Effect Assessment of TCSC on Algerian Transmission Line Protected by IDMT Directional Overcurrent Relay

Mohamed ZELLAGUI [1], Rabah BENABID [2,3], Abdelaziz CHAGHI [1], and Mohamed BOUDOUR[3]
[1] Department of Electrical Engineering, University of Batna, Batna, Algeria,
m.zellagui@univ-batna.dz, az_chaghi@univ-batna.dz
[2]Department of Electrical Engineering, Nuclear Center Research of Birine, Djelfa, Algeria rabah_benabid@yahoo.fr
[3] Department of Electrical Engineering, University of Sciences & Technology Houari Boumediene (USTHB), Algeria,
mboudour@ieee.org

***Abstract*— The paper presents the effect of apparent reactance and injected voltage by series Flexible AC Transmission System (FACTS) i.e. Thyristor Controlled Series Capacitor (TCSC) on transmission line high voltage protected by an Inverse Definite Minimum Time (IDMT) Directional Overcurrent Relay (DOCR) based International Electrotechnical Commission (IEC) standard characteristic curve. The DOCR is used to protect a 400kV transmission line of the Algerian transmission power systems which belong to the Algerian Company of Electrical. The effects of TCSC on protected transmission line parameters (reactance and resistance) as well as fault current and operation time of the DOCR in the presence of phase to earth fault with fault resistance for three cases study is investigated.**

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 and the prediction for the design and determination of the rating of the individual equipment and of the power system as a whole is necessary in the future. 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]. In order to reduce hazardous effects of over current caused by faults, faster operation of over-current protections is desirable which means maximum sensitivity of the DOCR relays to the current and a minimum operation time [2]. 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 [3] are single phase to ground type. Distance protection and overcurrent protection relays have been widely applied as a primary protection in high voltage transmission lines due to their simple operating principle and capability to work independently under most circumstances [4].

The basic operation principle of DOCR relay is based on the fact that the fault current measured by relay is fairly constant with respect to the line length [5]. 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. Some of the concerns include the rapid changes in line impedance and the transients introduced by the fault occurrence with the associated control action of the FACTS Controllers. The presence of the FACTS devices in the faulted loop introduces changes to the line parameters seen by the distance relay and fault current seen by DOCR relay. The effect of FACTS devices on distance protection and DOCR 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. DOCR are good technical and economic alternative for the protection of interconnected systems and secondary protection of transmission systems [6]. These relays are provided in power systems to isolate only the faulted lines in the power system. Relay is a logical element that generates a trip signal to the circuit breaker if a fault occurs within the relay jurisdiction.

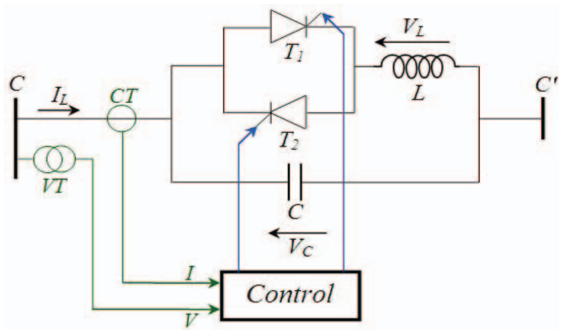
The DOCR's are usually placed at both ends of each line and their coordination is an important aspect in the protection system design. Relay coordination problem is to determine the sequence of relay operations for each possible fault location so that faulted section is isolated, with sufficient coordination margins, and without excessive time delays. This sequence selection is a function of power network topology relay characteristics and protection philosophy [7].

The protective devices must be set up according to the new conditions of the changed power system or the conventional protective devices must be upgraded to a higher short-circuit current rating [8]. In [9] the influence of the superconducting fault current limiter (SFCL) introduced into the feeder's entrance of the distributed power system on the operational characteristics of the overcurrent relay was analyzed through the short-circuit experiments, while in [10] a study to determine the optimal resistance of a SFCL connected to a wind turbine generation system (WTGS) in series considering its protective coordination is reported. The effect for distributed generation on IDMT relay and optimal relay setting based on linear programming approach is reported in [11] and differential evolution algorithm in [12]. In [13], the effect of distributed renewable generation on DOCR coordination based on two approaches (adaptive and non-adaptive protection systems) is proposed to solve the coordination problem while the effect of series capacitor (SC) in optimal coordination is given in [14].

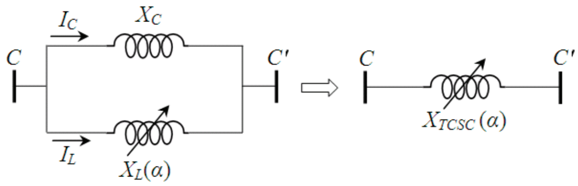
In this paper, we study on one hand the effect of TCSC parameters such as the apparent reactance and injected voltage on the parameters of protected transmission line and on the other hand, the effect on fault current and operation time of IDMT directional overcurrent relay in the presence of phase to earth fault with fault resistance at the end of 400 kV Algerian transmission line.

