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A Comparative Study of Ground Fault Analysis for a Practical Case of a Transmission Line Equipped with Different Series FACTS Devices

Due to the rising power demand and increasing population worldwide, electrical power networks have been extensively growing and striving to satisfy the escalating loads. This necessitates the need for using Flexible AC Transmission System (FACTS) devices which have become indispensable during normal and abnormal operating conditions. This paper investigates the impact of using series FACTS devices, namely Thyristor Controlled Series Capacitor (TCSC), GTO Controlled Series Capacitor (GCSC) and Thyristor Controlled Series Reactor (TCSR), on the impedance and power flow of a practical 400 kV transmission line in the Algerian power network. It also investigates the effect of varying the fault resistance on short-circuit calculations in the case of a phase to ground fault that occurs at the end of the compensated line. Analytical formulas of the employed FACTS devices, the system model under fault and short-circuit calculations are deduced and presented in the paper. Simulations results obtained using MATLAB are demonstrated for the compensated line and without compensation. These simulations are compared to show the effect of using these devices for the studied cases.

It is concluded that GCSC provides better performance in the active and reactive power flow of the line under normal operating conditions and in reducing the fault current during abnormal operating conditions when the fault resistance increases. On the other hand, TCSR shows a better performance in maintaining higher voltages under fault with the increase of fault resistance.

Key words: Thyristor Controlled Series Capacitor (TCSC), GTO Controlled Series Capacitor (GCSC), Thyristor Controlled Series Reactor (TCSR), Algerian power network, Phase to ground fault, Fault resistance, Short-circuit calculations.

Usporedna analiza greške uzemljenja za praktični slučaj transmisijske linije s različitim FACTS uređajima. Zbog rastuće potražnje za električnom energijom i porasta svjetske populacije elektroenergetske mreže ubrzano rastu i podnose sve veće terete. Takav razvoj situacije doveo je do korištenja fleksibilnih AC transmisijskih sustava (FACTS) koji su postali nezamjenjivi tijekom normalnih i narušenih uvjeta na mreži. U ovom se radu istražuje utjecaj korištenja FACTS uređaja, tiristorski upravljani serijski kondenzatori, GTO upravljani serijski kondenzatori i tiristorski upravljana serijska reaktancija, na impedanciju i tok snage kod 400 kV transmisijske lijene u alžirskom elektroenergetskom sustavu. Istražuje se i utjecaj promjene otpora greške pri izračunu kratkog spoja u slučaju spoja faze na zemlju koje se događa na krajevima linije. Analitičke formule korištenog FACTS uređaja, model sustava s greškom i izračun kratkog spoja su izvedeni i prikazani u radu. Simulacijski rezultati dobiveni korištenjem MATLB-a prikazani su za linije sa i bez kompenzacije. Simulacije su uspoređene kako bi se prikazao učinak korištenja različitih uređaja. Zaključeno je da GTO upravljani serijski kondenzatori ima bolja svojstva kod toka radne i jalove snage kroz liniju tijekom normalnog rada i kod smanjenja struje greške tijekom narušenih uvjeta kada otpor greške raste. S druge strane, tiristorski upravljani serijski kondenzatori bolji su kod održavanja visokog napona tijekom greške uz povećanje otpora greške.

Ključne riječi: tiristorski upravljani serijski kondenzatori, GTO upravljani serijski kondenzatori, tiristorski upravljana serijska reaktancija, alžirski elektroenergetski sustav, greška spoja faze i zemlje, otpor greške, izračun kratkog spoja

1 INTRODUCTION

Power systems are the backbone of the country's economy and industry. Therefore, continuity and quality of electrical supply are maintained through proper planning, careful design, good maintenance and thorough operation of the network. Nevertheless, short-circuit faults can still

happen as they cannot be fully avoided. Faults can occur due to external factors such as lightning strokes that lead to voltage surges, accumulation of moisture and contaminants mainly in humid environments, damage of cables due to earth construction works, etc. Internal factors can also result in faults such as these attributed to the deterioration of insulation material due to ageing, overheated equipments as a result of loose connections, voltage or mechanical stresses applied to system equipments, system-generated voltage surges due to switching, and connection/disconnection of loads and equipments, [1-2].

Short circuit fault analysis determines the make and break fault levels in the system for all types of faults which allows the proper determination of equipments' ratings, settings and coordination, [1].

Based on the complexity of the system, the calculations could also be too much involved. Short-circuit analysis and accurate fault current calculations are normally carried out using the method of symmetrical components, [3]. This method is based on the principle that a set of unbalanced vectors can be represented by a set of three balanced quantities which are known as direct, inverse and zero sequence components. The method of symmetrical components is used to analyze different types of faults which may occur in the network. For example, in Algeria, the 220 and 400 kV overhead transmission network normally has more than 83 % of the occurring faults as single phase to ground faults, 11 % as phase to phase faults and the remaining 6 % are three phase faults, [4].

In literature, researchers investigated the impact of fault resistance on system performance under short-circuit such as studying; the error in fault distance estimation in the presence of ground faults, [5], distance protection performance based MHO and polygonal characteristics, [6], adaptive digital distance relaying scheme for double transmission line, [7], distance relaying scheme to compensate fault location errors, [8] and an adaptive digital relaying scheme to tackle recloser-fuse mis-coordination for Distributed Generation (DG), [9]. More studies were conducted concerning the effect of fault location in distribution power systems, [10], unbalanced three-phase distribution systems, [11], transmission power system, [12], hybrid transmission lines, [13] and radial distribution systems with DG, [14]. Further studies addressed the effect of distributed generators on arcing faults, [15], current zero estimation technique to control the arcing time of circuit breakers, [16], bus-bar protection, [17], impedance fault protection in high voltage transmission lines, [18], ground-fault feeder detection, [19], and an equivalent circuit of a high resistance grounded power supply transformer in the case of ground fault, [20]. With the growing stress on the aging existing grids, power systems face an unprecedented range of technical, economical, environmental and security

challenges and constraints. This situation has increased the interest and potential for FACTS which can offer many benefits to the network and have successfully contributed in solving several problems in power systems, [2].

