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The Impact of TCSC on IDMT Relays in SLG Fault in Distribution Networks

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ABSTRACT

IDMT Directional Over-Current Relays protection is one of the basic protective relaying for distribution systems, for fault detection and clearing as soon as possible. Its function would generally be changed in presence of FACTS devices. In this paper a study to investigate the direct effect of varying reactance of the TCSC on single-line-to-ground (SLG) fault in compensated distribution systems. This paper, therefore presents the calculation of fault component, and directional over-current relay operating time characteristics for phase-to-earth fault involving the TCSC. The case study is compared between compensated and uncompensated system. The coordination of the relays is a nonlinear programming problem and it is solved by using MATLAB software.

1. Introduction

The equipments of electric power systems represent some of the oldest industrial machinery still in general use today. Another dimension of automation in the case of transmission systems is the direct modification of the grid's properties with the aid of solid-state technology essentially ; various types of transistors scaled up and combined to handle large power applications in a new category of equipments called flexible A.C. transmission systems (FACTS). Transmission lines generally have physically fixed parameters such length and impedance that become firm constraints in modeling and analysis. Other components such as transformers and capacitors may have variable states or settings, but conventionally these settings are discrete and require mechanical switching. FACTS technology offers ways to modify the electrical characteristics of transmission components much more rapidly, even in real time, so as to increase operating efficiency and relieve constraints without the need for adding major equipments. FACTS devices include various types of reactive compensation, phase shifting, and power flow control [1]. The idea is to

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effectively change the impedance of a given transmission link as seen by the system on an instantaneous basis by means of an appropriately designed solid-state electronic circuit.

However the fault location in distribution networks shows known problems because of the network branching, laterals and dynamical change of loads along the network sections. The problem is made more difficult when the network neutral is isolated or compensated. In such networks a fault current during the phase-to-ground fault considerably depends on the network capacitance and has a resonant character [1]. The fault-loop impedance is relatively high, which results in low fault current. The fundamental component fault current and voltage phasors do not contain information on distance to fault [2]. Over-current protection is one of the basic protective relaying principles for distribution systems. An over-current relay must be capable of protecting the zone under its primary protection and only if the primary protection system does not clear the fault, the back-up protection should initiate tripping. Mal-operation of the backup relays should be avoided to reduce power outages. The relay's mal-operation includes fail-to-trip or mal-trip. Fail-to-trip event occurs when the relay fails to trip in the presence of faults and mal-trip event occurs when the relay trips even though it is in healthy condition. A mal-trip event results in more severe damage to the system compared to fail-to-trip event [3].

The authors in [4] study the effects of GCSC on fault current and DOCRs operation time in the presence of phase to earth fault with fault resistance. Our paper, therefore presents the calculation of fault component, and directional over-current relay operating time for single-line-to-ground fault involving a TCSC compensator. The TCSC will be always present in the fault loop and will influence the relay setting characteristic. The effects of the earth fault resistance and TCSC control parameters on the settings of both primary relay and backup relay is investigated in this paper.

2. TCSC structure and operation

The basic Thyristor Controlled Series Capacitor scheme, proposed in 1986 by Vithayathil with others as a method of "rapid adjustment of network impedance," is shown in Fig.1 [5]-[6]. It consists of the series compensating capacitor shunted by a Thyristor Controlled Reactor.

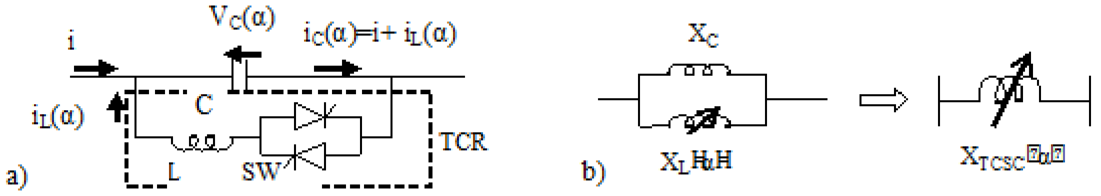

Fig. 1 – Principal of TCSC (a) Basic TCSC scheme and (b) Apparent TCSC reactance.