II. Transmission Line In The Presence TCSC

Series connected FACTS devices TCSC are usually utilized to regulate the voltage at their connection point. The model of these devices and their general model are presented in this section. The compensator TCSC mounted on figure 1.a is a type of series FACTS compensators. It consists of a capacitance (C) connected in parallel with an inductance (L) controlled by a valve mounted in anti-parallel thyristors conventional (T_1 and T_2) and controlled by an angle of extinction (α) which is varied between 90° and 180°.



(a)



(b)

Fig. 1. Transmission line in presence of TCSC:
a). Equivalent circuit, b). Apparent reactance.

This compensator injected in the transmission line a variable reactance (X_{TCSC}) indicated by figure 1.b. Its value is function of the reactance of the line X_L where the device is located.

The apparent reactance X_{TCSC} is defined by the following equation [15], [16]:

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

The expression of X_{TCSC} is directly related to the angle α, which varies, following the above equation:

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

Where,

$$X_{L.\max} = L.\omega \quad (3)$$

$$X_C = \frac{1}{C.\omega} \quad (4)$$

Taking account of the equation (2), final the equation (1) becomes:

$$X_{TCSC}(\alpha) = \frac{X_C . X_L\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right]}{X_C + X_L\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right]} \quad (5)$$

The curve of X_{TCSC} as a function of α is divided into three different regions: inductive, capacitive, and resonance as summarized in the figure 2.

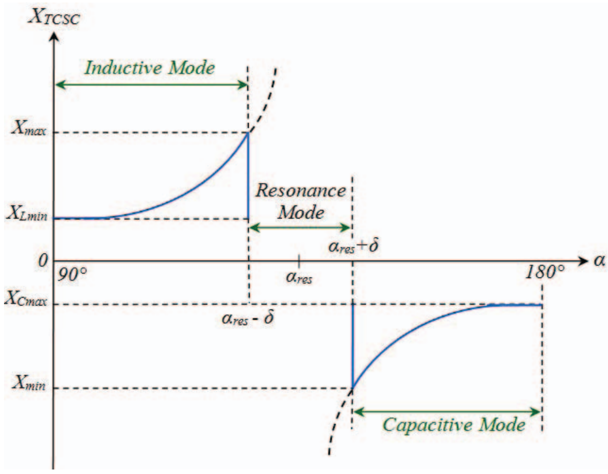


Fig. 2. Characteristic curve $X_{TCSC} = f(\alpha)$.

III. Phase To Earth Fault Calculation

Figure 3 shows transmission line in case of a single phase (phase A) to ground fault at busbar B (n_F = 100 %), with fault resistance (R_F) in the presence of a series compensator TCSC inserted on midline AB, while figure 4 shows the equivalent circuit.

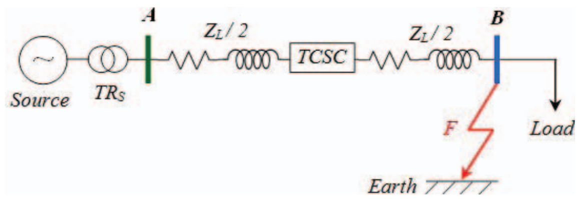


Fig. 3. Transmission line with TCSC.

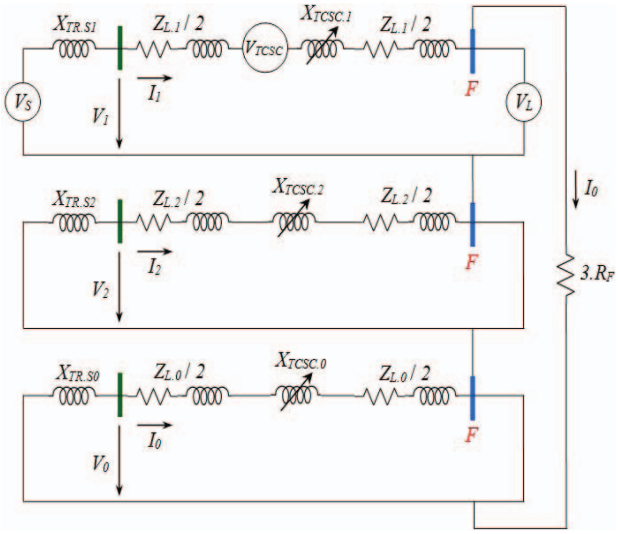


Fig. 4. Earth fault equivalent circuit with TCSC.