One of the frequently used series FACTS devices is Thyristor Controlled Series Capacitor (TCSC) which was addressed by many researchers to study its effect on the protection of transmission lines in the presence of faults, [21-22], the variation of the measured impedance in interphase faults when using TCSC on an adjacent line, [23] and the effect of the voltage transformers connection point on the measured impedance at the relaying point for different types of faults when using TCSC, [24]. Further studies presented the optimal placement of TCSC to improve the voltage stability limit while considering its impact on distance relays, [25], the effect of TCSC on the behavior of a transformer differential protection, [26], and a relaying algorithm for the protection of transmission lines compensated by TCSC based on the pattern of traveling waves generated during a fault, [27].

GTO Controlled Series Capacitor (GCSC) is a more recent FACTS device which is also used for series compensation by controlling the power flow of transmission lines. The basic structure of GCSC is made of a pair of anti-parallel GTO switches and a capacitor which is connected in series with the line. The principle of operation of GCSC is based on varying the turn-off angle of the GTO switches to control the voltage of the capacitor and thus control the series compensation of the line, [28]. Researchers explored the impact of GCSC parameters on the impedance measured by MHO distance protection relay for a 220 kV line in the Algerian power network in the case of a single phase to ground fault, [29]. Another analysis was conducted to investigate the effect of GCSC parameters on the operating time of Inverse Definite Minimum time (IDMT) directional overcurrent protection relay, protected line impedance and fault current of a 400 kV line in the Algerian network in the presence of a phase to ground fault, [30].

TCSR is a series FACTS device which consists of a series reactor connected in shunt with a Thyristor Controlled Reactor (TCR). In order to control the reactance of the compensated line, the inductive reactance of TCSR is smoothly controlled through the variation of the firing angle of thyristors, [31]. The effect of the reactance controlled by TCSR on distance relays, protected line and short-circuit calculations was investigated in the case of a phase to ground fault, [32].

Similar studies were conducted to explore the effect of using another series FACTS device which is Static Synchronous Series Compensator (SSSC) on the impedance measured by distance relays for a 400 kV transmission line under normal conditions, [33]. Researchers also addressed the effect of SSSC in the presence of a single phase to

ground fault for a 220 kV transmission line in the Algerian network, [34], and in the case of inter phase, phase to phase and three phase faults, [35]. SSSC location in the middle of the line was shown to divide the trip characteristics of distance relay into two sections through analysis of several cases and the zero sequence of the voltage injected by 48 pulse SSSC converters appeared to have the most impact on the apparent impedance seen by digital distance relay in the case of phase to ground fault, [36]. A recent study investigated the effect of shunt capacitance of a medium/long transmission line compensated by SSSC, presented the ideal tripping characteristics of the distance protection of the line and demonstrated the extent to which neglecting the shunt capacitance would contribute to misoperation of the distance relay, [37].

Algeria is one of the largest countries in North Africa which possesses an extensive power network. In 2012, the total length of its transmission network was 23,802 km with an increase of 6.29% when compared to 2011. In 1977, the electrification rate was only 57% and nowadays more than 96% of Algeria is connected to the grid.

The case study used in this paper is for a high voltage transmission line in the Algerian power network which is similar to that used in [38] where the authors investigated the effect of the controlled voltage injected by Thyristor Controlled Voltage Regulator (TCVR) in the case of a phase to ground fault.

In this paper, authors address the compensation of a practical 400 kV transmission line in the Algerian power network using different series FACTS devices. The line connects two 400/220 kV substations, namely Ain Beida and M'Sila in northern Algeria. It is compensated by Thyristor Controlled Series Capacitor (TCSC), GTO Controlled Series Capacitor (GCSC) or Thyristor Controlled Series Reactor (TCSR). The effect of each device on the line impedance as well as the active and reactive power flow is studied and compared. Formulas are derived for the calculation of short-circuit parameters in the case of a phase to ground fault that occurs at the end of the line while using a fault resistance denoted by R_F. The effect of varying R_F is also explored and compared when no compensation is used and when using different FACTS devices for compensation.

Section II presents the structure and the mathematical model of the three mentioned FACTS devices. Short-circuit calculations in the case under discussion are derived in Section III. In Section IV, the case study is presented and the obtained simulation results are demonstrated and compared. Section V provides the main contribution and conclusions of the paper.
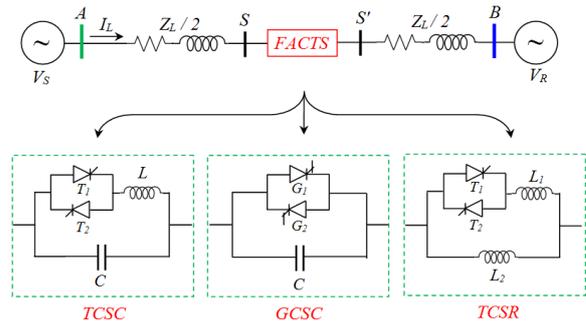

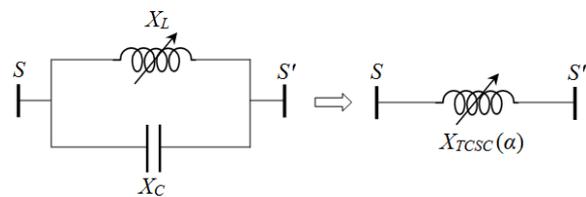*Fig. 1. Series FACTS devices on transmission line.*

Fig. 2. Apparent reactance controlled by TCSC.

2   LINE REACTANCE CONTROLLED BY DIFFERENT SERIES FACTS DEVICES

Figure 1 represents the basic structure of three series FACTS devices which are installed in series with the transmission line that connects bus-bars *A* and *B*.

2.1   TCSC

As shown in Figure 1, TCSC consists of a fixed capacitor of capacitance (C) which is connected in parallel with an inductor (L) whose inductance is controlled by anti-parallel conventional thyristors (T_1 and T_2) through the variation of the conduction angle (α) of thyristors between $90°$ and $180°$, [21-27].

In Figure 2, TCSC is modeled as a variable apparent reactance ($X_{TCSC}(\alpha)$). Hence, TCSC controls the impedance of the line by introducing the series variable apparent reactance ($X_{TCSC}(\alpha)$) whose value is controlled by the conduction angle of thyristors.