In a practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics. However, the basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially canceling the effective compensating capacitance by the TCR [4]. Since, the TCR at the fundamental system frequency is a continuously variable reactive impedance, controllable by delay angle α, the steady-state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance, X_c, and a variable inductive impedance, $X_L(\alpha)$, that is,

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

Where : XL = ωL

The TCSC thus presents a tunable parallel LC circuit to the line current that is substantially a constant alternating current source. As the impedance of the controlled reactor, X_L (α). Is varied from its maximum (infinity) toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, X_{TCSC}^{min} =X_c = 1/ωC, (and thereby the degree of series capacitive compensation) until parallel resonance at X_c = X_L (α) is established and X_{TCSC}^{max} theoretically becomes infinite [6].

TCSCs vary the electrical length of the compensated distribution system with little delay. This characteristic enables the TCSC to be used to provide fast active power flow regulation.

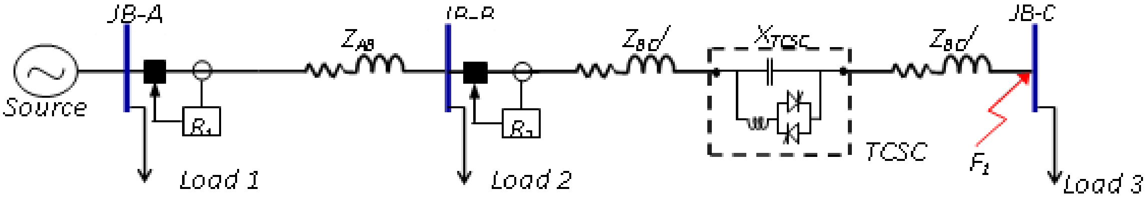

Fig. 2 – Diagram of distribution path with TCSC.

The rated value of TCSC is a function of the reactance where the TCSC is installed and expressed as :

$$X_{line}=X_{BC}+X_{TCSC} \qquad (2)$$

Where

$$X_{TCSC}=K_{TCSC}\times X_{line} \qquad (3)$$

X_{line} is the overall line reactance between bus-B and C with TCSC installation. XTCSC is the reactance of TCSC and KTCSC is the coefficient which represents the compensation level of TCSC ($-0.7\leqslant K_{TCSC}\leqslant 0.2$). The working range of reactance of TCSC is fixed between −0.7 (capacitive) X_{line} and 0.2 (inductive) X_{line} [7-9].

3. Directional over-current relay coordination

Inverse Definite Minimum Time (IDMT) directional over-current relay is inverse in the initial part, which tends to definite minimum operating time as the current becomes very high. The reason for the operating time becoming definite minimum, at high values of current, is that in the electromechanical relays the flux saturates at high values of current. Ideally, we may demand that the operating time inverse in nature throughout the operating range [10]. The mathematical relation between the current and the operating time of IDMT characteristic can be written as :

$$T = TDS \times \frac{a}{M^b - 1} \tag{4}$$

Where :

M is the multiple of pickup current

TDS is the time dial setting of the relay.

Where, a and b are constants depending on the type of selected characteristics [3] : Standard Inverse (SI), Very Inverse (VI) or Extremely Inverse (EI) and Long time inverse are indicated in Tables 1.

Table 1 – Parameters for different inverse characteristics.

Inverse characteristics	a	b
Standard inverse	0.2	0.14
Very inverse	1	13.5
Extremely inverse	2	80
Long time inverse	1	120

3.1. Backup-primary constraint

In order to coordinate two over-current relays, one as primary relay (i) and the other as backup relay (j), the difference between the operation time of backup relay and main relay should be more than Coordination Time Interval (CTI). So the constraints for coordination of over-current relays (i) and (j) will be in the form of inequality (5), if R_i is the primary relay for fault at k, and R_j is backup relay for the same fault, the Coordination constraint can be stated as [11]-[12] ;

$$T_j^K - T_i^K \geq CTI \tag{5}$$

T_j^K and T_i^K time interval for coordination of primary and backup relay and it can take a value between 0.2 and 0.5 seconds. In this paper we selected 0.3 s of CTI [12]-[13].