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

$$Z_{L-TCSC} = R_L + j\left[X_L + X_{TCSC}(\alpha)\right] \tag{6}$$

Regarding the references [17] and [18], the basic equations for this fault are as follows:

$$I_b = I_c = 0 \tag{7}$$

$$V_a = V_1 + V_2 + V_0 = R_F.I_a \neq 0 \tag{8}$$

The symmetrical components of currents are:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{9}$$

From equation (7) and matrix (9), the symmetrical components of currents become:

$$I_1 + I_2 + I_0 = \frac{I_A}{3} \tag{10}$$

The symmetrical components of voltages are:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{11}$$

From equation (9) and matrix (11), the direct components of voltage become:

$$V_1 = -\left(V_0 + V_2\right) + R_F.I_A \tag{12}$$

And,

$$V_s + V_{TCSC} - I_1\left[\frac{Z_{L.1}}{2} + X_{TCSC.1} + \frac{Z_{L.1}}{2}\right] = A + B + C \tag{13}$$

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

$$A = -\frac{1}{3}\left[-\left(\frac{Z_{AB.0}}{2} + X_{TCSR.0} + \frac{Z_{AB.0}}{2}\right).I_0\right] \tag{14}$$

$$B = -\frac{1}{3}\left[-\left(\frac{Z_{AB.2}}{2} + X_{TCSR.2} + \frac{Z_{AB.2}}{2}\right)I_2\right] \tag{15}$$

$$C = R_F.I_A \tag{16}$$

The coefficients Z_{L-T} and X_{TCSC-T} are defined for simplicity as:

$$Z_{L-T} = Z_{L.1} + Z_{L.2} + Z_{L.0} \tag{17}$$

$$X_{TCSC-T} = X_{TCSC.1} + X_{TCSC.2} + X_{TCSC.0} \tag{18}$$

$$V_s + V_{TCSC} = \frac{I_A}{3}\left[\frac{Z_{L-T}}{2} + X_{TCSC-T} + \frac{Z_{L-T}}{2}\right] + R_F.I_A \tag{19}$$

From equations (17), (18) and (19), the current at phase (A) in presence TCSC on midline is given by:

$$I_A = \frac{3.\left(V_S + V_{TCSC}\right)}{\left(\frac{Z_{L-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{L-T}}{2}\right) + 3.R_F} \tag{20}$$

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

$$I_1 = I_2 = I_0 = \frac{V_S + V_{TCSC}}{\left(\frac{Z_{L-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{L-T}}{2}\right) + 3.R_F} \tag{21}$$

The positive components of voltages in presence of TCSC are:

$$\begin{aligned} V_1 &= V_S + V_{TCSC} - \left(\frac{Z_{L.1}}{2} + X_{TCSC.1} + \frac{Z_{L.1}}{2}\right).I_1 \\ \Rightarrow V_1 &= \frac{\left(V_S + V_{TCSC}\right).\left[Z_L' + X_{TCSC}' + 3.R_F\right]}{\frac{Z_{L-T}}{2} + X_{TCSC-T} + \frac{Z_{L-T}}{2} + 3.R_F} \end{aligned} \tag{22}$$

Where, the coefficients Z_L' and X_{TCSC}' are defined as:

$$Z_L' = Z_{L.2} + Z_{L.0} - 2.Z_{L.1} \tag{23}$$

$$X_{TCSC}' = X_{TCSC.2} + X_{TCSC.0} - 2.X_{TCSC.1} \tag{24}$$

The negative components of voltages in presence TCSC are:

$$\begin{aligned} V_2 &= -\left(\frac{Z_{L.2}}{2} + X_{TCSC.2} + \frac{Z_{L.2}}{2}\right).I_2 \\ \Rightarrow V_2 &= -\frac{\left(V_S + V_{TCSC}\right).\left[Z_{L.2} + X_{TCSC.2}\right]}{\left(\frac{Z_{L-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{L-T}}{2}\right) + 3.R_F} \end{aligned} \tag{25}$$

The zero components of voltages in presence TCSC are:

$$V_0 = -\left(\frac{Z_{L.0}}{2} + X_{TCSC.0} + \frac{Z_{L.0}}{2}\right).I_0 - R_F.I_0$$
$$\Rightarrow V_0 = -\frac{(V_S + V_{TCSC}).\left[Z_{L.0} + X_{TCSC.0} + R_F\right]}{\left(\frac{Z_{L-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{L-T}}{2}\right) + 3.R_F} \quad (26)$$

The new coefficients are defined as:

$$Z_2' = Z_{L.2} + X_{TCSC.2} \quad (27)$$

$$Z_0' = Z_{L.0} + X_{TCSC.0} \quad (28)$$

$$S_a = 3.a^2 - 1 \quad (29)$$

$$S_b = 3.a - 1 \quad (30)$$

$$A_a = a^2 - a \quad (31)$$

$$A_b = a^2 - 1 \quad (32)$$

$$A_c = a - a^2 \quad (33)$$

$$A_d = a - 1 \quad (34)$$

From equations (22), (25) and (26), the three phase voltages on transmission line in presence of TCSC are:

$$V_A = \frac{3.R_F.\left(V_S + V_{TCSC}\right)}{\left(\frac{Z_{L-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{L-T}}{2}\right) + 3.R_F} \quad (35)$$

$$V_B = \frac{\left(V_S + V_{TCSC}\right).\left[A_a Z_2' + A_b Z_0' + S_a R_F)\right]}{\left(\frac{Z_{L-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{L-T}}{2}\right) + 3.R_F} \quad (36)$$

$$V_C = \frac{\left(V_S + V_{TCSC}\right).\left[A_c Z_2' + A_d Z_0' + S_b R_F)\right]}{\left(\frac{Z_{L-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{L-T}}{2}\right) + 3.R_F} \quad (37)$$

