Impact of GCSC on IDMT Directional Overcurrent Relay in the Presence of Phase to Earth Fault

Mohamed Zellagui[1], Rabah Benabid[2], Abdelaziz Chaghi[1], Mohamed Boudour[3]

Abstract: This paper presents the impact of GTO Controlled Series Capacitor (GCSC) parameters on the Inverse Definite Minimum Time (IDMT) Directional Overcurrent Relay (DOCR) based on the International Electrotechnical Commission (IEC) standards. The DOCR is used to protect a single 400 kV transmission line of the Algerian transmission network which belongs to the Algerian Company of Electrical and Gas (Group Sonelgaz). The effects of GCSC on transmission line protected parameters as well as fault current and DOCR operation time in the presence of phase to earth fault with fault resistance are investigated considering three scenarios.

Keywords: GTO Controlled Series Capacitor (GCSC), Apparent reactance, Phase to earth fault, Directional Overcurrent Relay (DOCR), Inverse Definite Minimum Time (IDMT), Operation time.

1 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].

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[1]LSP-IE Laboratory, Department of Electrical Engineering, University of Batna, Campus CUB, Street Med El Hadi Bouklouf, 05000**,** Banta, Algeria;   E-mails: m.zellagui@ymail.com; az_chaghi@univ-batna.dz
[2]Department of Electrical Engineering, Nuclear Research Center of Birine (CRNB), BP: 180, 17200, Djelfa, Algeria;   E-mail: rabah_benabid@yahoo.fr
[3]LSEI Laboratory, Department of Electrical Engineering, University of Sciences and Technology Houari Boumediene (USTHB), BP: 32, El Alia, Bab Ezzouar, Algiers, Algeria;   E-mail: m.boudour@ieee.org

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 impact 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 sub-transmission systems and secondary protection of transmission systems [6]. These relays are provided in electrical 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 (DG) on IDMT overcurrent relay and optimal relay setting based on linear programming approach is reported in [11] and differential evolution algorithm in [12]. In [13], the impact 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 of DOCR is given in [14].

In this paper, we study the impact of GCSC parameters such as the apparent reactance and the injected voltage on the parameters of protected transmission line, the 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 transmission line.

2   Transmission Line in the Presence of GCSC

The compensator GCSC presented in the Fig. 1a is the first that appears in the family of series compensators. It consists of a capacitance (C) connected in series with the electrical transmission line and controlled by a valve-type GTO thyristors mounted in anti-parallel and controlled by a firing angle (γ) varied between 0° and 180° [15, 16].
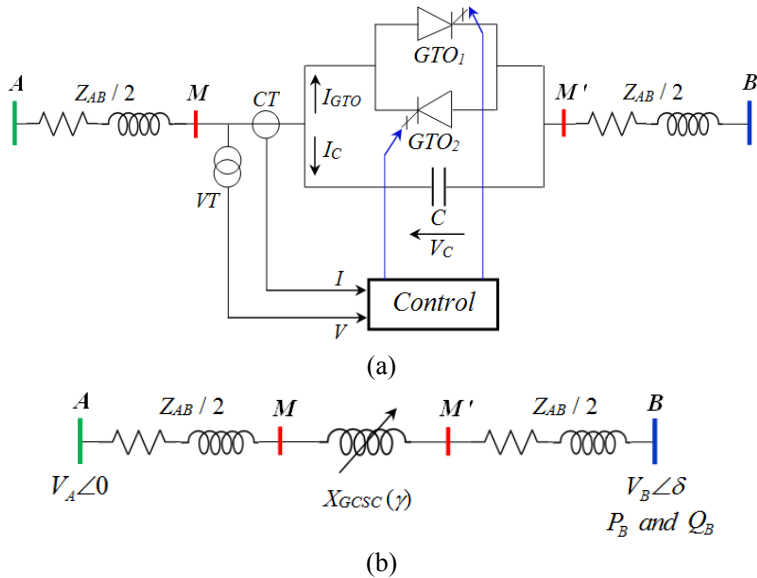

(a)

(b)

Fig. 1 – *Transmission line in the presence of* GCSC *device:*
a) Control principle, b) Apparent reactance.