The apparent reactance $X_{TCSC}(\alpha)$ is given by [25], [39]:

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

The reactance of the inductor (($X_L(\alpha)$)) varies according to the conduction angle α according to the following equation, [25], [39]:

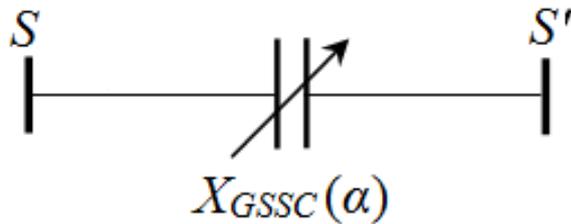$$X_L(\alpha) = X_{L\,\max}\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right] \qquad (2)$$

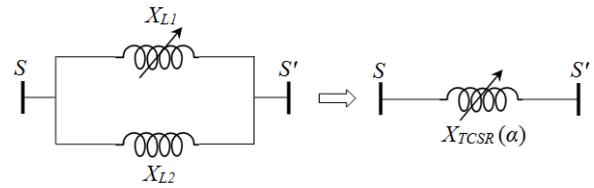Fig. 3. Apparent reactance controlled by GCSC.

Fig. 4. Apparent reactance controlled by TCSR.

2.3 TCSR

As shown in Figure 1, TCSR is connected in series with the transmission line. It consists of a fixed inductor of inductance (L_2) that is connected in shunt with another inductor (L_1) whose inductance is controlled by a pair of anti-parallel thyristors (T_1 and T_2) through varying the conduction angle (α) between $90°$ and $180°$.

In Figure 4, TCSR is modeled as a variable apparent reactance ($X_{TCSR}(\alpha)$) which takes the following form, [32], [40]:

$$X_{TCSR}(\alpha) = \frac{X_{L1}(\alpha).X_{L2}}{X_{L1}(\alpha) + X_{L2}} \qquad (9)$$

where,

where,

$$X_{L\max} = j.L.\omega \text{ and } X_C = \frac{1}{j.C.\omega} \qquad (3)$$

Substituting by equations (2) and (3) into equation (1) yields:

$$X_{TCSC}(\alpha) = \left[\frac{j.L.\omega.\pi}{\pi - 2\alpha - \sin(2\alpha) - L.C.\omega^2.\pi} \right] \qquad (4)$$

2.2 GCSC

As shown in Figure 1, GCSC consists of a fixed capacitor of capacitance (C) which is connected in series with the line and controlled by a pair of GTO thyristors. These GTOs (G_1 and G_2) are mounted in anti-parallel and controlled by varying the firing angle (γ) between $0°$ and $180°$.

In Figure 3, GCSC is modeled as a variable capacitive apparent reactance ($X_{GCSC}(\gamma)$) that controls the line impedance through varying the firing angle (γ). $X_{GCSC}(\gamma)$ takes the following form, [29-30]:

$$X_{GCSC}(\gamma) = X_C \left[1 - \frac{2}{\pi}\gamma - \frac{1}{\pi}\sin(2\pi\gamma) \right] \qquad (5)$$

where,

$$X_C = \frac{1}{j.C.\omega} \qquad (6)$$

The conduction angle (α) which varies between $0°$ to $90°$ is given by:

$$\alpha = \pi - 2\gamma \text{ or } \gamma = \frac{\pi - \alpha}{2} \qquad (7)$$

Substituting by equations (6) and (7) into equation (5) yields:

$$X_{GCSC}(\alpha) = \left[\frac{\alpha - \sin(\pi(\pi - \alpha))}{j.C.\omega.\pi} \right] \qquad (8)$$

$$X_{L1}(\alpha) = X_{L1\max} \left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)} \right], \qquad (10)$$

$$X_{L1\max} = j.L_1.\omega \qquad (11)$$

and

$$X_{L2} = j.L_2.\omega. \qquad (12)$$

Substituting by equations (10), (11) and (12) into equation (9) yields:

$$X_{TCSR}(\alpha) = \left[\frac{j.L_1.L_2.\pi.\omega}{L_1.\pi + L_2(\pi - 2\alpha - \sin(2\alpha))} \right] \qquad (13)$$

3 PHASE TO GROUND FAULT CALCULATIONS IN THE PRESENCE OF FACTS DEVICES

The method of symmetrical components has been widely used in the analysis of unbalanced three-phase systems, unsymmetrical fault currents, and rotating electrodynamics machinery. The method was originally presented by C.L. Fortescue in 1918 and has been popular ever since [41-42].

Figure 5 shows the equivalent sequence circuits of a transmission line AB whose impedance is Z_{AB}. The line is compensated by a series FACTS device whose impedance is given by Z_{FACTS}. It is subjected to a phase to ground fault F at phase A which occurs at a fault location denoted by n_F in the presence of a fault resistance R_F. Fault location (n_F) is equal to zero if the fault occurs at bus-bar A
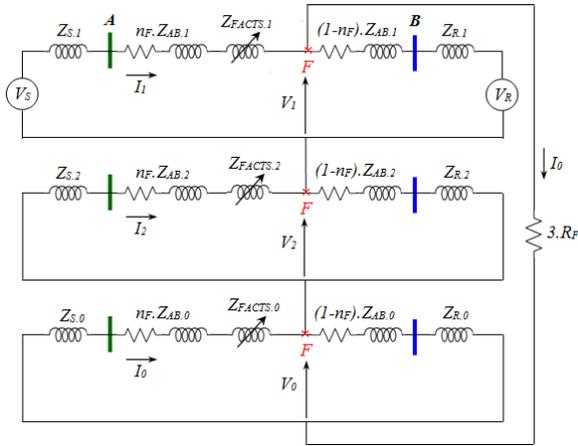
Fig. 5. Equivalent sequence circuits for ground fault with series FACTS device and fault resistance.

and it is 100% if it occurs at bus-bar B. The generator internal impedance denoted by Z_S is ignored due to its small magnitude when compared with the impedance of the line.

