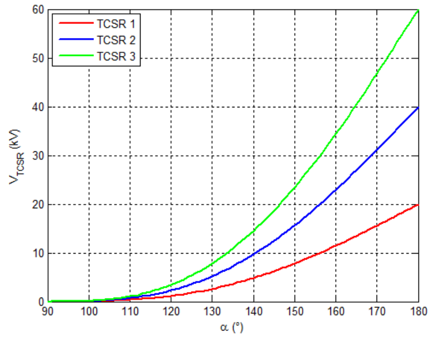


Fig. 7 Electrical networks study in presence TCSR

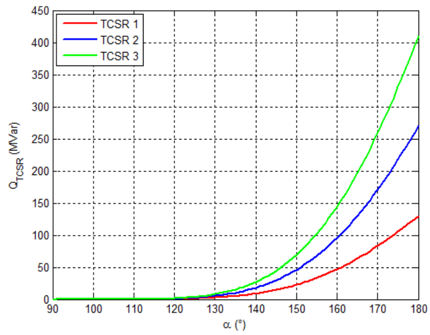
Fig. 8 show the X_{TCSR}, V_{TCSR} and Q_{TCSR} characteristics curves as function of the firing angle (α) respectively of the three TCSR used in case study.



(a)



(b)



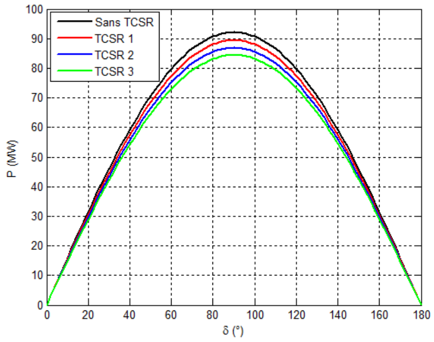
(c)

Fig. 8 Characteristic curve of TCSR study
a) X_{TCSR} (α), b) V_{TCSR} (α), c) Q_{TCSR} (α)

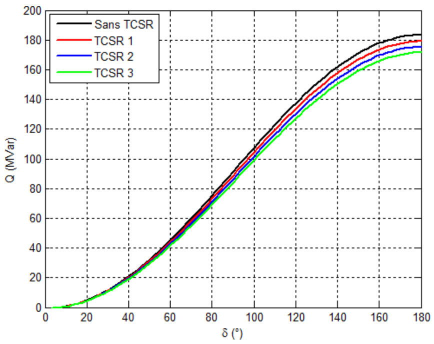
A. Impact on Protected Transmission Line

The Fig. 9 (a) and (b) show the impact of TCSR insertion on the active and reactive power variation of transmission line protected respectively at busbar B (load) with line angle (δ) varied between 0° to 180°.

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:7, No:6, 2013



(a)

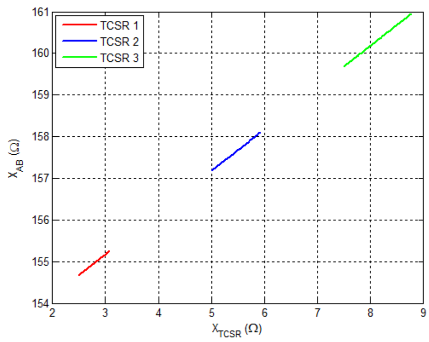


(b)

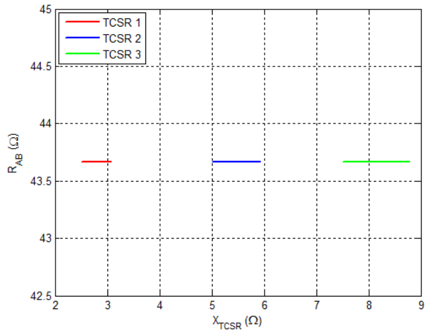
Fig. 9 Impact of TCSR on active and reactive power line
a) P_L (δ) , b) Q_L (δ)

In the presence of TCSR, the active and reactive power will be reduced following insertion of an inductive reactance in the middle point of the transmission line as show in Fig. 9.