If the GTOs are kept turned-on all the time, the capacitor *C* is bypassed and it does not realize any compensation effect. On the other hand, if the positive-GTO (GTO$_1$) and the negative-GTO (GTO$_2$) turn off once per cycle, at a given angle γ counted from the zero-crossings of the line current, the main capacitor *C* charges and discharges with alternate polarity. Hence, a voltage V_C appears in series with the transmission line, which has a controllable fundamental component that is orthogonal (lagging) to the line current.

Fig. 2 shows that the control signal for GTO$_2$ can be made as the complement of GTO$_1$. In this case, although the gate pulse duration is 180º, the positive-GTO start to conduct the line current only when the capacitor voltage (V_C) returns to zero and tries to cross the zero voltage level with positive slope. The same occurs with the negative-GTO, but when the voltage is crossing zero with negative slope. It should be pointed out that the waveforms of *i* and V_C, which is often called SVC if in parallel with capacitor banks. It is possible to see in Fig. 2 that the GCSC capacitor stays permanently inserted if γ equal 90º. This corresponds to the maximum series compensation, given by the capacitor's reactance at the fundamental frequency. Contrarily, the capacitor stays permanently bypassed if γ equal 180º.
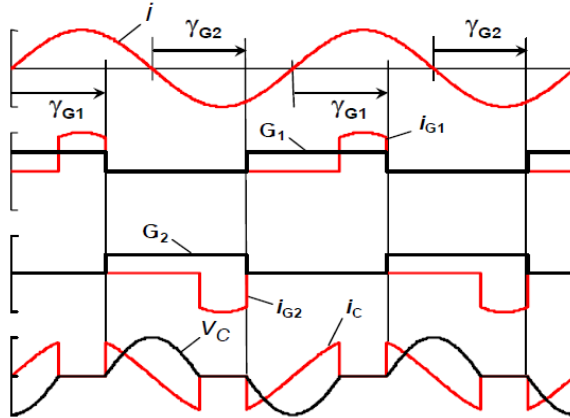

Fig. 2 – *Voltage, current and control signals.*

This compensator is installed in midline of the transmission line AB between busbars *A* (source) and *B* (load) and modeled as a variable capacitive reactance (X_{GCSC}). From Fig. 1b, this capacitive reactance is defined by the following equation [17]:

$$X_{GCSC}(\gamma) = X_{C.Max}\left[1 - \frac{2}{\pi}\gamma - \frac{1}{\pi}\sin(2\pi)\right], \qquad (1)$$

where

$$X_{C.Max} = \frac{1}{C_{GCSC}\omega} \cdot \tag{2}$$

The conduction angle (β) which varies between 0 to 90°, is defined by the next relation:

$$\beta = \pi - 2\gamma = 2\left(\frac{\pi}{2} - \gamma\right). \tag{3}$$

From (3), the equation (2) becomes:

$$X_{GCSC}(\beta) = X_{C.Max}\left[1 - \left(\frac{\pi - \beta}{\pi}\right) - \frac{1}{\pi}\sin\left(\pi(\pi - \beta)\right)\right]. \tag{4}$$

The relation of injected voltage is calculated by the flowing equation:

$$V_{GCSC}(\beta) = V_{GCSC-Max}\left[1 - \left(\frac{\pi - \beta}{\pi}\right) - \frac{1}{\pi}\sin\left(\pi(\pi - \beta)\right)\right], \tag{5}$$

where, $V_{GCSC-Max}$ is maximum voltage injected by GCSC.