Basic equations for this type of fault at phase A are given by, [1], [42-43]:

$$I_B = I_C = 0 \tag{14}$$

$$V_A = V_0 + V_1 + V_2 = R_F.I_A \tag{15}$$

The symmetrical components of line currents are given by, [41-42]:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{16}$$

From equations (14) and (16), the current symmetrical components take the following form:

$$I_0 = I_1 = I_2 = \frac{I_A}{3} \tag{17}$$

Similarly, the voltage symmetrical components are given by, [41-42]:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{18}$$

From equation (15), the direct voltage component is given by:

$$V_1 = R_F.I_A - V_0 - V_2 \tag{19}$$

The symmetrical components of impedances are given by, [41-42]:

$$\begin{bmatrix} Z_0 \\ Z_1 \\ Z_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} Z_A \\ Z_B \\ Z_C \end{bmatrix} \tag{20}$$

Hence, the symmetrical components of the transmission line impedance Z_{AB} and the apparent reactive impedance of the FACTS device Z_{FACTS} are defined according to equation (20) as follows:

$$Z_{AB} = Z_{AB.0} + Z_{AB.1} + Z_{AB.2} \tag{21}$$

$$Z_{FACTS} = Z_{FACTS.0} + Z_{FACTS.1} + Z_{FACTS.2} \tag{22}$$

From Figure 5, V_1, V_0 and V_2 take the following form:

$$V_1 = V_s - (n_F.Z_{AB.1} \pm Z_{FACTS.1}).I_1 \tag{23}$$

$$V_2 = - (n_F.Z_{AB.2} \pm Z_{FACTS.2}).I_2 \tag{24}$$

$$V_0 = - (n_F.Z_{AB.0} \pm Z_{FACTS.0}).I_0 \tag{25}$$

Substituting by the above equations (23), (24) and (25) in equation (19) using equation (17) yields:

$$V_s = \frac{I_A}{3}(n_F.Z_{AB} \pm Z_{FACTS} + 3.R_F) \tag{26}$$

From equation (26), the current of phase (A) in the presence of a series FACTS device is given by:

$$I_A = \frac{3.V_S}{(n_F.Z_{AB} \pm Z_{FACTS} + 3.R_F)} \tag{27}$$

From equations (17) and (27), the current symmetrical components in the presence of a series FACTS take the following form:

$$I_0 = I_1 = I_2 = \frac{I_A}{3} = \frac{V_S}{(n_F.Z_{AB} \pm Z_{FACTS} + 3.R_F)} \tag{28}$$

Substituting by I_1 from equation (28) into equation (23) while using equations (21) and (22), the direct voltage component takes the following form:

$$V_1 = \frac{V_S\left[n_F(Z_{AB.0} + Z_{AB.2}) \pm (Z_{FACTS.0} + Z_{FACTS.2}) + 3R_F\right]}{(n_F Z_{AB} \pm Z_{FACTS} + 3R_F)} \tag{29}$$

Similarly, using equations (24) and (28), the inverse voltage component becomes:

$$V_2 = -\frac{V_S.[n_F.Z_{AB.2} \pm Z_{FACTS.2}]}{(n_F.Z_{AB} \pm Z_{FACTS} + 3.R_F)} \tag{30}$$

Using equations (25) and (28), the zero component of the voltage becomes:

$$V_0 = -\frac{V_S.[n_F.Z_{AB.0} \pm Z_{FACTS.0}]}{(n_F.Z_{AB} \pm Z_{FACTS} + 3.R_F)} \tag{31}$$

In order to obtain the phase voltages at the fault point in the presence of FACTS device and fault resistance, the following equation is used, [41-42]:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \tag{32}$$
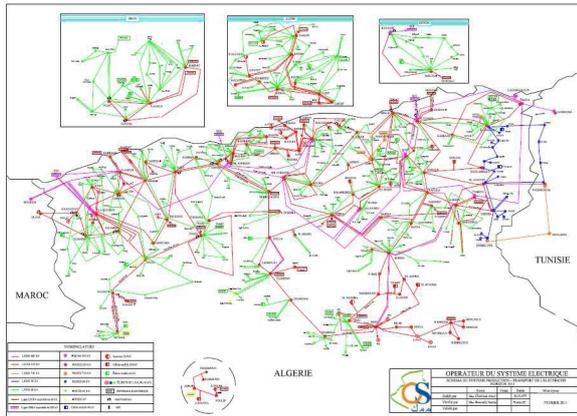
Fig. 6. Algerian electrical transmission network [44].

Substituting by equations (29), (30) and (31) into equation (32) yields:

$$V_A = \frac{3.R_F.V_S}{(n_F.Z_{AB} \pm Z_{FACTS} + 3.R_F)} \quad (33)$$

$$V_B = \frac{V_S. \left[\left(a^2 - a\right) Z_2' + \left(a^2 - 1\right) Z_0' + 3.a^2.R_F \right]}{(n_F.Z_{AB} \pm Z_{FACTS} + 3.R_F)} \quad (34)$$

$$V_C = \frac{V_S. \left[\left(a - a^2\right) Z_2' + \left(a - 1\right) Z_0' + 3.a.R_F \right]}{(n_F.Z_{AB} \pm Z_{FACTS} + 3.R_F)} \quad (35)$$

The coefficients Z_2' and Z_0' are defined as follows:

$$Z_2' = n_F Z_{AB.2} \pm Z_{FACTS.2} \quad (36)$$

$$Z_0' = n_F Z_{AB.0} \pm Z_{FACTS.0} \quad (37)$$

Hence, the short-circuit calculations in the discussed case are shown to be related to the following parameters:

- FACTS device impedance Z_{FACTS} and operation mode.
- Fault conditions presented in fault-location (n_F) and fault-resistance (R_F).

4 CASE STUDY AND ANALYSIS OF SIMULATION RESULTS

The case study of this research work is for a 400 kV, 50 Hz, transmission line connecting Ain Beida and M'Sila substations in the northern part of the Algerian power system which is shown in Figure 6, [44]. The series FACTS devices is installed between bus-bar A at Ain Beida substation and bus-bar B at M'Sila substation. The system data are given in the Appendix.
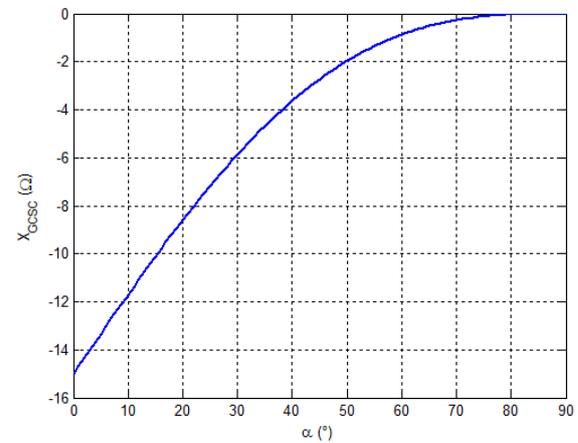
4.1 Characteristic curves of employed FACTS devices

Figures 7.a, b and c represent the characteristic curves of the TCSC, GCSC and TCSR used in this study as a function of the conduction angle.