In this fault, the fault current equals the current at phase (A):

$$I_F = I_A \quad (38)$$

From equations (20) and (38), the fault current measured by IDMT directional overcurrent relay is only related to: Parameters of transmission line (U_n, R_L, and X_L), Parameters of TCSC installed (V_{TCSC} and X_{TCSC}), Fault resistance (R_F).

IV. IDMT Directional Ouvercurrent Relay

The basic task of the overcurrent relays is to sense faults on the lines and to rapidly isolate these faults by opening all the current paths. This sensing and switching must occur as fast as possible to minimize damage. However, it should be very selective so no more of the network is removed from service than is necessary.

In order to increase reliability, this need has led to the practice of providing both "primary" protections with "backup" protection which should function only if one of the primary devices fails. Overcurrent relays are classified on the basis of their operation time [20, 21].

Inverse Definite Minimum Time (IDMT) overcurrent relay, has an inverse time characteristic, this means that the relay operating time is inversely proportional to the fault current. If the fault current is higher, the operating time will be lesser [19]. It can be graded for a very large range of operating times and fault currents [20].

The characteristics of an IDMT overcurrent relay depend on the type of standard selected for the relay operation. These standards can be ANSI, IEEE, IEC or user defined. The relay calculates the operation time by using the characteristic curves and their corresponding parameters [21]. Any of the above mentioned standards can be used to implement a characteristic curve for an overcurrent relay. The overcurrent relay will then calculate the operation time corresponding to that particular characteristic curve.

The primary protection system is designed for speed and the minimum network disturbance while backup system operates more slowly (thereby giving the primary system a chance to operate). In order to have proper coordination of the primary and backup protective relays all the possible faults have to be accounted for each line has a variety of relays on each end. Typically there are both directional overcurrent relays for protection against phase faults on the line. The tripping time of the relay follows a time over current delayed curve, in which the time delay depends upon current.

A. Relay characteristics

The IDMT overcurrent relays employed in this paper are considered as numerical and directional with standard IDMT characteristics that comply with the IEC 60255-3 standard, and have their tripping direction away from the bus [22].

$$T_i = TDS \times \frac{\beta}{\left(I_m / I_P\right)^{\alpha} - 1} \quad (39)$$

Where, TDS is the time dial setting and I_P is pickup current setting of the IDMT relay respectively, and I_m is the fault current measured by the i^{th} relay.

However, it can be shown that the proposed method can be easily applied to a system with combination of DOCRs with different characteristics.

In figure 5, the current I equal I_m/I_P, the measured relay fault current is defined by:

$$I_m = \frac{I_F}{K_{CT}} \quad (40)$$

Where, K_{CT} is the ratio of current transformer and I_F the fault current in protected transmission line.

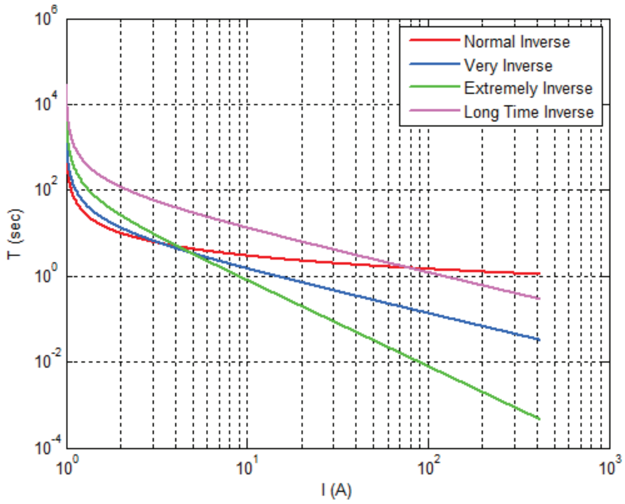


Fig. 5. Time-current of IDMT overccurent relaying characteristics.

B. *Relay Settings*

The calculation of the two settings, *TDS* and I_P is the essence of the overcurrent relay coordination study. Therefore this constraint can be formulated as [23]:

$$TDS_i^{\min} \le TDS_i \le TDS_i^{\max} \tag{41}$$

Practically, the value of *TDS* varied between 0.05 to 1.20 [24], [25].

$$\max\left(I_L^{\max}, I_P^{\min}\right) \le I_{Pi} \le \min\left(I_F^{\min}, I_P^{\max}\right) \tag{42}$$

The minimum pickup current setting of the relay is the maximum value between the minimum available current setting (I_P^{min}) and the maximum load current (I_L^{max}). In similar, the maximum pickup current setting is chosen as the minimum value between (I_P^{max}) of the relay and the minimum measured fault current (I_F^{min}).