3 Phase to Earth Fault Current Calculation in the Presence of GCSC

Fig. 3 shows the equivalent circuit of the transmission line in the presence of phase to ground fault. This last, is occurred in phase A at busbar B ($n_F = 100\%$), with a fault resistance (R_F). The GCSC is inserted on the midline AB.
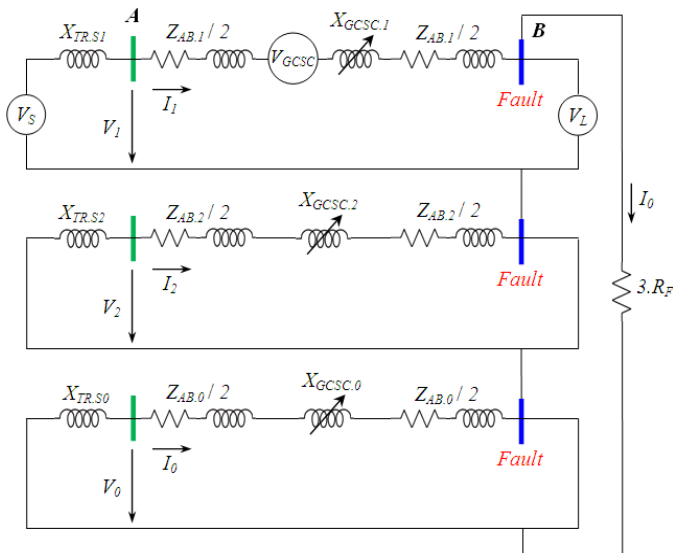

Fig. 3 – *The equivalent circuit with* GCSC.

The total transmission line ($Z_{AB\text{-}GCSC}$) impedance with GCSC inserted on the midline is given by:

$$Z_{AB-GCSC} = R_{AB} + j\left[X_{AB} - X_{GCSC}(\beta)\right].$$ (6)

Regarding the references [18] and [19], the basic equations for this fault are as follows:

$$I_B = I_C = 0,$$ (7)

$$V_A = V_1 + V_2 + V_0 = R_F I_A \neq 0.$$ (8)

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

$$Z_{AB-T} = Z_{AB.1} + Z_{AB.2} + Z_{AB.0},$$ (9)

$$X_{GCSC-T} = X_{GCSC.1} + X_{GCSC.2} + X_{GCSC.0}.$$ (10)

From Fig. 3, the symmetrical currents components are:

$$V_s + V_{GCSC} = \frac{I_A}{3}\left[\frac{Z_{AB-T}}{2} + X_{GCSC-T} + \frac{Z_{AB-T}}{2}\right] + R_F I_A,$$ (11)

$$I_1 = I_2 = I_0 = \frac{V_S + V_{GCSC}}{\left(\dfrac{Z_{AB-T}}{2}\right) + X_{GCSC-T} + \left(\dfrac{Z_{AB-T}}{2}\right) + 3R_F},$$ (12)

where

$$I_1 + I_2 + I_0 = \frac{I_A}{3}.$$ (13)

From (12) and (13), the current in phase A is:

$$I_A = \frac{3\left(V_S + V_{GCSC}\right)}{\left(\dfrac{Z_{AB-T}}{2}\right) + X_{GCSC-T} + \left(\dfrac{Z_{AB-T}}{2}\right) + 3R_F},$$ (14)

$$I_F = I_A.$$ (15)

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

From (14) and (15), the fault current measured by IDMT directional overcurrent relay is only related to:

   – Parameters of transmission line: U_n, l_L, R_{AB}, and X_{AB},

   – Parameters of GCSC: V_{GCSC} and X_{GCSC},

   – Fault conditions: location n_F and resistance R_F.

4   IDMT Directional Overcurrent 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, in the following three categories:

Instantaneous Overcurrent Relay (IOR): These relays instantaneously send a trip command to the breaker as soon as the fault is detected (input current greater than the present value). They do not have any intentional time delay. They are usually implemented close to the source where the fault current level is very high and a small delay in operation of relay can cause heavy damage to the equipment. So an instantaneous relay is used there to detect and respond to a fault in few cycles.

Definite Time Overcurrent Relay (DTOC): This type of overcurrent relay is used for backup protection (e.g. back up protection for transmission line where primary protection is distance relay). If the distance relay does not detect a line fault and does not trip the breaker, then after a specific time delay, the overcurrent relay will send a trip command to the breaker.

Inverse Definite Minimum Time (IDMT) *Overcurrent Relay*: This 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 [20]. It can be graded for a very large range of operating times and fault currents [21]. 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 [22]. 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.