From Figure 7, it is clear that these series FACTS devices are modeled as series inductive or capacitive reactances whose magnitudes depend on the conduction angle (α). In the case of TCSC, it can be modeled as an inductive or capacitive reactance according to the value of the conduction angle which determines its mode of operation. GCSC is represented by a pure capacitive reactance while TCSR is modeled as a pure inductive reactance.
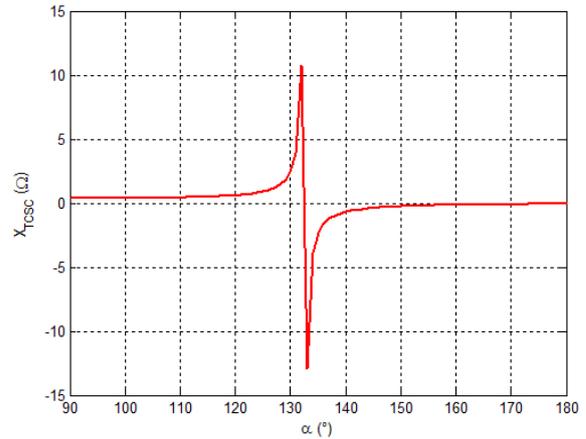
(a)

(b)
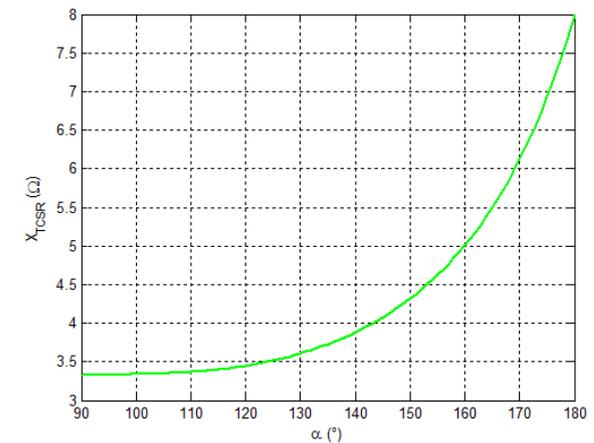
(c)

Fig. 7. Characteristic curves of series FACTS devices. a)$X_{TCSC}(\alpha)$, b) $X_{GCSC}(\alpha)$, c) $X_{TCSR}(\alpha)$

4.2 Impact of FACTS devices on the line impedance and power flow

Figures 8.a, and b, represent the variation of the total reactance (X_L) and resistance (R_L) of the transmission line under
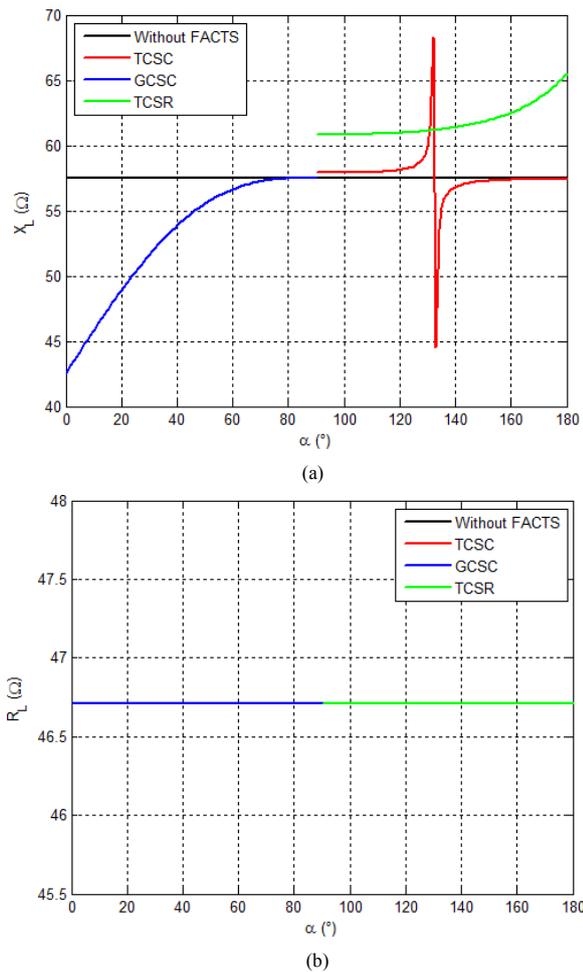
Fig. 8. *Impact of the conduction angle on the total resistance and reactance of the line.*
a)$R_L = f(\alpha)$, b) $X_L = f(\alpha)$

Fig. 9. *Impact of the power angle on the line active and reactive power. a)$P_L = f(\delta)$, b) $Q_L = f(\delta)$*

study as a function of the conduction angle of FACTS devices for different cases. Simulation results of the line are shown when it is compensated by one of the three mentioned FACTS devices and without compensation.

As shown in Figures 8.a, and b, the reactance of the line without compensation is equal to 57.5 Ω. In the capacitive mode when using TCSC or GCSC, the reactance decreases as a result of the continual injection of variable capacitive reactance in series with the line. However, in the inductive mode when using TCSC or TCSR, the reactance of the line increases as a result of the continual injection of variable inductive reactance. Hence, there is a direct impact of the conduction angle of the FACTS device on the total reactance of the compensated line. This does not apply to the resistive part of the line impedance which remains constant at 46.7 Ω. This is attributed to the fact that the employed FACTS devices are used to control the imaginary reactive component of the line impedance and not the real resistive component.

