A Comparative Study of FSC and GCSC Impact on MHO Distance Relay Setting in 400 kV Algeria Transmission Line

Mohamed ZELLAGUI and Abdelaziz CHAGHI

Abstract: This paper presents a comparative study of the performances of MHO distance protection relay setting in 400 kV transmission line used in Eastern Algerian transmission networks at Sonelgaz Group (Algerian Company of Electricity and Gas). The line is compensated by two different technologies of series compensation. The first one is statics compensator based fixed series compensation (FSC) modeled by a capacitive reactance of fixed value (X_FSC) and the second one is a dynamic compensator based Controlled Series Capacitor (GCSC) modeled by a variable reactance value (X_GCSC) in capacitive and inductive boost mode depending of the firing angle (γ). These series compensators are connected at the midpoint of the transmission line employing MHO distance protection relay. The facts are used for controlling transmission voltage of a margin 10 kV and reactive power injected for different values.

The effects of FSC and GCSC insertion on the total impedance transmission line (Z_{AB}) protected by MHO distance relay are carried out and compared for the two compensators. The modified setting zone protection for three zones (Z_1, Z_2 and Z_3) is have been investigate in order to prevent circuit breaker nuisance tripping and improve the performances of MHO distance relay protection. The simulation results are performed in MATLAB software.

Keywords: Transmission line HV, Series Compensation, FSC, GCSC, MHO Relay Model, Reactance, Setting Zones.

1. INTRODUCTION

Many methods have been investigated to increase the power transfer capability of existing transmission line systems. Due to the cost and environmental concerns, more and more series compensated lines are being installed. Series compensation, using capacitors has been widely used for upgrading the existing power system to compensate for the inductive reactance of long transmission lines [1-6]. Adding the capacitors makes sense because they are inexpensive, simple and could be installed for 20 to 30% of the total cost of the installation of a new transmission line. They can also provide the advantages of better voltage regulation, increased system capability and reduced system losses. The series compensation based fixed or variable value of capacity is highly effective in both controlling power flow in the line and in improving stability. With series compensation the overall effective series transmission impedance from the sending end to the receiving end can be arbitrarily decreased thereby influencing the power flow [4-8]. This capability to control power flow can effectively be used to increase the transient stability limit and to provide power oscillation damping.

However, the series capacitors introduce certain difficulties for protective relaying reach and fault location [4-5]. Due to these difficulties, it is essential for the distance protection scheme to perform the impedance measurement with sophisticated algorithms.

MHO distance relays are widely used for the protection of series compensated transmission lines to detect and initiate remedial actions for each and every fault scenario to isolate the particular section of the line covered by the relay. Various models and algorithms have been put forward for solving various power system steady state control problems [10]. The literature shows an increasing interest in this subject for the last two decades, where the enhancement of system stability using FACTS controllers has been extensively investigated [9-11].

Many researches in [11-14] study the impact of Static Synchronous Series Compensator (SSSC) on measured impedance by distance relay. Reference [15] investigates the impact for the setting zones in digital distance relay used in single transmission line and adjacent transmission lines in inter phase faults. Reference [16-17] study the impact of Controlled Series Capacitor (TCSC), on measured impedance at the relaying point in the case of symmetrical (three phase) and asymmetrical (single phase to ground and phase to phase) faults on 400 kV transmission line. In [18] the

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study is done first analytically by using simple model. The simulated results of power system and the protective relays in Real Time Digital Simulator (RTDS) for 345 kV transmission line are stated in [19]. The impact MOV operation on distance relay over-reaching in case of TCSC installed in next transmission line for inter phase faults is given in [20]. The impact on measured impedance by distance relay with positive sequence voltage memory, and effects of voltage transformers connection point for inter phase faults in presence of TCSC is also investigated in [21].

In this paper, the setting zones consideration for a MHO distance relay on a 400 kV single transmission line installed in Algerian electrical networks in presence of two differences series compensation: static based FSC and dynamic GCSC are investigated.