4.1. Relay Characteristics

The 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 [23].

$$T_i = TDS \times \frac{K}{\left(\dfrac{I_m}{I_p}\right)^\alpha - 1}, \qquad (16)$$

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 ith relay. However, it can be shown that the proposed method can be easily applied to a system with combination of DOCRs with different characteristics as presented in Fig. 4.

Fig. 4 – *Time-current of* IDMT *overccurent relaying characteristics.*

In Fig. 4, the current *I* equal I_m/I_p, the fault current measured relay is defined by:

$$I_m = \frac{I_F}{K_{CT}} \qquad (17)$$

and

$$K_{CT} = \frac{I_{n1}}{I_{n2}}, \qquad (18)$$

where I_F is the fault current in the protected transmission line, and K_{TC} is ration of current transformers. **Table 1** below shows the constants values corresponding to each curve characteristic made standard IEC 60255-3 [23]:

Table 1

Different type of inverse characteristics curves.

Relay Characteristic Type	K	α
Normal Inverse	0,14	0,02
Very Inverse	13,5	1,00
Extremely Inverse	80	2,00
Long Time Inverse	120	1,00

4.2 Relay settings

The calculation of the two settings, *TDS* and I_p is the essence of the directional overcurrent relay coordination study. It is very important to mention that in general, the directional overcurrent relays allow for continuous time dial settings but discrete (rather than continuous) pickup current settings. Therefore this constraint can be formulated as [24]:

$$TDS_i^{\min} \leq TDS_i \leq TDS_i^{\max} . \tag{19}$$

Practically, the value of TDS varied between 0.05 to 1.20 [25, 26].

$$\max\left(I_L^{\max}, I_P^{\min}\right) \leq I_{Pi} \leq \min\left(I_F^{\min}, I_P^{\max}\right) . \tag{20}$$

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 $(I_F^{\min})$.

4.3 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 0.3 s to 0.4 s, while for numerical relay, it is of the order of 0.1 s to 0.2 s [2]. 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:

$$T_{Backup} - T_{Primary} \geq CTI , \tag{21}$$

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

5   Case Study and Simulation Results

The power system studied in this paper is the 400 kV, 50 Hz in Algerian electrical transmission networks at Algerian Company of Electrical and Gas (group Sonelgaz) which is shows in Fig. 5 [28].
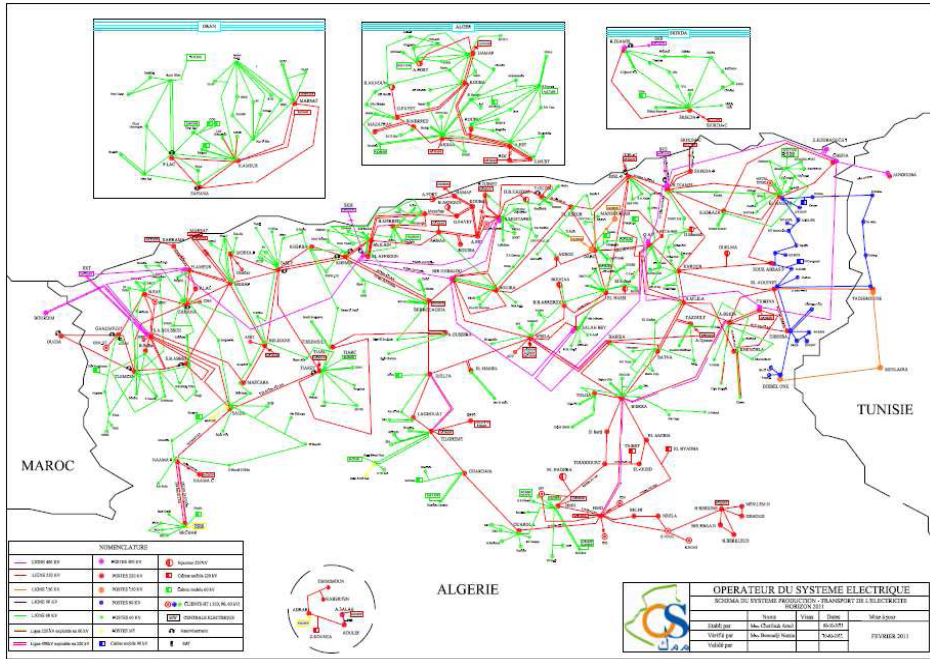

Fig. 5 – *Electrical power system study.*

The GCSC 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 as shown in Fig. 6. The parameters of transmission lines, the GCSC study, fault conditions, and IDMT overcurrent relays setting are summarized in the appendix.