The essence of the directional over-current relay coordination study is the calculation of its TDS and IP. It worth mentioning that DOCR allow for continuous time dial setting, but rather discrete pickup current setting [14]. Formulating the above constraints gives :

$$TDS_i^{\min} \leq TDS_i \leq TDS_i^{\max} \tag{6}$$

$$I_{pi}{}^{\min} \leq I_{pi} \leq I_{pi}{}^{\max} \tag{7}$$

4. Single line to ground fault current calculation with TCSC

Figure 3 shows the connection of the sequence networks for a single-line-to-ground fault (A–G fault) in presence of TCSC installed at midpoint of branch BC. The sequence networks are connected in series and additionally the triple fault resistance (3.RF) is included.

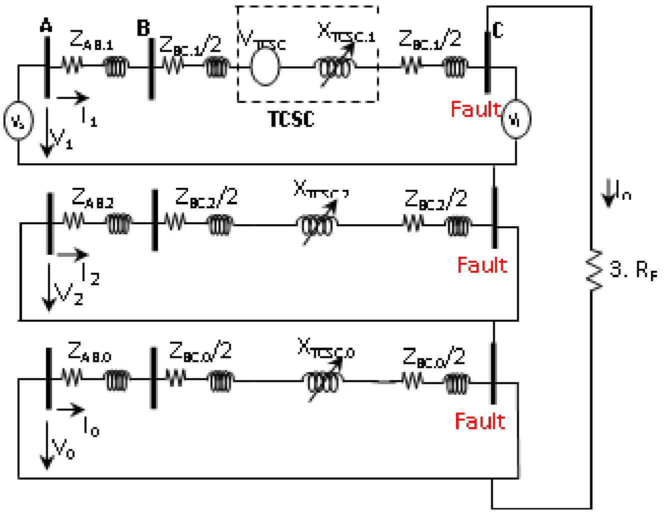

Fig. 3 – Equivalent circuit diagram of the single-line-to-ground fault (A-G fault) involving fault resistance R_F in presence of TCSC installed at midpoint.

The total impedance of system with TCSC ($Z_{BC-Total}$) is :

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

At fault occurrence at bus-bar C the basic equations for this type of fault [4] are :
The direct component of currents in presence TCSC on midline is :

$$I_1 = \frac{V_s + V_{TCSC}}{Z_{AB-T} + \left(\frac{Z_{BC-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{BC-T}}{2}\right) + 3R_f} \tag{9}$$

And :

$$I_1 = I_2 = I_0 \tag{10}$$

Where the indices T is the sum of Symmetrical components (direct, inverse and zero components).

The current at phase (A) current in presence TCSC on midline is given by :

$$I_a = \frac{3 \times (V_s + V_{TCSC})}{Z_{AB-T} + \left(\frac{Z_{BC-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{BC-T}}{2}\right) + 3R_f} \tag{11}$$

The current at phase (B) and phase (C) currents are :

$$I_b = I_c = 0 \tag{12}$$

The direct, inverse and zero components of voltage in presence of TCSC on midline is :

$$\begin{aligned} V_1 &= V_s + V_{TCSC} - \left[Z_{AB-1} + \left(\frac{Z_{BC-1}}{2}\right) + X_{TCSC-1} + \left(\frac{Z_{BC-1}}{2}\right)\right].I_1 \\ &= \tfrac{(V_s+V_{TCSC}).\left[Z_{AB}'+Z_{BC}'+X_{TCSC}'+3R_f\right]}{Z_{AB-T}+\left(\frac{Z_{BC-T}}{2}\right)+X_{TCSC-T}+\left(\frac{Z_{BC-T}}{2}\right)+3R_f} \end{aligned} \tag{13}$$

$$\begin{aligned} V_2 &= -\left[Z_{AB-2} + \left(\frac{Z_{BC-2}}{2}\right) + X_{TCSC-2} + \left(\frac{Z_{BC-2}}{2}\right)\right].I_2 \\ &= -\tfrac{(V_s+V_{TCSC}).[Z_{AB-2}+Z_{BC-2}+X_{TCSC-2}]}{Z_{AB-T}+\left(\frac{Z_{BC-T}}{2}\right)+X_{TCSC-T}+\left(\frac{Z_{BC-T}}{2}\right)+3R_f} \end{aligned} \tag{14}$$

$$\begin{aligned} V_0 &= -\left[Z_{AB-0} + \left(\frac{Z_{BC-0}}{2}\right) + X_{TCSC-0} + \left(\frac{Z_{BC-0}}{2}\right)\right].I_0 - R_f.I_0 \\ &= -\tfrac{(V_s+V_{TCSC}).\left[Z_{AB-0}+Z_{BC-0}+X_{TCSC-0}+R_f\right]}{Z_{AB-T}+\left(\frac{Z_{BC-T}}{2}\right)+X_{TCSC-T}+\left(\frac{Z_{BC-T}}{2}\right)+3R_f} \end{aligned} \tag{15}$$