2. MHO DISTANCE RELAY SETTING

Distance protection has been widely used in the protection of EHV and HV transmission lines. The basic principle of operation of distance protection is shown in figure 1 [22-25]. The MHO distance relay uses three distance measuring units, can be three separate units or one unit for the first and second zone with a timing unit to increase the delay of the former and a second unit for the third zone.

Figure 1 shows the application of distance relaying. At each end of the line, three separate sets of relays are arranged to provide three protective zones. The first and second protective zone provides primary protection, and the second and third zone provides remote back up for the adjacent line [25-26].

2.1. Setting Zones:

The MHO distance relay uses three measuring distance units as shown in figure 3 and which can be three separate units or one unit for the first zone (Z1) and second zone (Z2) with a timing unit to increase the delay of the former and a second unit for the third zone (Z3). At each end of the line, three separate sets of relays are arranged to provide three protective zones. The first and second protective zones provide primary protection, and the second and third zone provides remote back up for the adjacent line [25-26].

2.1.1. First Zone

It is normal practice to adjust the first zone relays (Z1) at A to protect only up to 80% of the protective line AB. This is a high speed unit and is used for the primary protection of the protected line. Its operation is instantaneous [26]. This unit is not set to protect the entire line to avoid undesired tripping due to over reach. Over reach may occur due to transients during the fault condition.

2.1.2. Second Zone

It is set to cover about 20% of the second line (BC). The main object of the second zone unit is to provide protection to the end zone of the first section which is beyond the reach of the first unit. The setting of the second unit is so adjusted that it operates the
relay even for arcing faults at the end of the line. To achieve this, the unit must take care beyond the end of the line. In other words its setting must take care of under reach caused by arc resistance [26]. Under reach is also caused by intermediate current sources, errors in CT, and VT and measurement performed by the relay. To take into account the under reaching tendency caused by these factors, the normal practice is to set the second zone reach up to 20% of the shortest adjoining line section. The protective zone of the second unit is known as the second zone of protection. The second zone unit operates after a certain time delay. Its operating time is 0.3 sec.

2.1.3. Third Zone

It is provided for back-up protection of the adjoining line. Its reach should extend beyond the end of the adjoining line under the maximum under reach, which may be caused by arcs, intermediate current sources and errors in CT, VT and measuring unit. The protective zone of the third stage is known as the third zone of protection. The setting of the third zone of protection covers the first line i.e. the protected line plus the longest second line plus 20% of the third line. The time delay for the third unit is usually 1 to 1.5 sec.

The setting zones for protected transmission line without series compensators are given by:

\[ Z_2 = R_2 + jX_2 = 80\% Z_{AB} = 0.8 (R_{AB} + jX_{AB}) \]  
\[ Z_3 = R_3 + jX_3 = R_{AB} + jX_{AB} + 0.2. (R_{SC} + jX_{SC}) \]  
\[ Z_4 = R_4 + jX_4 = 60\% Z_{AB} = 0.6 (R_{AB} + jX_{AB}) \]

The total impedance of transmission line AB measured by MHO distance relay is:

\[ Z_{AB} = K_Z Z_L, \quad K_Z = \frac{K_{VT}}{K_{CT}} \]  

Where, \( Z_{AB} \) is real total impedance of line AB, and \( K_{VT} \) and \( K_{CT} \) is ratio of voltage to current respectively.

3. FIXED SERIES COMPENSATION (FSC)

3.1. Voltage Regulation

Let consider a typical FSC radial circuit installed in midline between busbars A and B. The approximated voltage drop per phase from source to load obtained from phasor diagram is given by equation:

\[ \Delta V = R_I \cdot I_x \cos (\phi_x) + (X_L - X_{SC}) \cdot I_L \cdot \sin (\phi_x) \]  
\[ \Delta V = \frac{P_I \cdot R_I + Q_{SC} \cdot (X_L - X_{SC}) \cdot I_L \cdot \sin (\phi_x)}{E_R} \]  

Equation (7) shows that the voltage regulation provided by the series capacitor is continuous and instantaneous. In case of voltage fluctuations due to large variations of the load, a series capacitor will improve the quality at the loads downstream from the series capacitor. Figure 4 shows the influence of the series capacitor on the voltage profile for a radial power distribution line with inductive loads.