The Fig. 10 (a) and (b) show the impact of TCSR insertion on the parameters of protected transmission line: reactance (X_{AB}) and resistance (R_{AB}) respectively as a function of the apparent reactance injected (X_{TCSR}) by TCSR study.



(a)



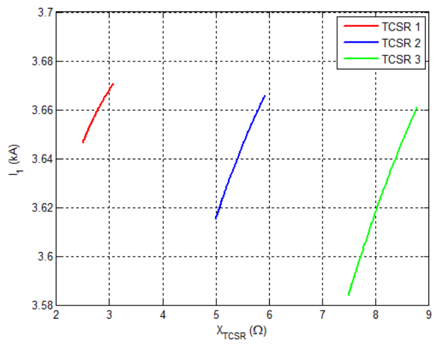
(b)

Fig. 10 Impact of TCSR on reactance a resistance line
a) R_{AB} (X_{TCSR}), b) R_{AB} (X_{TCSR})

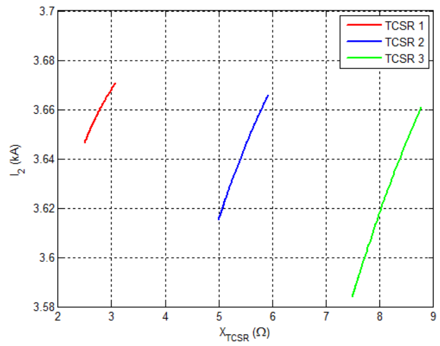
From Fig. 10, the apparent reactance injected has a direct influence on the total impedance Z_{AB}. This effect is being observed especially on the reactance X_{AB} while there is *no* influence on the resistance R_{AB}.

B. Impact On Short-Circuit Calculation

Fig. 11 (a), (b) and (c) represent the variation of the symmetrical component currents I_1, I_2 and I_0 respectively and Fig. 12 (a), (b) and (c) represent the variation of line current I_A, I_B and I_C respectively as a function of the apparent reactance injected by TCSR.

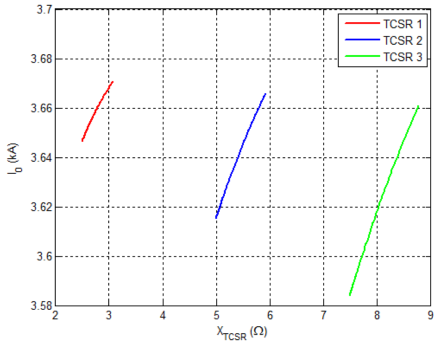


(a)



(b)

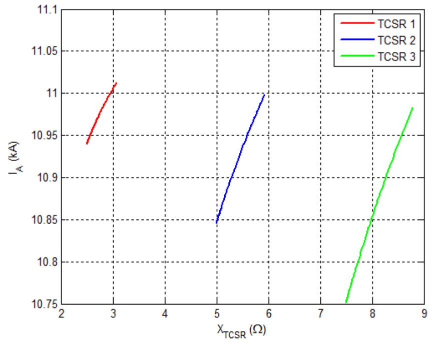
International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:7, No:6, 2013



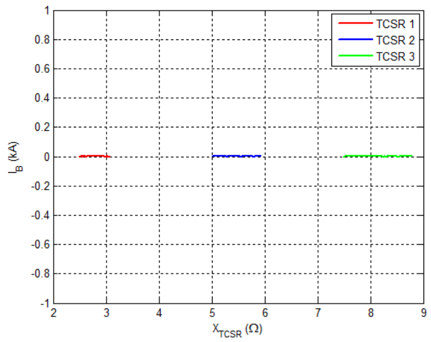
(c)

Fig. 11 Impact of TCSR on symmetrical currents
a) $I_1 = f(X_{TCSR})$, b) $I_2 = f(X_{TCSR})$, c) $I_0 = f(X_{TCSR})$

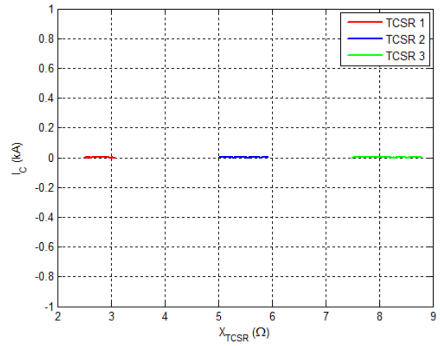
From Fig. 11 as can be seen, increasing the apparent reactance injected by TCSR also increases symmetrical currents for the three cases studied.