The voltages in presence TCSC on midline is given by :
Single line-to-ground fault voltage with TCSC is given by :

$$V_{a-g} = R_f \times I_a \tag{16}$$

$$V_{A-G} = \frac{3.R_f.\left(V_s + V_{TCSC}\right)}{Z_{AB-T} + \left(\frac{Z_{BC-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{BC-T}}{2}\right) + 3R_f} \tag{17}$$

$$V_B = \frac{(V_s + V_{TCSC}).\left[(a^2 - a)Z_2' + (a^2 - 1)Z_0' + T_a.R_f\right]}{Z_{AB-T} + \left(\frac{Z_{BC-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{BC-T}}{2}\right) + 3R_f} \tag{18}$$

$$V_C = \frac{(V_s + V_{TCSC}).\left[(a - a^2)Z_2' + (a - 1)Z_0' + T_b.R_f\right]}{Z_{AB-T} + \left(\frac{Z_{BC-T}}{2}\right) + X_{TCSC-T} + \left(\frac{Z_{BC-T}}{2}\right) + 3R_f} \tag{19}$$

Where :

$$X_{TCSC}' = X_{TCSC-2} + X_{TCSC-0} - 2.X_{TCSC-1} \tag{20}$$

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

$$Z_{BC}' = Z_{BC-2} + Z_{BC-0} - 2.Z_{BC-1} \tag{22}$$

$$Z_2' = Z_{AB-2} + Z_{BC-2} + X_{TCSC-2} \tag{23}$$

$$Z_0' = Z_{AB-0} + Z_{BC-0} + X_{TCSC-0} \tag{24}$$

$$T_a = (3.a^2 - 1) \tag{25}$$

$$T_b = (3.a - 1) \tag{26}$$

5. Case study and results

The case study based on Fig. 2 shows a part of 11-kV distribution network, where : the positives impedances of branches from A to B : $Z_{AB} = 0.922 + 0.470j$, and from B to C : $Z_{BC} = 0.4930 + 0.2511j$. Positive and negative sequence impedances are assumed equal and zero sequence impedance are assumed three of positive sequence impedance. With the given parameters of a TCSC, the values of capacitor and inductor are 213.5 μF and 9.57mH respectively.

Two branches protected by R1 and R2, which are directional over-current relays. Each protective relays is assigned a primary function to clear faults in a specific zone and a backup function to clear faults in another zones. The over-currant relay characteristics can be seen by using the IEC standard inverse curve.

The single-phase fault applied in this study is phase A to earth at bus-3 with a variable fault resistance. With a variable fault resistance and the TCSC operation for fault durations. The case study presented simulations results of current and voltage symmetrical components and phase's values are presented in Figures 5, 6, 7 and 8 respectively.

Fig.5 represent the variation of the symmetrical components of currants I_1, I_2 and I_0 respectively and Fig.6 represent the variation of Three phases currents on distribution line as a function RF varied from 0 to 100 Ω on inductive and capacitive modes.

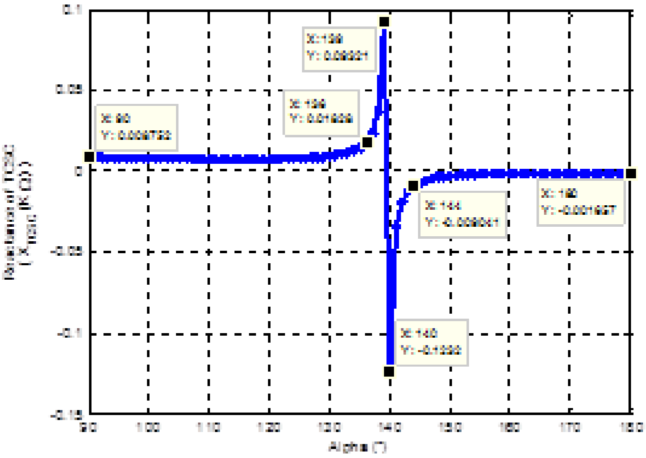

Fig. 4 – Characteristic Curve of TCSC study $X_{TCSC}\,(\alpha)$.