Assuming constant receiving end apparent power, series capacitor improves power factor seen by the sending end by bringing negative reactive power.

3.2. Injected Reactance

The capacitive reactance \( (X_{FSC}) \) injected by FSC is a fixed value, which is represented in figure 5 and given by:

\[ X_{FSC} = \frac{1}{jC_{FSC} \cdot \delta} \]  

And,

\[ C = \frac{Q_{FSC}}{V^2 \cdot \delta} \]  

3.3. Power transfer

Series compensation transmission lines HV and UHV utilize FSC to reduce the net series inductive reactance of the line in order to enhance the power transfer capability of the line. The power transfer along a transmission line is often explained in terms of the simple two busbar power system. If a series capacitor having reactance \( X_C \) is inserted, the net series reactance becomes \( (Z_L - F_{FSC}) \) and the active \( P_{L,FSC} \) and reactive power \( Q_{L,FSC} \) transfer with FSC over a transmission line is given by:

\[ \begin{align*}
P_{L,FSC} &= \frac{V_A \cdot V_B}{Z_L - X_{FSC}} \cdot \sin (\delta) \\
Q_{L,FSC} &= \frac{V_A \cdot V_B}{Z_L - X_{FSC}} \cdot \cos (\delta)
\end{align*} \]  

The \( P_{FSC} \) and \( Q_{FSC} \) power transfer over a transmission line for different value of the \( X_{FSC} \) are represent in figure 6.a and 6.b respectively.

![Fig. 4. Voltage profile with series capacitor.](image)

![Fig. 5. FSC Injected Reactance on transmission line.](image)
From equations (4) and (5) it can be noticed that for the same magnitude of $V_S$ and $V_R$, $P_{R1}$ is higher than $P_{R2}$. The increase in power is given by:

$$P_{R1} = \frac{Z_L}{Z_L - X_C} \left(1 - \frac{X_C}{Z_L}\right) = \frac{1}{1 - S} \left(1 - \frac{X_C}{Z_L}\right)$$

(11)

Where, $S$ is the Degree of series compensation.

**3.4. Impact on transmission line impedance**

The reactance of the FSC ($X_{FSC}$) has a direct influence on the total impedance of the protected line ($Z_{AB}$), especially on the reactance $X_{AB}$ but has no influence on the resistance $R_{AB}$ as represented in figure 7.

**4. GTO CONTROLLED SERIES CAPACITOR (GCSC)**

**4.1. Operation Principal**

The compensator GCSC mounted on figure 8.a is one of the in series family compensators. It consists of a capacitance ($C$) connected in series with the transmission line and controlled by a valve-type GTO thyristors mounted in anti-parallel and controlled by an angle of extinction ($\gamma$) which varies between $0^\circ$ and $180^\circ$. 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 $\gamma$ 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 [30-34].
Figure 8.b shows that the control signal for GTO2 can be made as the complement of GTO1. In this case, although the gate pulse duration is 180°, the positive-GTO start to conduct the line current only when the capacitor voltage (\(V_\phi\)) 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 \(V_C\) in figure 8.b are the dual of those in a shunt Thyristor Controlled Reactor (TCR) unity, which is often called SVC if in parallel with capacitor banks [34]. It is possible to see in figure 8 that the GCSC capacitor stays permanently inserted if \(\gamma\) equal 90°. This corresponds to the maximum series compensation, given by the capacitor’s reactance at the fundamental frequency. Contrarily, the capacitor stays permanently bypassed if \(\gamma\) equal 180°.