Fig. 6 – *Radial electrical networks in presence GCSC device.*

Fig. 7 repesents the characteristcs curves (time-current) for the three IDMT directional overccurent relays (R_A, R_B and R_C) installed in the three busbar based IEC 60255-3 standard.
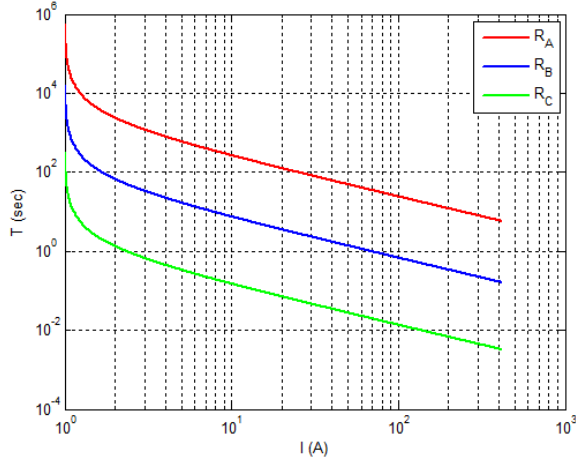

Fig. 7 – *Characteristics curves of the installed relays.*

Fig. 8 shows the X_{GCSC} and V_{GCSC} characteristics curves as function of the conduction angle (β) respectively of the three GCSC used in case study.
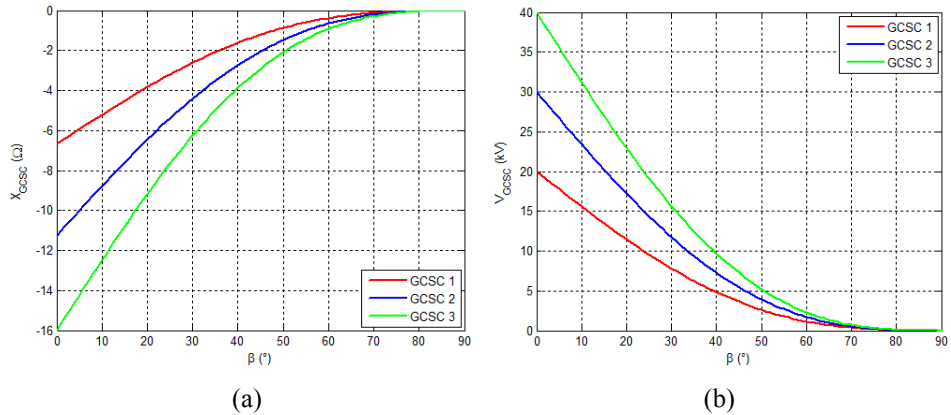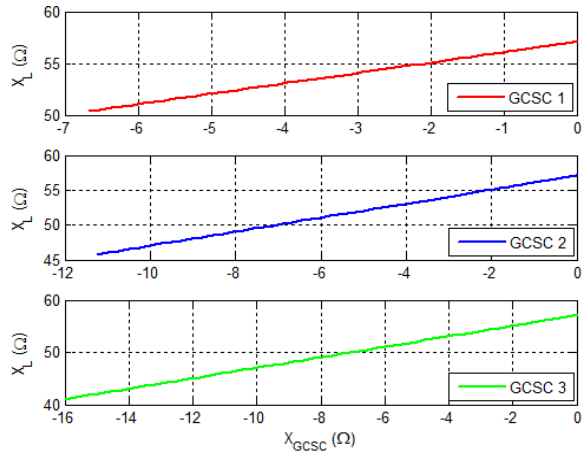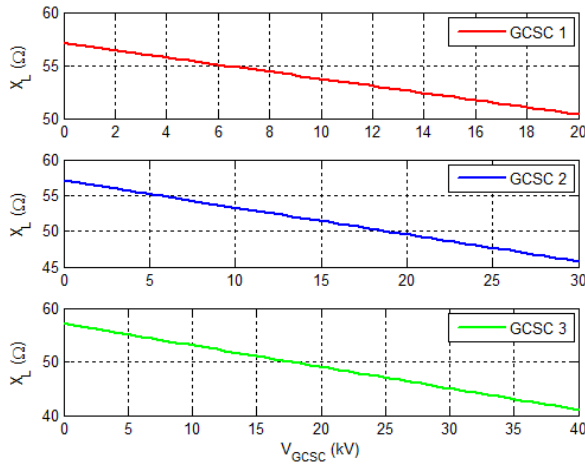