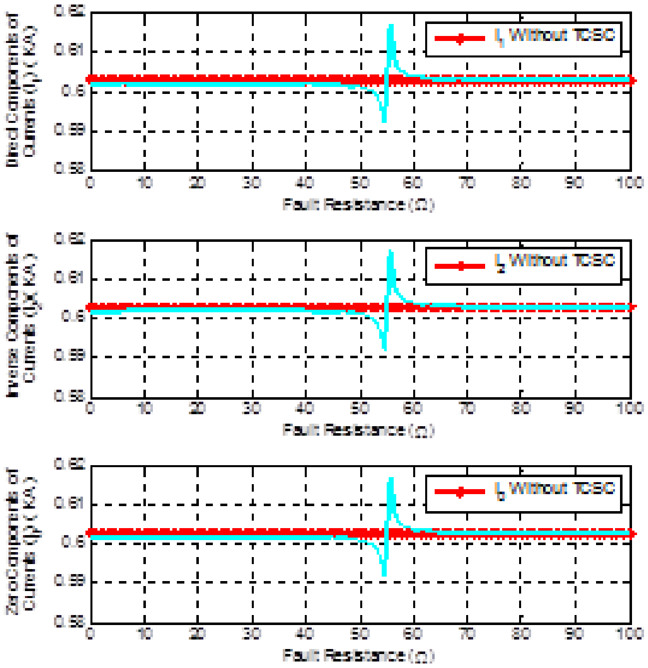

Fig. 5 – Symmetrical components of current.

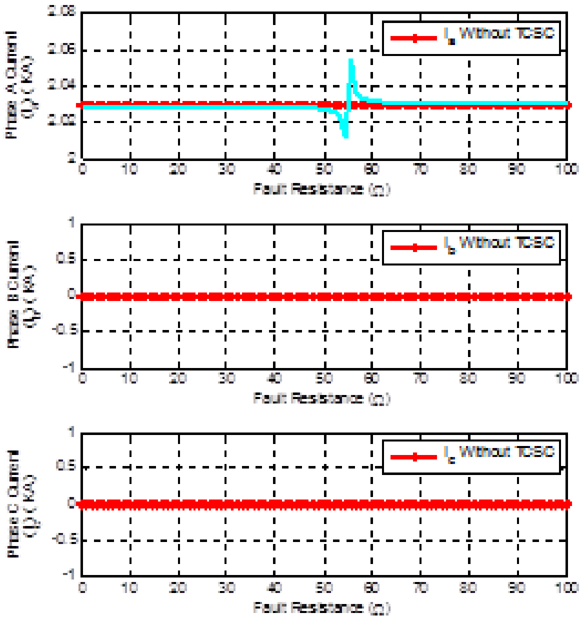

Fig. 6 – Three phases currents on distribution line.

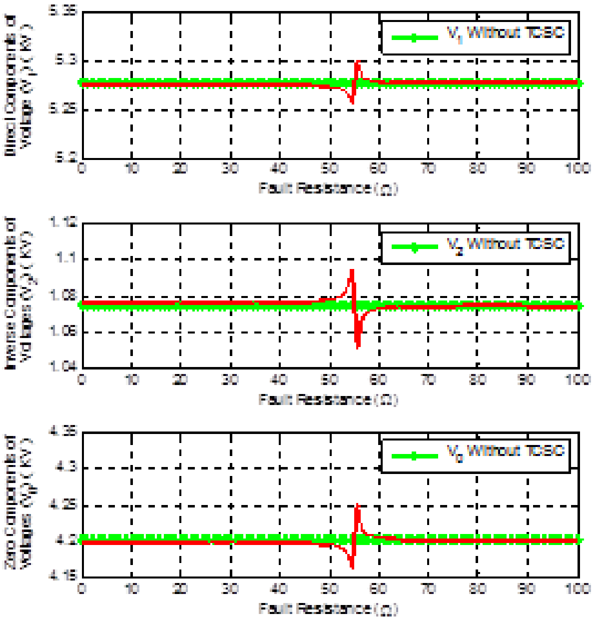

Fig. 7 – Symmetrical components of voltages.