### 4.2 Injected Reactance

Figure 9 represents the reactance \(X_{GCSC}\) injected by GCSC on the transmission line [32-34].

![GCSC Reactance injected on transmission line.](image)

This reactance \(X_{GCSC}\) has a variable value and is defined by the following equation [6-8], [10]:

\[
X_{GCSC}(\gamma) = X_{max} \left[1 - \frac{2}{\pi} \gamma - \frac{1}{\pi} \sin(2\pi)\right]
\]

(12)

Where, \(X_{max} = \frac{1}{\sqrt{C_{GCSC} \gamma}}\)

The curve of \(X_{GCSC}\) as a function of angle \(\gamma\) is divided into two different regions (capacitive and inductive), as specified in figure 10.

![Characteristic curve XGCSC = f (\(\gamma\)).](image)

### 4.3 Power transfer

The GCSC could be used in applications where FSC, is used today, mainly to control power flow and provide damping of power and generator speed oscillations. The GCSC can operate in an open loop mode controlling the capacitive reactance added in series with the transmission line. It can also operate in a closed loop mode where it controls the real power flow in the transmission line or maintain a constant compensation voltage. One interesting point is that GCSC can be used to retrofit existing fixed series compensation just by adding controlled switches and its controller to the fixed capacitor bank. The active and reactive powers in this case are expressed by:

\[
\begin{align*}
P_{GCSC} &= \frac{V_S V_C}{Z_L + X_{GCSC}(\gamma)} \sin(\delta) \\
Q_{GCSC} &= \frac{V_S V_C}{Z_L + X_{GCSC}(\gamma)} \cos(\delta)
\end{align*}
\]

(13)

### 4.4 Impact on relay measured impedance \(Z_{AB}\)

The reactance \(X_{GCSC}\) of the GCSC has a direct influence on the total impedance of the protected line \((Z_{AB})\), especially on the reactance \(X_{AB}\) and no influence on the resistance \(R_{AB}\). For two boost modes (inductive and capacitive), figure 11 shows the direct influence of the GCSC on the reactance \(X_{AB}\) and no influence on the resistance \(R_{AB}\).

![GCSC impact on the Impedance \(Z_{AB}\).](image)

### 5. CASE STUDIES, SETTINGS AND RESULTS

The electrical networks 400 kV, 50 Hz studied in this paper is the eastern Algerian electrical transmission networks at group Sonelgaz (Algerian company of Electrical and Gas) is shown in figure 12. The MHO distance relay is located in the busbar at Ramdane Djamel substation Skikda to protect a single transmission line between busbar A and busbar B at Oued El Athmania substation in Mila. The busbar C is located at Salah Bay substation in Sétif. The series compensators (FSC and GCSC) are installed in the midpoint of the line protected by a MHO distance relay. The parameters of transmission line, FSC and GCSC are summarized in the appendix.

The study was carried out for three different values of injected reactive power i.e. 60, 80 and 120MVar.
5.1. FSC Impact

The impact of FSC insertion on reactance ($X_{AB}$) and resistance ($R_{AB}$) of a 400 kV transmission line for three different injected reactive power ($Q_{GSCS}$) i.e. 60, 80 and 120 MVar is represent in figure 13.a and 13.b respectively.

5.2. GCSC Impact

Figure 14 is represented the characteristic curve of the GCSC for three different value of injected reactive power $Q_{GSCS}$ i.e. 60, 80 and 120 MVar.

![Diagram of 400 kV Algerian electrical networks](image)

**Fig. 12.** 400 kV Algerian electrical networks.

The impact of insertion FSC for different value of $Q_{FSC}$ on reactance ($X_{AB}$) and resistance ($R_{AB}$) for 400 kV line is represent in figure 15.a and 15.b respectively.

5.3. Setting zones in presence of FSC

The MHO distance relays setting for three zone protection (Z1, Z2 and Z3) in presence of FSC installed in midline for three case studies where $Q_{FSC}$ is equal 60, 80 and 120 MVar is represent in figure 16.