C. *Coordination Time Interval*

In any power system, a primary protection has its own backup one for guaranteeing a dependable power system. The two protective systems (primary and back-up) should be coordinated together. Coordination Time Interval (*CTI*) is the criteria to be considered for coordination.

It's a predefined coordination time interval and it depends on the type of relays. For electromagnetic relays, *CTI* is of the order of 0,30 to 0,40 second, while for numerical relay, it is of the order of 0,10 to 0,20 second [26, 27].

To ensure the reliability of the protective system, the backup scheme shouldn't come into action unless the primary (main) fails to take the appropriate action. Only when *CTI* is exceeded, backup relay should come into action. This case is expressed as:

$$T_{Backup} - T_{Primary} \ge CTI \tag{43}$$

Where, T_{Backup} is operating time of the backup relay, and $T_{Primary}$ is operating time of the primary relay.

V. Case Study and Simulation Results

The power system studied in this paper is the 400 kV and 50 Hz in Algerian electrical transmission networks at Algerian Company of Electrical and Gas (group Sonelgaz) which is shows in figure 6 [27, 28].

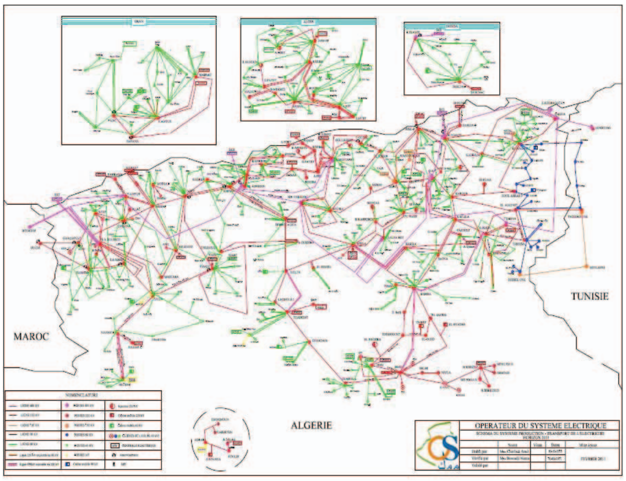


Fig. 6. Electrical power system study.

The TCSC is located between Oued El Athmania substation in Mila (busbar *B*) and Salah Bay substation in Sétif (busbar *C*), where busbar *A* is Ramdane Djamel substation in Skikda.

The parameters of transmission lines, the TCSC study, fault conditions, and IDMT directional overcurrent relays setting are summarized in the appendix.

Figure 7 repesents the characteristcs curves (time-current) for three IDMT directional overccurent relays (R_A, R_B and R_C) installed in the three HV busbar *A*,*B* and *C* respectively based IEC 60255-3 standard.

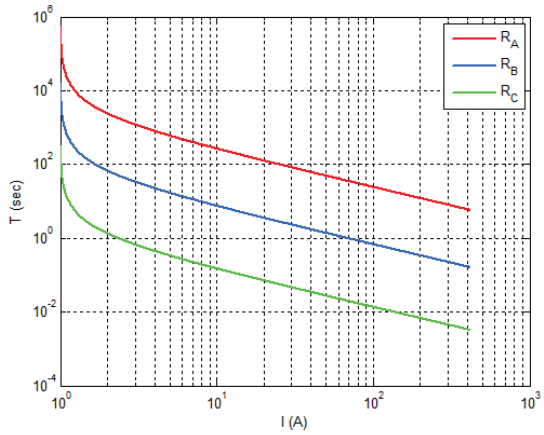


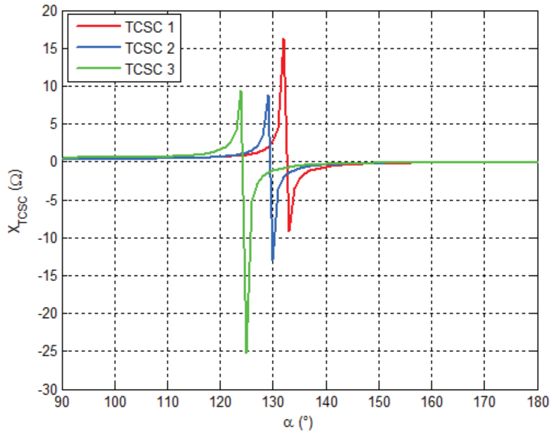
Fig. 7. Characteristics curves of the installed relays.

Figures 8.a and 8.b show the X_{TCSC} and V_{TCSC} characteristics curves as function of the firing angle (α) respectively of the three TCSC used in case study.