(a)



(b)

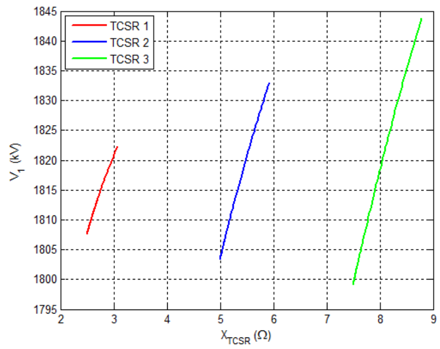


(c)

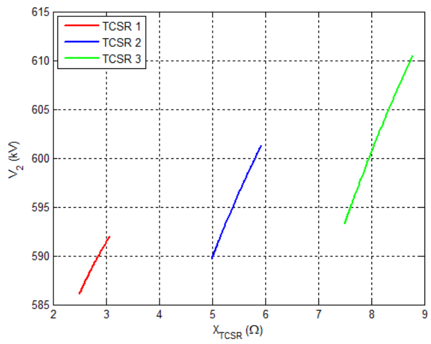
Fig. 12 Impact of TCSR on transmission line currents
a) $I_A = f(X_{TCSR})$, b) $I_B = f(X_{TCSR})$, c) $I_C = f(X_{TCSR})$

From Fig. 12 as can be seen as well, increasing apparent reactance injected by TCSR also increases line current in phase A, while line current in phases B and C remain zero value whatever the variation of the apparent reactance for the three cases studied.

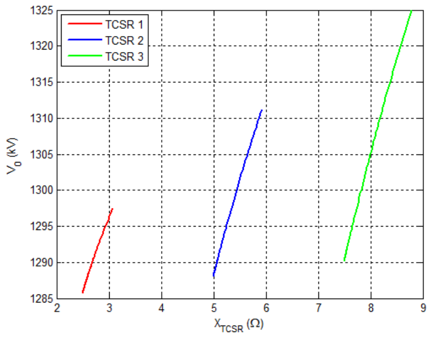
Fig. 13 (a), (b) and (c) represent the variation of the symmetrical component voltages V_1, V_2 and V_0 respectively and Fig. 14 (a), (b) and (c) represent the variation of line voltages V_A, V_B and V_C respectively as a function of the apparent reactance injected by TCSR.



(a)



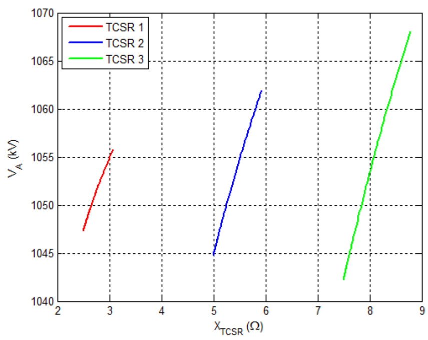
(b)



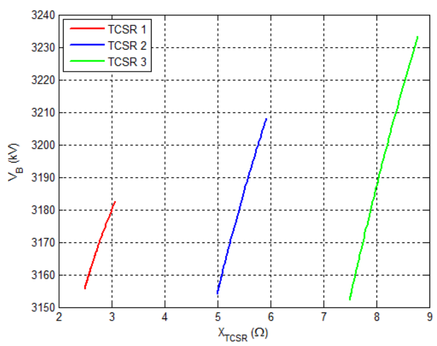
(c)