(a)   (b)

Fig. 8 – *Characterisic curve for GCSC study: a) $X_{GCSC} = f$ (β); b) $V_{GCSC} = f$ (β).*

5.1 Impact on the protected transmission line impedance

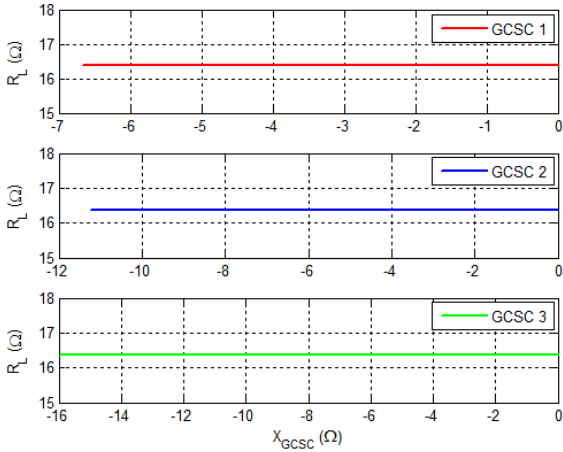Figs. 9a and 9b show the impact of X_{GCSC} and V_{GCSC} of the three GCSC on the transmission line reactance (X_L).
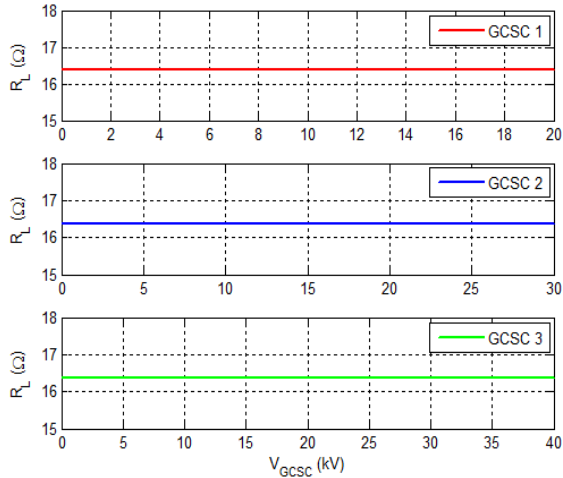
(a)

(b)

Fig. 9 – *Impact of* GCSC *on the line reactance:*
a) $X_L = f(X_{GCSC})$; *b)* $X_L = f(V_{GCSC})$.

Fig. 10 shows the impact of X_{GCSC} and V_{GCSC} of three GCSC on the transmission line resistance (R_L).

From Figs. 9 and 10, the apparent reactance and voltage injected by the GCSC, have 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.

(a)

(b)

Fig. 10 – *Impact of GCSC on the line resistance:*
a) $R_L = f(X_{GCSC})$; b) $R_L = f(V_{GCSC})$.

5.2 Impact of GCSC on the fault current

Figs. 11a and 11b show the impact of X_{GCSC} and V_{GCSC} of the three GCSC on the fault current in the presence of phase to earth fault with R_F at busbar C.