Figures 9.a, b, represent the variation of the reactive power (Q_L) and active power (P_L) of the line, respectively, as a function

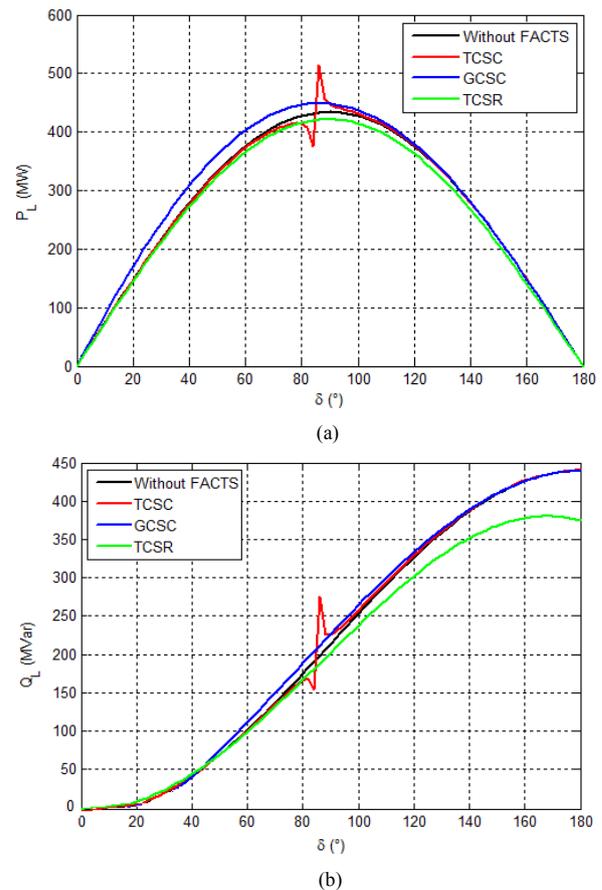of the power angle (δ) of the line with and without compensation.

From Figures 9.a, b, it is shown that increasing the power angle of the line is accompanied with a very slight change in the active and reactive power of the line compensated with TCSC when compared with their corresponding values of the uncompensated line. It is also noticed that using GCSC leads to increase the active and reactive power, while TCSR causes a reduction in the active and reactive power when compared with those of the uncompensated line. It can be concluded that under normal operating conditions, a better performance of the line power is provided when using GCSC. This is followed by TCSC which nearly matches the power of the uncompensated line. Then TCSR comes last as it shows less active and reactive power magnitudes than those obtained when no compensation is used.

4.3 Impact of fault resistance on short-circuit calculations

In the case of a phase A to ground fault, this section investigates the impact of varying the fault resistance R_F on the short-circuit parameters, namely the symmetrical current components (I_1, I_2 and I_0), transmission line currents (I_A, I_B and I_C), voltage symmetrical components (V_1, V_2 and V_0), and transmission

line voltages (V_A, V_B and V_C) of the line with and without compensation. The fault resistance varies between 0 to 50 Ω due to practical considerations, while the fault location is kept constant at bus-bar B at M'Sila.

Figures 10.a, b, c represent the variation of the current symmetrical components I_1, I_2 and I_0, respectively, and Figures 11.a, b, c represent the variation of the line currents I_A, I_B and I_C, respectively, as a function of the fault resistance for various cases.

From Figure 10, it is clear that the three symmetrical current components are shown to be equal for each individual case, according to equation (17). The increase of R_F magnitude leads to reduce the magnitudes of the three studied current components which is the main function of using R_F.

In Figure 11, the line currents of phases B and C are always equal to zero since the fault occurs at phase A, according to equation (14). The increase of R_F magnitude leads to reduce the magnitude of the fault current at phase (A). This is valid in all cases; with or without using FACTS devices according to equation (27).

Increasing the fault resistance (below 40 Ω approximately) while using GCSC shows a better system performance represented in a reduced magnitude of the fault current when compared with that of the uncompensated line. For higher R_F magnitudes, the exhibited fault currents match their corresponding values of the uncompensated line.

When using TCSC, the fault current nearly matches its corresponding value when there is no compensation, while using TCSR shows a higher fault current than that obtained by the uncompensated line.

Figures 12.a, b, c represent the variation of the voltage symmetrical components V_1, V_2 and V_0, respectively, and Figures 13.a, b, c represent the variation of the line voltages V_A, V_B and V_C, respectively, as a function of the fault resistance with and without using FACTS devices.

From Figure 12, it can be observed that increasing R_F leads to increase the direct voltage component for all the studied cases.

From Figure 13, it is clear that the increase of R_F leads to an increase in the system voltages in the presence or absence of series FACTS devices, according to equations (33), (34) and (35). In the meanwhile, results obtained when using TCSR are shown to provide better results as they exhibit higher fault voltages than those obtained in the other cases. Using GCSC exhibits less voltage and TCSC results nearly match the voltages obtained for the uncompensated line.

5 CONCLUSION

The paper investigated the use of three series FACTS devices which are TCSC, GCSC and TCSR in a high voltage system under both normal and abnormal operating conditions. Models and mathematical formulas of the devices were deduced and presented.