Fig. 13 Impact of TCSR on symmetrical voltages
a) $V_1 = f(X_{TCSR})$, b) $V_2 = f(X_{TCSR})$, c) $V_0 = f(X_{TCSR})$

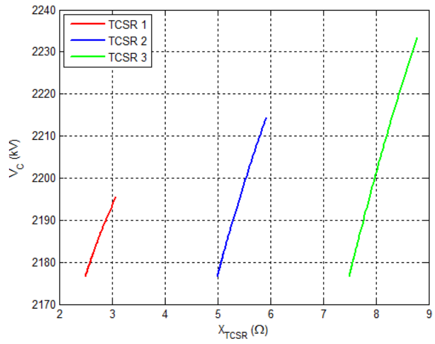
From Fig. 13, increasing the apparent reactance injected by TCSR also increases symmetrical voltages for the three cases studied.



(a)



(b)



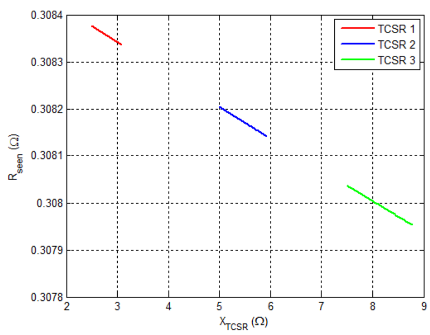
(c)

Fig. 14 Impact of TCSR on transmission line voltages
a) $V_A = f(X_{TCSR})$, b) $V_B = f(X_{TCSR})$, c) $V_C = f(X_{TCSR})$

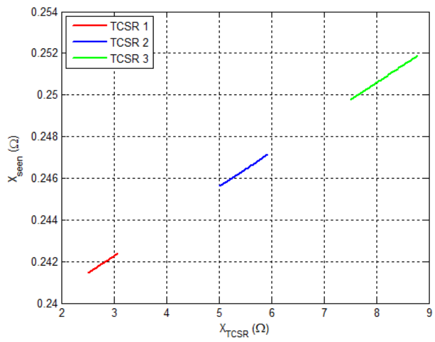
From Fig. 14, increasing the apparent reactance injected by TCSR also increases transmission line voltages for the three cases are studied.

C. Impact on the Measured Impedance

Fig. 15 (a) and (b) show the variation of resistance R_{seen} and reactance X_{seen} measured by distance relay respectively as a function of reactance X_{TCSR} for different cases studied.



(a)



(b)

Fig. 15 Impact of the TCSR on the measured impedance
a) $R_{seen} = f(X_{TCSR})$; b) $X_{seen} = f(R_{TCSR})$

From Fig. 15, increasing the apparent reactance decrease the resistance measured and increases the reactance measured by distance relay for the three cases study.

In presence TCSR for three cases studied the values of short-circuit calculation is varied between minimum and maximum value as reported in following table.

TABLE I
MINIMUM AND MAXIMUM VALUE FOR SHORT CIRCUIT PARAMETERS

	Case No. 1		*Case No. 2*		*Case No. 3*	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*
α (°)	90	180	90	180	90	180
X_{TCSR} (Ω)	2,500	3,070	5,000	5,920	7,500	8,780
V_{TCSR} (kV)	0,000	20,00	0,000	40,00	0,000	60,00
Q_{TCSR} (MVar)	0,000	130,0	0,000	270,0	0,000	410,0
I_1 (kA)	3,646	3,670	3,615	3,666	3,584	3,660
I_2 (kA)	3,646	3,670	3,615	3,666	3,584	3,660
I_0 (kA)	3,646	3,670	3,615	3,666	3,584	3,660
I_A (kA)	10,939	11,012	10,845	10,997	10,751	10,982
I_B (kA)	0,000	0,000	0,000	0,000	0,000	0,000
I_C (kA)	0,000	0,000	0,000	0,000	0,000	0,000
V_1 (kV)	1807,6	1822,3	1803,3	1833,0	1700,1	1843,7
V_2 (kV)	586,07	592,00	589,71	592,00	583,27	610,51
V_0 (kV)	1285,7	1297,4	1288,0	1311,2	1290,2	1324,9
V_A (kV)	1047,3	1055,7	1044,7	1061,9	1042,2	1068,0
V_B (kV)	3155,6	3182,6	3154,0	3207,9	3152,2	3233,1
V_C (kV)	2176,5	2195,4	2176,6	2214,3	2176,7	2233,4