From Fig. 11, apparent reactance and voltage injected by GCSC has a direct influence on the fault current. As can be seen from (14) and (15), the reactance is increased following the insertion of a capacitive reactance (increase of X_{GCSC} and V_{GCSC}) in the protected transmission line.
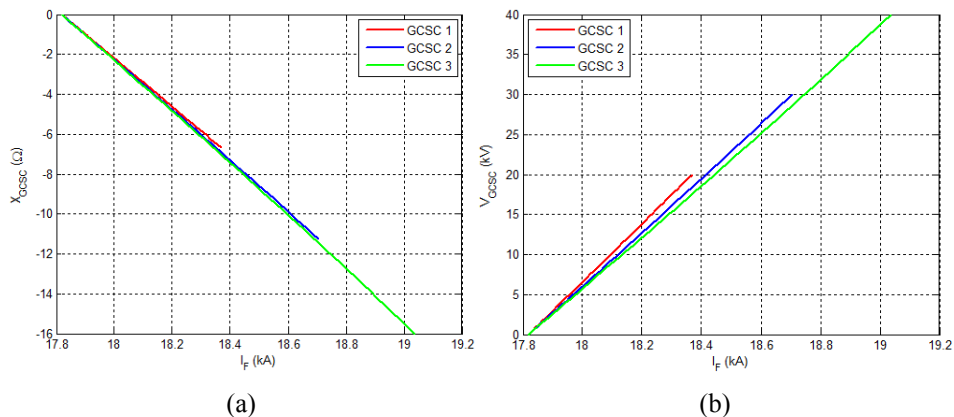
393

(a)   (b)

Fig. 11 – *Impact of* GCSC *on fault current: a)* $I_F = f(X_{GCSC})$; *b)* $I_F = f(V_{GCSC})$.

5.3 Impact of GCSC on the IDMT curve

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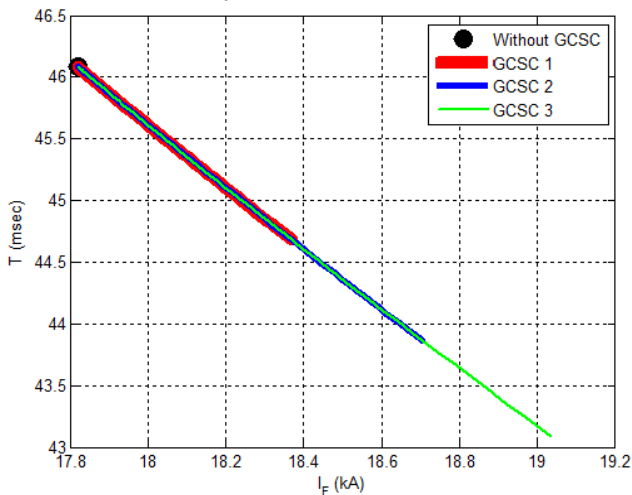

Fig. 12 – *Impact of fault current variation on the* IDMT *operating time.*

From Fig. 12, the fault current variation has a direct influence on the operating time of the relay, as confirmed by (16) and (17).

The Fig. 13 show the characteristic curve (time-current) of IDMT overcurrent relay installed in busbar *B* without and with the presence of three GCSC device.
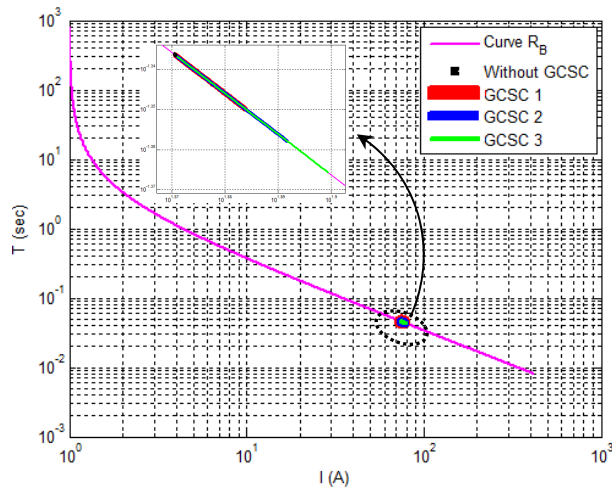
Fig. 13 – *Time-current for relay B in the presence of GCSC.*