The case study used to verify the presented theoretical analysis was for a 400 kV transmission line in the northern part of the Algerian power network. Simulation results using the developed MATLAB program were used to compare the effect of each device on the system operation.
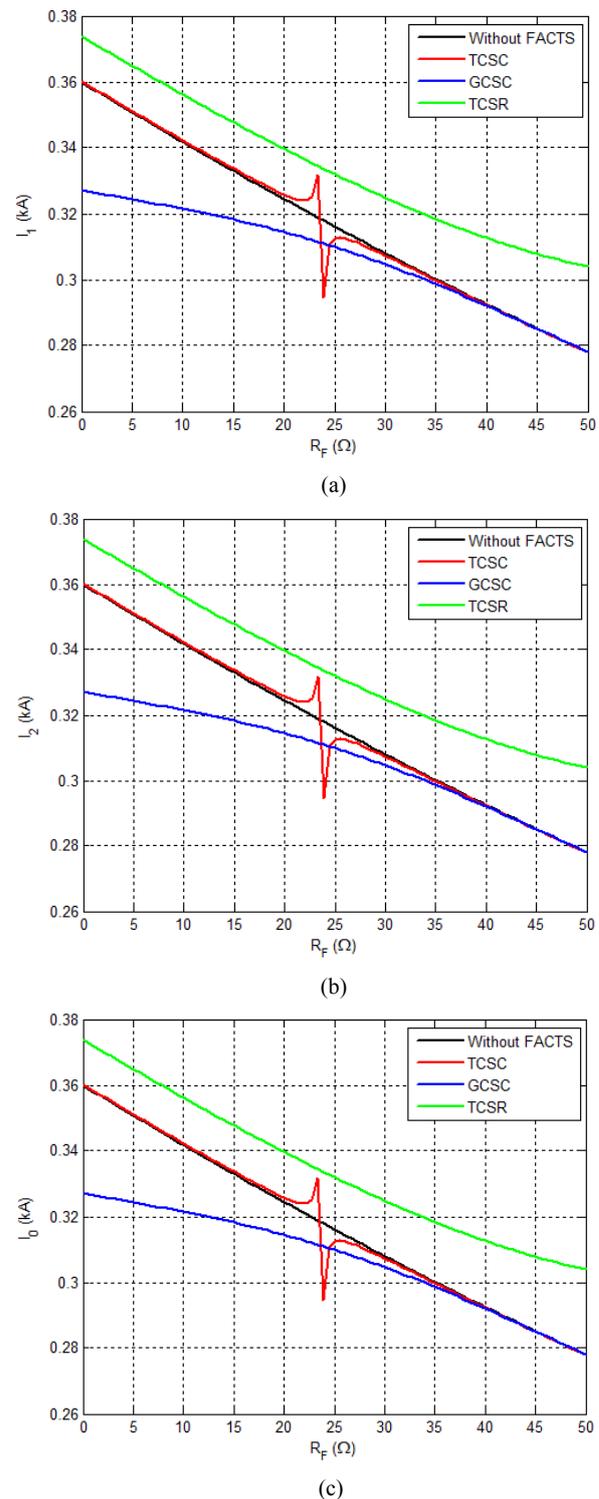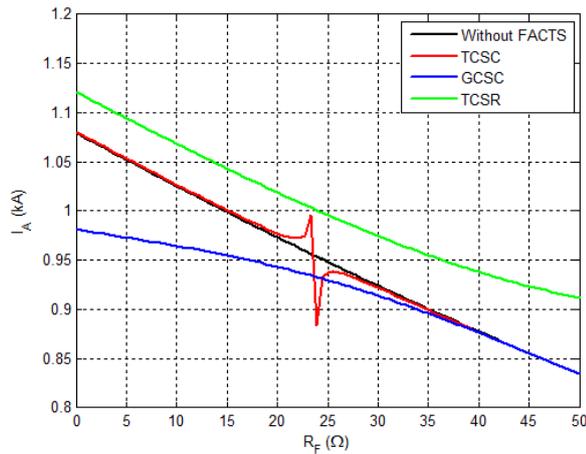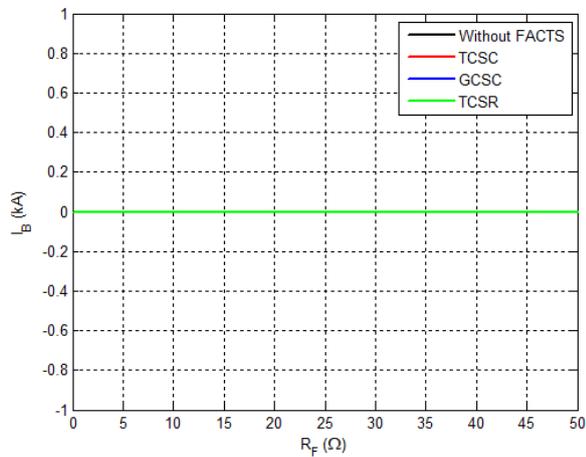

Fig. 10. Impact of R_F on the current symmetrical components. a)$I_1 = f(R_F)$, b)$I_2 = f(R_F)$, c)$I_0 = f(R_F)$
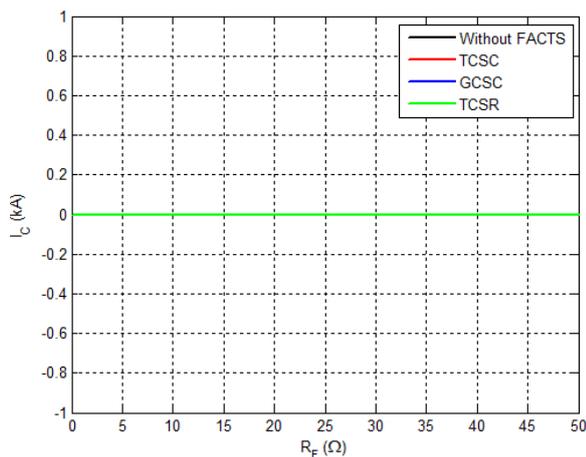
Under normal operating conditions, the effect of the devices on the compensated line impedance as well as active and reactive
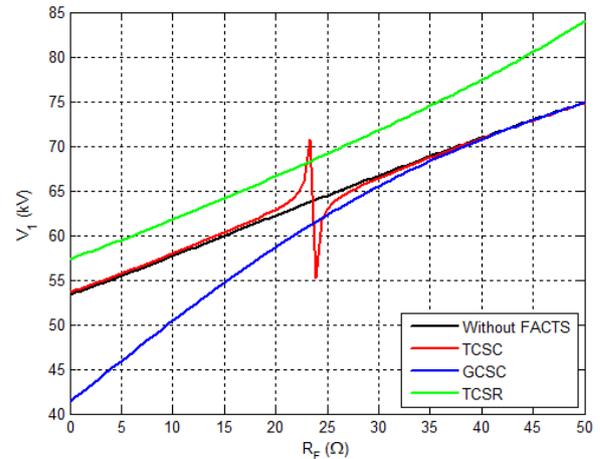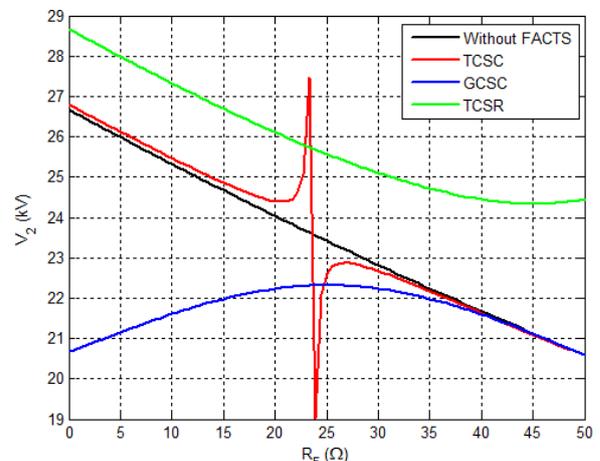
Fig. 11. *Impact of R_F on the transmission line currents.* a)$I_A = f(R_F)$, b)$I_B = f(R_F)$, c)$I_C = f(R_F)$