Table I represents the minimum and maximum values for short circuit parameters. These values are important for calculating the settings for overcurrent relay protection in presence in case of ground fault, The new setting for transmission line composed by TCSR is between minimum and maximum value of fault current (I_F), Where $I_F = I_A$.

TABLE II
MINIMUM AND MAXIMUM VALUE OF THE MEASURED IMPEDANCE PARAMETERS BY DISTANCE RELAY

	Case No. 1		*Case No. 2*		*Case No. 3*	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*
α (°)	90	180	90	180	90	180
X_{TCSR} (Ω)	2,500	3,070	5,000	5,920	7,500	8,780
V_{TCSR} (kV)	0,000	20,00	0,000	40,00	0,000	60,00
Q_{TCSR} (MVar)	0,000	130,0	0,000	270,0	0,000	410,0
R_{seen} (Ω)	0,3083	0,3084	0,3081	0,3082	0,3079	0,3080
X_{seen} (Ω)	0,2414	0,2424	0,2456	0,2471	0,2497	0,2519

Table II represents the minimum and maximum values for impedance measured by distance relay protection. These values are important for calculating the settings zones parameters for distance relay protected transmission line compensated by series FACTS devices i.e. TCSR.

VI. CONCLUSION

A procedure of short circuit parameters calculation and measured impedance by distance relay of system with TCSR on transmission line 400 kV during single phase to ground fault with fault resistance is outlined. In this research paper, the effect of apparent reactance injected by TCSR on the impedance measured by protective relay protection is being considered.

The results are presented in relation to a typical single electrical transmission system employing different TCSR (130 MVar/20 kV, 270 MVar/40 kV and 410 MVar/60 kV). The compensator is connected at the midpoint of a protected transmission line by distance relay. The simulation results show clearly the impact of TCSR on distance relay performance. The impedance Z_{seen} is influenced by the injected reactance X_{TCSR} of the TCSR. Since deviation of the measured impedance is not constant, because of the varying parameters of the injected reactance by TCSR, adaptive methods should be utilized.

In order to increase the total system protection performance and avoid unwanted tripping of circuit breaker in the presence of series FACTS devices compensator on electrical transmission line care must be taken. For specified systems, settings for different protection zones can be achieved based on the proposed setting principles. Moreover following state of TCSR changing the setting relay of overcurrent protection is necessary.

APPENDIX

A. Power Source

U_s = 11 kV, f_n = 50 Hz.

B. Power Transformer

U_{TR} = 11/400 kV, Coupling: Y/Δ, S_{TR} = 200 MVA,
X_{TR1}= *j* 0,235 Ω, X_{TR0} = *j* 0,751 Ω,

C. Transmission Line

U_L = 400 kV, ΔV = 35 kV, *Length* = 360 km,
Z_1 = 0, 1213 + *j* 0, 4227 Ω/km,
Z_0 = 0, 3639 + *j* 1, 2681 Ω/km.

D. TCSR Study

Case 1. V_{Max} = 20 kV, Q_{Max} = 130 MVar, L_1 = 0, 0424 H, L_2 = 0, 0080 H.
Case 2. V_{Max} = 40 kV, Q_{Max} = 270 MVar, L_1 = 0, 1019 H, L_2 = 0, 0159 H.
Case 3. V_{Max} = 60 kV, Q_{Max} = 410 MVar, L_1 = 0, 1637 H, L_2 = 0, 0239 H.

E. Fault Conditions

n_F = 100%, R_F = 0 to 100 Ω.