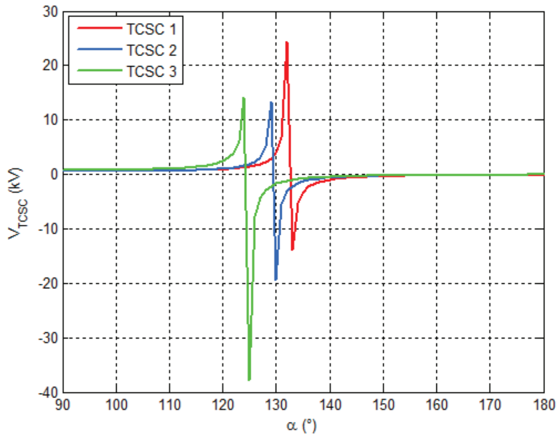
A. *Effect on the Transmission Line Impedance*

Figures 9.a and 9.b show the effect of X_{TCSC} and V_{TCSC} by three different TCSC insertion on the transmission line reactance (X_L) respectively between busbar *B* and *C*.

Figures 10.a and 10.b show the effect of X_{TCSC} and V_{TCSC} by three different TCSC insertion on the transmission line resistance (R_L) respectively between busbar *B* and *C*.

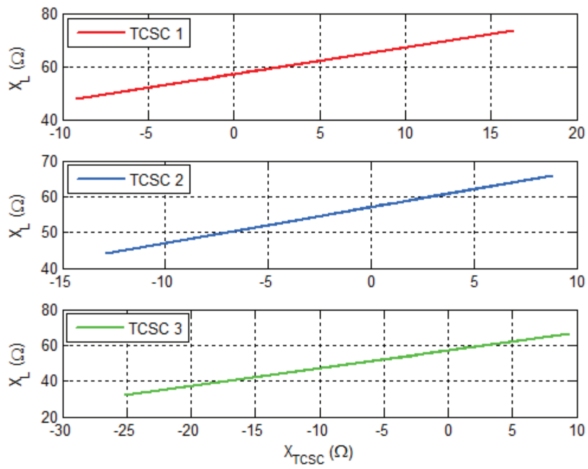


(a)

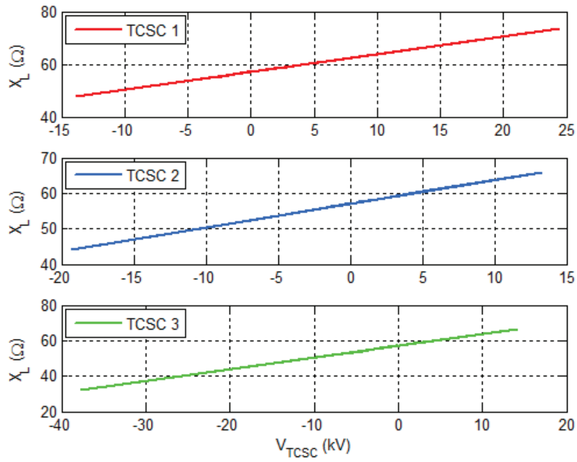


(b)

Fig. 8. Characterisic curve for TCSC study:
a). $X_{TCSC} = f(\beta)$, b).$V_{TCSC} = f(\beta)$.

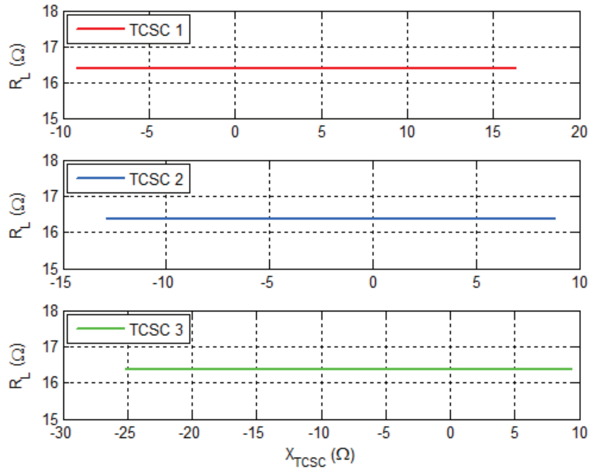


(a)

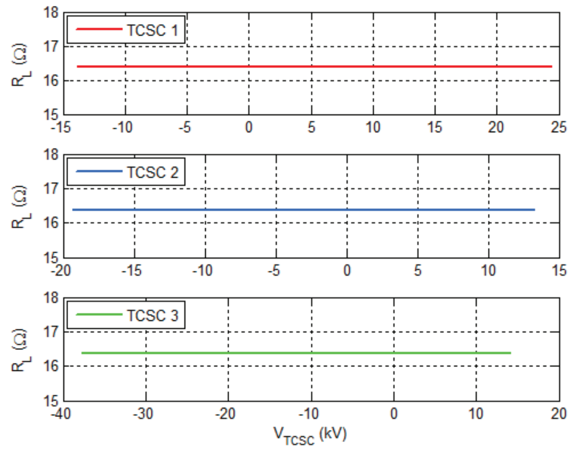


(b)

Fig. 9. Effect of TCSC on the transmission line reactance:
a). $X_L = f(X_{TCSC})$, b). $X_L = f(V_{TCSC})$.