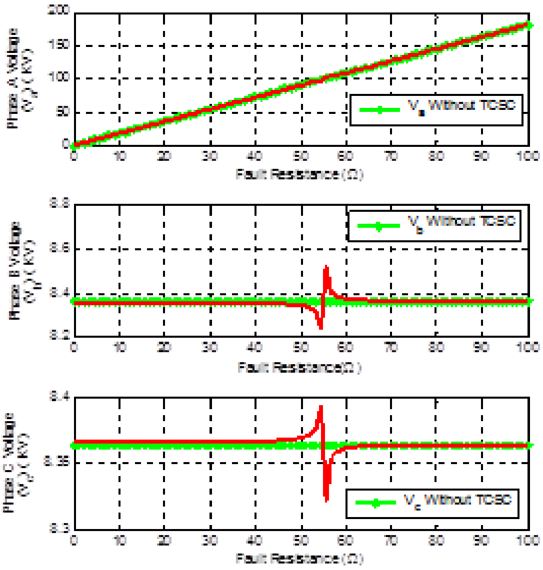

Fig. 8 – Three phases voltages on distribution line.

It is observed that the fault phase A to ground with resistance of default is large compared to those of without resistance. It can be seen as well that there is an effect of the inductive mode and capacitive mode on the voltage in phase B and C.

In fig. 9 PRC, BRC and O.T are Primary Relay Characteristic, Backup Relay Characteristic and Operating Time respectively.

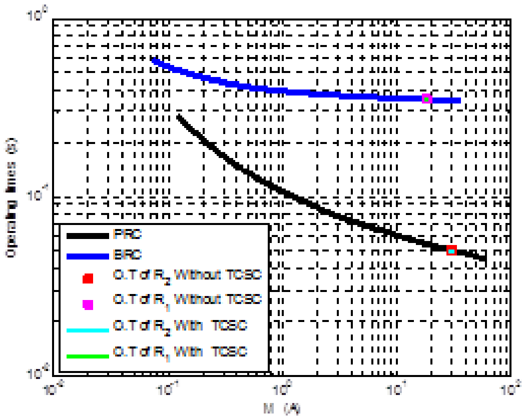

Fig. 9 – Operating times characteristics of primary and backup relays for Earth fault with and without TCSC.

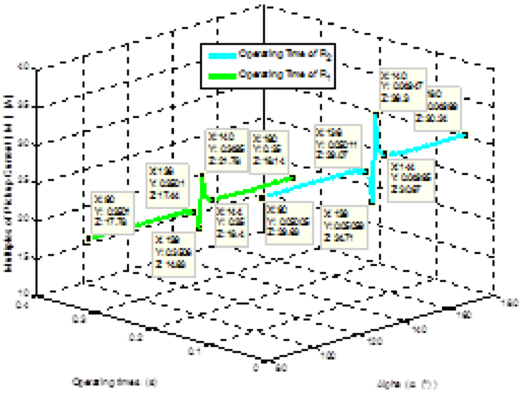

Fig. 10 – Zoom of Impact of TCSC modes on operating times of R2 and R1 for the fault F1.

It clears in Fig. 10 the effect of the varying reactance of the TCSC with firing angle alpha on operating time of the relays. Where for a fixed $I_P = 1$, the value M is variable car the value of fault currant is variable on function of reactance injected by the TCSC.

6. Conclusion

The effects of TCSC compensator on the variation of three phase's currents on distribution line as a function of an earth fault R_F varied from 0 to 100 Ω in inductive and capacitive mode are presented. The impact of earth fault with the presence of a TCSC on the operating time for a primary relay is investigated. The effects of varying mode of TCSC on multiple of pickup current and operating times are clear in 3-D. The CTI is taken as 0.3s. The coordination of the relays is a nonlinear programming problem and it is solved by using MATLAB software.

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