REFERENCES

[1] J. Schlabbach, "Short-Circuit Currents", second edition, Published by the Institution of Engineering and Technology (IET), London, United Kingdom, June 2008.
[2] Group Sonelgaz/OS, "Rapport: Statistics of Faults on Electrical Networks 220 kV and 400 kV", Algiers, Algeria, December 2011.
[3] AREVA T&D, "Network Protection and Automation Guide", second edition, Published by AREVA, France, January 2010.
[4] G. Zigler, "Numerical Distance Protection: Principles and Applications", third edition, Publics Corporate Publishing, Germany, January 2008.
[5] M. Adamiak, and R. Patterson, "Protection Requirements for Flexible AC Transmission Systems", *CIGRE*, Paris, France, October 1992.
[6] N. Christl, R. Hedin, R. Johnson, P. Krause, and A. Montoya, "Power System Studies and Modeling for the Kayenta 230 kV Substation Advanced Series Compensation", *International Conference on AC and DC Power Transmission (ACDC)*, London, United Kingdom, pp. 33-37, September 1991.

[7] IEEE Standard 1534, "IEEE Recommended Practice for Specifying Thyristor Controlled Series Capacitor", IEEE Power and Energy Society, New York, USA, 20 November 2009.
[8] R.M. Mathur, and R.K. Varma, "Thyristor based FACTS Controllers for Electrical Transmission Systems", John Wiley & Sons, Inc. Publication ant IEEE Press, New York, USA, 2002.
[9] M. Khederzadeh, and T.S. Sidhu, "Impact of TCSC on the Protection of Transmission Lines", *IEEE Transactions on Power Delivery*, Vol. 21, No.1, pp. 80-87, January 2006.
[10] T.S. Sidhu, and M. Khederzadeh, "TCSC Impact on Communication Aided Distance Protection Schemes and Mitigation", *IET Conference on Generation, Transmission and Distribution*, Vol. 152, No. 5, pp. 714-728, Sep. 2005.
[11] S. Jamali, A. Kazemi, and H. Shateri, "Measured Impedance by Distance Relay for Inter Phase Faults with TCSC on a Double Circuit Line", *The 18th Australasian Universities Power Engineering Conference (AUPEC)*, Sydney, Australia, 14-17 December 2008.
[12] S. Jamali, A. Kazemi, and H. Shateri, "Measured Impedance by Distance Relay for Inter Phase Faults in Presence of TCSC on Next Line", *IEEE Region 10 Conference (TENCON)*, India, 19-21 November 2008.
[13] S. Jamali, A. Kazemi, and H. Shateri, "Effects of Voltage Transformers Connection Point on Measured Impedance at Relaying Point for Inter Phase Faults in Presence of TCSC", *2nd IEEE International Conference on Power and Energy (PECon)*, Johor Baharu, Malaysia, Dec.1-3, 2008.
[14] A. Kazemi, S. Jamali, and H. Shateri, "Comparing TCSC Placements on Double Circuit Line Mid-point and Ends from Measured Impedance Point of View", *IEEE International Conference on Industrial Technology (ICIT'2008)*, Chengdu 21-24 April 2008.
[15] M. Zellagui, and A. Chaghi, "Impact of TCSC on Measured Impedance by MHO Distance Relay on 400 kV Algerian Transmission Line in Presence of Phase to Earth Fault", *Journal of Electrical Systems (JES)*, Vol. 8, No. 3, pp. 273-291, September 2012.
[16] M. Zellagui, and A. Chaghi, "Measured Impedance by MHO Distance Protection for Phase to Earth Fault in Presence GCSC", *ACTA Technica Corviniensis - Bulletin of Engineering*, Tome 5, Fascicule 3, pp. 81-86, July-September 2012.
[17] M. Zellagui, and A. Chaghi, "Impact of GCSC on Measured Impedance by Distance Relay in the Presence of Single Phase to Earth Fault", *32th International Conference on Power Systems Engineering (ICPSE)*, Dubai, UAE, 8-9 October 2012.
[18] A. Shojaei, and S.M. Madani, "Analysis of Measured Impedance by Distance Relay in Presence of SSSC", *5th IET International Conference on Power Electronics, Machines and Drives (PEMD)*, Brighton, UK, 19-21 April 2010.