5.4 Impact of GCSC parameters on the operation time

The Figs. 14a and 14b show the impact of parameters of the three GCSC installed, i.e. X_{GCSC} and V_{GCSC} on the operation time respectively for the IDMT relay installed in busbar *B*.
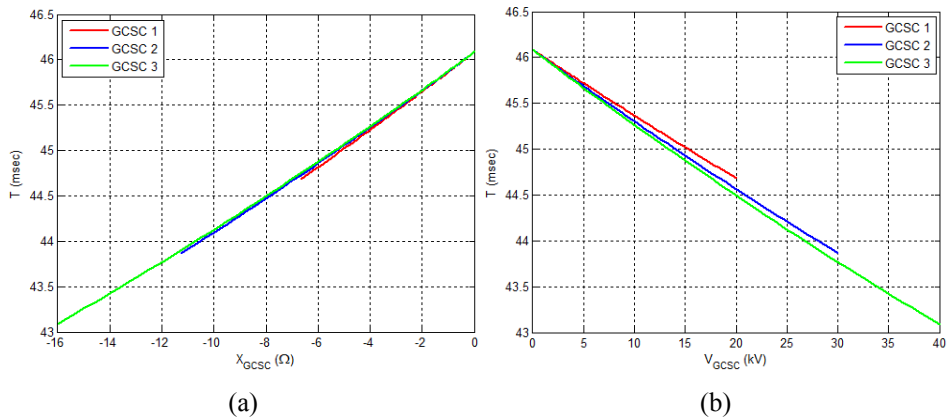

(a)

(b)

Fig. 14 – *Impact of* GCSC *on operation time: a)* $T = f(X_{GCSC})$ *; b)* $T = f(V_{GCSC})$.

From Fig. 14, apparent reactance and voltage injected by the GCSC have a direct influence on the operating time as confirmed by (16) and (17), where the measured fault current by relay is being increased.

6   Conclusion

In this paper we present the impact of GCSC parameters on the IDMT DOCR in the Algerian 400 kV transmission line. At first, the phase to earth fault computing model in the presence of GCSC and fault resistance is presented in detail. After that, the effect of apparent reactance and voltage injected GCSC devices on the operation time is being considered. For the comparison purpose, three GCSC designs are considered in this paper.

From the obtained results, we can conclude that he GCSC parameters have a direct influence on DOCR, since the deviation of the line impedance and fault current are varied with GCSC parameters. Therefore, Because of the varying parameters of the injected reactance, an adaptive method for the relays setting should be utilized.

Furthermore, in order to increase the total system protection performance and avoid unwanted tripping of the 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 impact on operation time, it is necessary to change the settings relay (*TDS* and I_P) to respect the relays coordination.

Moreover, we propose, in the future work, the application optimization techniques to find the optimal coordination of IDMT overcurrent relays in function of GCSC dynamic.

7   Appendix

7.1 Power source

$U_s = 11$ kV, $f_n = 50$ Hz.

7.2 Power transformer

$U_{TR} = 11/400$ kV, $S_{TR} = 200$ MVA,

$X_{TR} = $ j 0.213 Ω, $X_{TR0} = $ j 0.710 Ω.

7.3 Transmission line

$U_L = 400$ kV, $U_{min} = 380$ kV, $U_{max} = 440$ 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,

7.4 GCSC study

Case 1: $Q_{Max} = 60$ MVar, $V_{Max} = 20$ kV, $X_{C.max} = 6.667$ Ω,

Case 2: $Q_{Max} = 80$ MVar, $V_{Max} = 30$ kV, $X_{C.max} = 11.250$ Ω,

Case 3: $Q_{Max} = 100$ MVar, $V_{Max} = 40$ kV, $X_{C.max} = 16.000$ Ω.

7.5 IDMT overcurrent relay

K_{TC} = 1200/5,

Relay A: Very inverse, I_P = 1, TMS = 0.10,

Relay B: Very inverse, I_P = 1, TMS = 0.25,

Relay C: Very inverse, I_P = 1, TMS = 0.60.

7.6 Fault conditions

n_F = 100 %, R_F = 100 Ω.

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