![Graphs showing impact of FSC on protected impedance $Z_{AB}$](image)

**a).** $X_{AB} = f(X_{FSC})$

**b).** $R_{AB} = f(X_{FSC})$

**Fig. 13.** Impact of FSC on protected impedance $Z_{AB}$.
Fig. 14. Characteristic curve $X_{GCSC} = f(\gamma)$ for the studied case.

(a) Zone 1

Fig. 15. FSC Impact on impedance protected $Z_{AB}$.

(a) $X_{AB} = f(X_{FSC})$

(b) $R_{AB} = f(X_{FSC})$

(b) Zone 2

(c) Zone 3

Fig. 16. Setting zones in the presence of FSC.
5.4. Setting zones on presence GCSC

The MHO setting distance relays for the three protection zones \((Z_1, Z_2, Z_3)\) in presence of GCSC in case of inductive boost mode is summarized in the table I and on capacitive boost mode is summarized in the table II, for three injected reactive power \(Q_{\text{GCSC}}\) i.e. 60, 80 and 120 MVar:

**Table I: GCSC setting zones in inductive boost mode.**

<table>
<thead>
<tr>
<th>Case study</th>
<th>Settings</th>
<th>Firing angle (\alpha) for GTO (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N° 1</td>
<td>(X_2=) (Q)</td>
<td>6,3187, 5,0094, 4,7187</td>
</tr>
<tr>
<td></td>
<td>(R_2=) (Q)</td>
<td>0,4880, 0,4880, 0,4880</td>
</tr>
<tr>
<td>N° 2</td>
<td>(X_2=) (Q)</td>
<td>5,9187, 4,9367, 4,7187</td>
</tr>
<tr>
<td></td>
<td>(R_2=) (Q)</td>
<td>0,4880, 0,4880, 0,4880</td>
</tr>
<tr>
<td>N° 3</td>
<td>(X_2=) (Q)</td>
<td>5,5187, 4,8640, 4,7187</td>
</tr>
<tr>
<td></td>
<td>(R_2=) (Q)</td>
<td>0,4880, 0,4880, 0,4880</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case study</th>
<th>Settings</th>
<th>Firing angle (\alpha) for GTO (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N° 1</td>
<td>(X_2=) (Q)</td>
<td>8,4333, 6,7967, 6,4333</td>
</tr>
<tr>
<td></td>
<td>(R_2=) (Q)</td>
<td>0,6654, 0,6654, 0,6654</td>
</tr>
<tr>
<td>N° 2</td>
<td>(X_2=) (Q)</td>
<td>7,9333, 6,7058, 6,4333</td>
</tr>
<tr>
<td></td>
<td>(R_2=) (Q)</td>
<td>0,6654, 0,6654, 0,6654</td>
</tr>
<tr>
<td>N° 3</td>
<td>(X_2=) (Q)</td>
<td>7,4333, 6,6150, 6,4333</td>
</tr>
<tr>
<td></td>
<td>(R_2=) (Q)</td>
<td>0,6654, 0,6654, 0,6654</td>
</tr>
</tbody>
</table>

**Table II: GCSC setting zones in capacitive boost mode.**

<table>
<thead>
<tr>
<th>Case study</th>
<th>Settings</th>
<th>Firing angle (\alpha) for GTO (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N° 1</td>
<td>(X_2=) (Q)</td>
<td>8,9682, 7,3316, 6,9682</td>
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<tr>
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<td>(R_2=) (Q)</td>
<td>0,7207, 0,7207, 0,7207</td>
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<tr>
<td>N° 2</td>
<td>(X_2=) (Q)</td>
<td>8,4682, 7,2407, 6,9682</td>
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<tr>
<td></td>
<td>(R_2=) (Q)</td>
<td>0,7207, 0,7207, 0,7207</td>
</tr>
<tr>
<td>N° 3</td>
<td>(X_2=) (Q)</td>
<td>7,9682, 7,1499, 6,9682</td>
</tr>
<tr>
<td></td>
<td>(R_2=) (Q)</td>
<td>0,7207, 0,7207, 0,7207</td>
</tr>
</tbody>
</table>