(a)



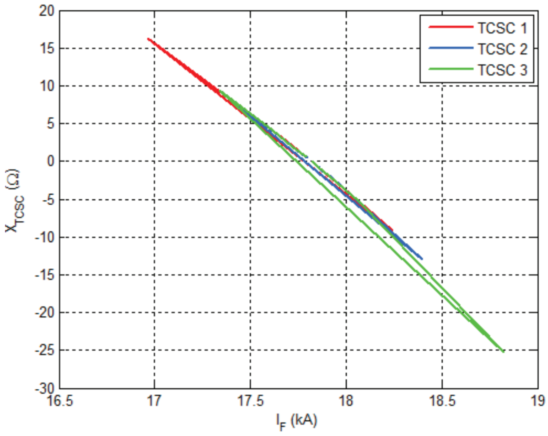
(b)

Fig. 10. Effect of TCSC on the transmission line resistance:
a). $R_L = f(X_{TCSC})$, b). $R_L = f(V_{TCSC})$.

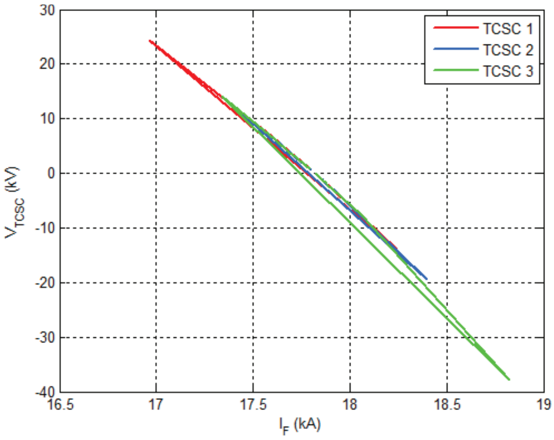
From figures 9 and 10, the apparent reactance and voltage injected by TCSC has a direct influence on the total impedance. This effect is being observed especially on the reactance X_L while there is no influence on the resistance R_L for the three cases study.

B. Effect on the Fault Current

Figures 11.a and 11.b show the effect of X_{TCSC} and V_{TCSC} by three TCSC insertions on the fault current respectively in presence phase to earth fault with R_F at busbar *C*.



(a)



(b)

Fig. 11. Effect of TCSC on fault current:
a). $I_F = f(X_{TCSC})$, b). $I_F = f(V_{TCSC})$.

From figures 11, apparent reactance and voltage injected by TCSC has a direct influence on the fault current. As can be seen from equations 20 and 34, the reactance is augmented following insertion of a capacitive reactance in capacitive mode and reduced following insertion of an inductive reactance in inductive mode in protected transmission line.

C. Effect on the IDMT Curve

The figure 12 show the effect of the fault current variation on the operating time of the IDMT directional overcurrent relay installed at busbar *B*.

From figure 12, the fault current variation has a direct influence on the operating time of the relay, as confirmed by equations 35 and 36.

Figure 13 shows the characteristic curve (time-current) of IDMT overcurrent relay installed in busbar *B* without and with the presence of three different TCSC devices on the transmission line.

D. Effect on the Operation Time

Figures 14.a and 14.b show the effect of parameters (X_{TCSC} and V_{TCSC}) of the three installed TCSC on the operation time respectively for an IDMT directional overcurrent relay installed at busbar *B*.

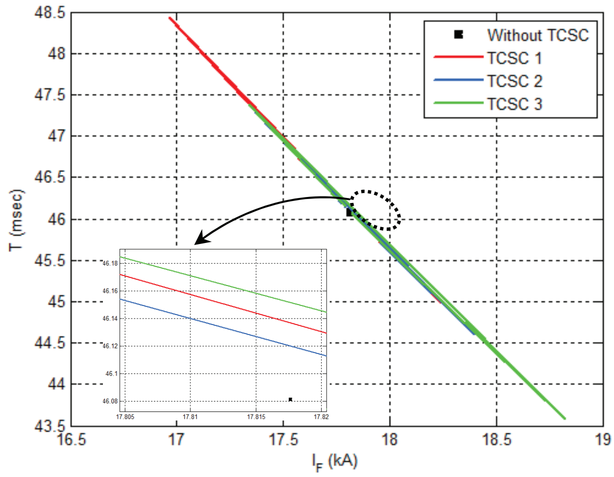


Fig. 12. Effect of fault current on operation time.