Fig. 12. *Impact of R_F on the voltage symmetrical components.* a)$V_1 = f(R_F)$, b)$V_2 = f(R_F)$, c)$V_0 = f(R_F)$
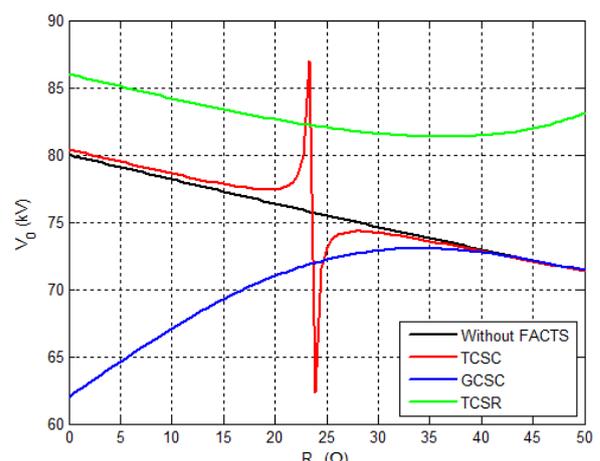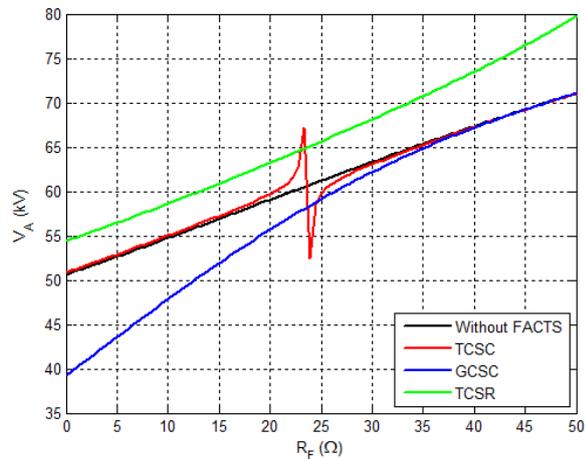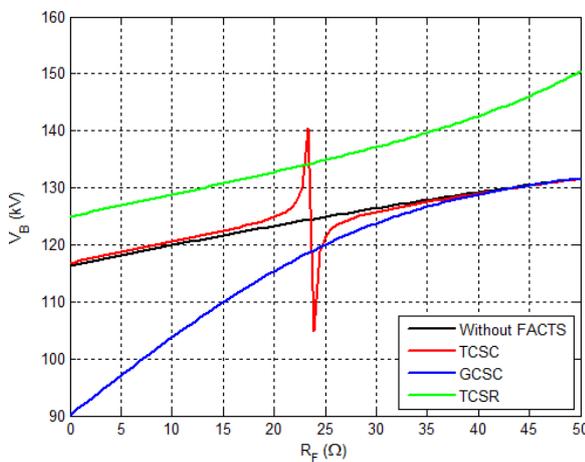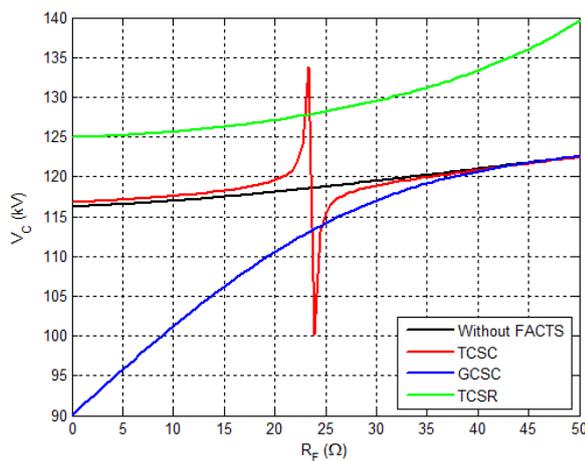
power flow of the line were studied and compared with the case

(a)

(b)

(c)

Fig. 13. Impact of RF on the transmission line voltages.
a)$V_A = f(R_F)$, b)$V_B = f(R_F)$, c)$V_C = f(R_F)$

of no compensation. The effect of the series FACTS devices was clearly shown on controlling the reactive part of the compensated line impedance.

During abnormal operating conditions of a ground fault, the system was modeled in the case of a phase A to ground fault occurring at the end of the line. The paper presented the derivation of the short-circuit calculation formulas for the fault current and voltages as well as the current and voltage symmetrical components while using the mentioned FACTS devices. The effect of varying the fault resistance was explored while using each of the three mentioned FACTS devices and without compensation.

From this research, it was concluded that GCSC was capable of providing higher active and reactive power flow of the line compared with the other studied cases under normal operating conditions, while varying the conduction angle of the device. It also provided the least fault current under fault conditions when compared with the rest of the studied cases, while increasing the fault resistance. On the other hand, TCSR showed a better performance compared with the studied cases in terms of providing higher voltages under fault conditions, while increasing the fault resistance. These conclusions lead to the recommendation that protection systems should consider the variation of the fault current while using series FACTS devices in order to avoid unnecessary tripping.

Further research work is currently undergoing to investigate the use of other FACTS Devices and study different types of faults for more complicated systems.

APPENDIX

1. Transmission line data

$V_s = 400$ kV, $f = 50$ Hz, $Length = 268.21$ km,

$Z_1 = 0.1741 + j0.2146$ Ω/km,

$Z_2 = 0.1741 + j0.2146$ Ω/km,

$Z_0 = 0.5229 + j0.6438$ Ω/km.

2. Data of series FACTS devices

TCSC: $Q_{Max} = 31/-42$ MVar, $C = 8.30$ μF, $L = 0.19$ mH.

GCSC: $Q_{Max} = -60$ MVar, $C = 212.20$ μF.

TCSR: $Q_{Max-L1} = 70$ MVar, $Q_{Max-L2} = 30$ MVar.

$L_1 = 10.610$ mH, $L_2 = 18.189$ mH.

3. Fault conditions

$n_F = 100$ %, $R_F = 0$ to 50 Ω.

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