6. CONCLUSION

The results are presented in relation to a typical 400 kV electrical transmission system protected by MHO distance relay and compensated by two different technologies of series compensation. The first one is a static compensator FSC based injected fixed capacitive reactance \(X_{SP}\) and the second is a dynamic compensator GCSC based inject variable reactance \(X_{\text{GCSC}}\) in capacitive and inductive boost mode with respect to angle \(\alpha\). These series compensators are installed at midpoint of the line. The facts are used for controlling transmission voltage of a margin 10 kV and reactive power injected for different values 60, 80 and 120 MVar. As can be seen the injected variable reactance \((X_{\text{ESC}})\) in the protected line result in direct impact on the total impedance of the protected line. In fact this effect varies the settings zones by decreasing performance of the total system protection and leading to unwanted tripping of circuit breaker.

7. ANNEXES

**APPENDIX A: TRANSMISSION LINE STUDY**

Nominal voltage: \(U_n = 400 \text{kV}\)
Maximum voltage: \(U_{\max} = 440 \text{kV}\)
Minimum voltage: \(U_{\min} = 380 \text{kV}\)
Nominal frequency: \(f_n = 50 \text{Hz}\)
Length of the line protected: \(l_2 = 247 \text{km}\)
Length of the line adjacent: \(l_{\text{Ja}} = 112 \text{km}\)
Line resistance: \(R_1 = 0.0393 \Omega/\text{km}\)
Line inductive reactance: \(X_L = 0.3184 \Omega/\text{km}\)

**APPENDIX B: FSC**

Maximum voltage injected: \(U_i = +40 \text{kV}\)
\(Q_{\text{GCSC}} = -60 \text{MVar}, C_{\text{GCSC}} = 0.1193 \text{mF}, X_{\text{GCSC}} = -j 26,667 \Omega\)
\(Q_{\text{ES}} = -80 \text{MVar}, C_{\text{ES}} = 0.1592 \text{mF}, X_{\text{ES}} = -j 20,000 \Omega\)
\(Q_{\text{FSC}} = -120 \text{MVar}, C_{\text{FSC}} = 0.2387 \text{mF}, X_{\text{FSC}} = -j 13,333 \Omega\)

**APPENDIX B: GCSC**

Maximum voltage injected: \(U_i = +40 \text{kV}\)
Maximum voltage absorbed: \(U_i = -40 \text{kV}\)
\(Q_{\text{GCSC}} = \pm 60 \text{MVar}, C_{\text{GCSC}} = 0.1193 \text{mF}, X_{\text{GCSC}} = -j 26,667 \Omega\)
\(Q_{\text{GCSC}} = \pm 80 \text{MVar}, C_{\text{GCSC}} = 0.1592 \text{mF}, X_{\text{GCSC}} = -j 20,000 \Omega\)
\(Q_{\text{GCSC}} = \pm 120 \text{MVar}, C_{\text{GCSC}} = 0.2387 \text{mF}, X_{\text{GCSC}} = -j 13,333 \Omega\)

**APPENDIX B: CURREN TRANSFORMER**

Primary current: \(I_{CT1} = 1500 \text{A}\).
Secondary current: \( I_{CT2} = 5 \, A \),
Transformation ratio: \( K_{CT} = 100 \).

**APPENDIX C: VOLTAGE TRANSFORMER**

Primary voltage: \( V_{VT1} = 4000000 / \sqrt{3} \, V \)
Secondary voltage: \( V_{VT2} = 100 / \sqrt{3} \, V \)
Transformation ratio: \( K_{VT} = 4000 \).

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