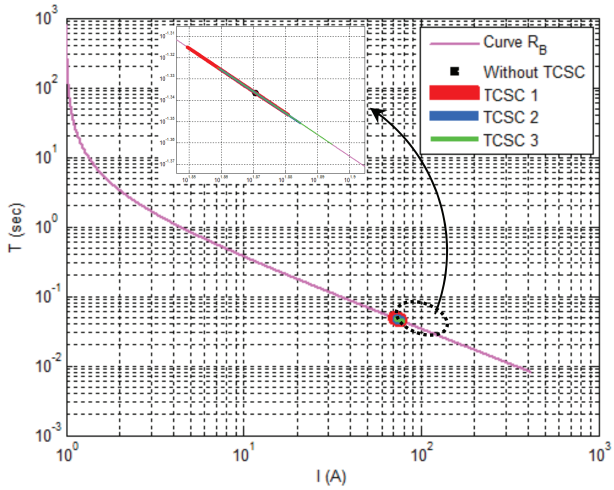
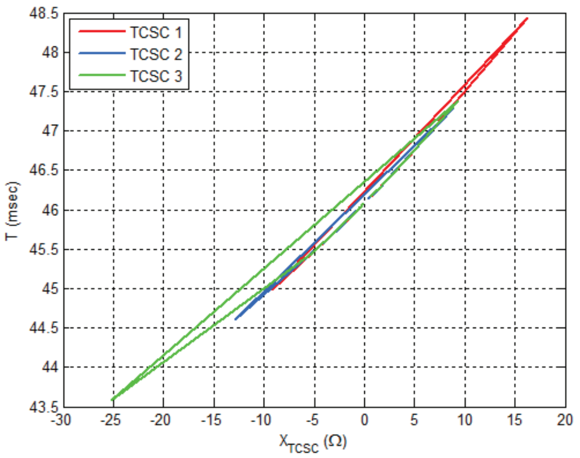


Fig. 13. Time-current for relay *B* in the presence of TCSC.

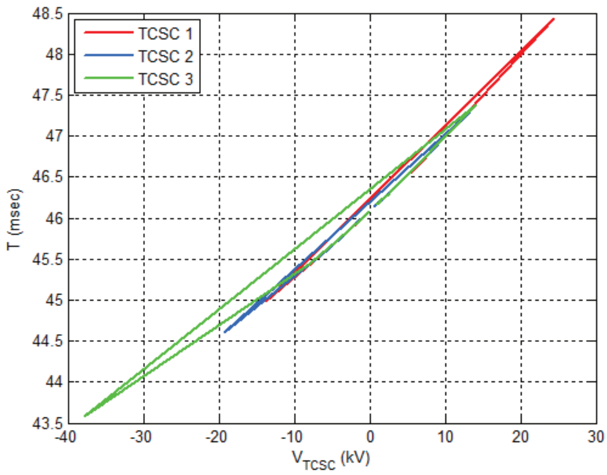
From figures 14, apparent reactance and voltage of the TCSC have a direct influence on the operating time as confirmed by equations 35 and 36, where the measured fault current by relay is varied in the two operation modes.

VI. Conclusion

A procedure of fault current calculation and operation time for on midline DOCR i.e. IDMT protected Algerian transmission line 400 kV employing different TCSC during single phase to ground fault with fault resistance is outlined. The effect of apparent reactance and voltage controlled by three different TCSC devices on the operation time is being considered.



(a)



(b)

Fig. 14. Effect of the TCSC parameters on operation time: a). $T = f\,(X_{TCSC})$, b). $T = f\,(V_{TCSC})$.

The compensator TCSC parameters have a direct influence on DOCR, since deviation of the transmission line impedance and fault current is not constant. Because of the varying parameters of the injected inductive and capacitive reactance, 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 transmission line care must be taken. Since the measured fault current by relay has an effect on operation time it is necessary to change the settings relay (*TDS* and I_P) to respect the coordination.

Moreover care must be taken following changing setting relay with respect to TCSC state, optimal coordination of directional overcurrent relays considering dynamic changes by series FACTS devices in the power systems by using optimization techniques (PSO, ACO and EA) which is our future research work.

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APPENDIX

A. Power source
U_s = 11 kV, f = 50 Hz.

B. Power transformer
U_{TR} = 11 / 400 kV, $X_{TR} = j$ 0.213 Ω, $X_{TR0} = j$ 0,710 Ω.

C. Transmission line
U_L = 400 kV, L_{AB} = 360 km, L_{BC} = 135 km,
Z_1 = 0.1213 + j 0.4227 Ω/km, Z_0 = 0.3639 + j 1.2681 Ω/km,

D. TCSC study
Case 1: L = 0.190 mH, C = 82.00 F,
Case 2: L = 0.150 mH, C = 86.00 F,
Case 3: L = 0.100 mH, C = 89.00 F.

E. IDMT overcurrent relay
K_{TC} = 1200 / 5,
Relay A: Very inverse, I_P = 1.00, TMS = 0.10,
Relay B: Very inverse, I_P = 1.00, TMS = 0.25,
Relay C: Very inverse, I_P = 1.00, TMS = 0.60.

F. Fault conditions
n_F = 100 %, and R_F = 100 Ω.