[19] S. Jamali, and H. Shateri, "Locus of Apparent Impedance of Distance Protection in the Presence of SSSC", *European Transactions on Electrical Power (ETEP)*, Vol. 21, Issue.1, pp. 398-412, 2011.
[20] M. Zellagui, and A. Chaghi, "Impact of SSSC on Measured Impedance in Single Phase to Ground Fault Condition on 220 kV Transmission Line", *Leonardo Journal of Sciences (LJS)*, Vol. 11, Issue 20, pp. 109-124, January-June 2012.
[21] S. Jamali, A. Kazemi, and H. Shateri, "Measured Impedance by Distance Relay for Inter Phase Faults in Presence of SSSC", *IEEE/PES Power Systems Conference and Exposition, (PSCE)*, USA, 15-18 March 2009.
[22] A. Salemnia, M. Khederzadeh, and A. Ghorbani, "Impact of Static Synchronous Compensator (STATCOM) on Performance of Distance Relay", *IEEE Power Tech Conference (PowerTech)*, Bucharest, Romania, 28 June - 2 July, 2009.
[23] M.V. Sham, and K. Panduranga Vittal, "Simulation Studies on the Distance Relay Performance in the Presence of STATCOM", *Journal of Electrical Engineering (JEE)*, Vol. 11, N° 3, Sept. 2011.
[24] K.K. Sen, and M.L. Sen, "Introduction to FACTS Controllers: Theory, Modeling and Applications", Published by John Wiley & Sons, Inc., and IEEE, New Jersey, USA, July 2009.
[25] M. Zellagui, and A. Chaghi, "Distance Protection Settings Based Artificial Neural Network in Presence of TCSR on Electrical Transmission Line", *International Journal of Intelligent Systems and Applications (IJISA)*, Vol. 4, No. 12, pp. 75-85, November 2012.
[26] Ha Heng Xu, and Zhang BaoHui, "Study on Reactance Relays for Single Phase to Earth Fault on EHV Transmission Lines", *International Conference on Power System Technology (ICPST)*, Singapore, 21-24 Nov. 2004.
[27] S. Jamali, and H. Shateri, "Impedance based Fault Location Method for Single Phase to Earth Faults in Transmission Systems", *10th IET International Conference on Developments in Power System Protection (DPSP)*, United Kingdom, 29 March - 1 April, 2010.
[28] L. Gérin-Lajoie, "A MHO Distance Relay Device in EMTP Works", *Electric Power Systems Research (EPSR)*, Vol. 79, No.3, pp. 484-49, March 2009.
[29] Sonelgaz Group/OS, "Topologies of Electrical Networks 400 kV", Algerian Company of Electrical Transmission Network", 30 December 2011, Algiers, Algeria

Mr. Mohamed Zellagui, Was born in Constantine, Algeria, 1984. He received the engineer and magister degree in Electrical Engineering (Electrical Networks) from department of Electrical Engineering at University of Constantine, Algeria in 2007 and 2010 respectively, PhD Student and member LSP-IE research laboratory from department of Electrical Engineering at Batna University, Algeria. Membership at International Association of Engineers (IAENG) and the Institution of Engineering and Technology (IET). Senior member in Universal Association of Computer and Electronics Engineers (UACEE) His areas of interest include electrical networks, power system protection, distance relay, overcurrent relay, wind energy and FACTS devices.

Pr. Abdelaziz Chaghi, Was born in Batna, Algeria, 1954. He received his BS degree from the University of Oran, Algeria 1980, and MS from the Manchester University, England 1984, and received his PhD from Batna University, Algeria 2004. He is currently a Professor at department of Faculty of Technology, Electrical Engineering and member LSP-IE research laboratory at University of Batna. His areas of interest include power systems, particle swarm optimization, harmonic, power quality and FACTS devices.