# The Effect of Fixed Series Capacitor on the Performance of Distance Protection Relays

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***Abstract—***

This paper describes the technical behavior of series capacitor banks during system faults, and presents a study about the impact of series capacitor banks on the performance of distance protection relay. Series capacitor banks can create several phenomena including current inversion, voltage inversion, and sub-synchronous oscillations, which can cause directional discrimination issues and reach problem. The main protection of series capacitor, metal oxide varistor which has a nonlinear characteristic can create extra complexity to the fault current analysis. The study case is modelled and simulated by using MATLAB/Simulink software for different fault conditions. The results of simulations are analyzed to check the existence of different phenomena, and investigate the effect of these phenomena on the performance of distance protection relays.

*Index Terms*—Series capacitor banks, distance protection relay, current inversion, voltage inversion, and sub-synchronous oscillations, metal oxide varistor.

## I. INTRODUCTION

IN recent years, modern high voltage transmission systems become more and more heavily loaded, and building of new transmission lines is costly, and it's difficult to obtain new transmission line corridors

The common practice, the simplest and the cheapest way is using of the Series capacitor compensation devices which are widely used in high voltage transmission lines.

The main purpose of installing of series capacitor compensated devices is to add a capacitive reactance to the transmission line, subsequently to cancel out a part of the inductive reactance, thereby increasing the power transfer capability of transmission line [1], [2], [3]. There are several other reasons for applying of series capacitor compensated devices to a long HV transmission lines, such as to improve power flow control, improve voltage profiles, and improve power oscillation damping and transient stability of power systems, additionally that is the reason of cost benefits of series capacitor compensated [1], [2], [4].

Series capacitor devices may be installed at one or both line ends, which are the most typical of series capacitor device locations, and the other possible location is at the middle of line, which is quite difficult and costly.

The series capacitor devices are forcing the distance relay to measure negative reactance for a close-in faults, due to directional discrimination issues related to the current inversion phenomenon and voltage inversion phenomenon, as well as the reach problems related to the sub-synchronous oscillations (SSO) phenomenon. Additionally, the parallel combination of Series Capacitor and Metal Oxide Varistor (MOV) during different fault current conditions can modify the apparent impedance measured by the distance relay and add further complex problems [1],[2],[5],[6]. Thus, the installation of series capacitors devices in HV transmission line may fetch several protection problems including directional discrimination issues and reach problems, and may lead the distance protection relay to operate incorrectly [1],[2].

## II. SERIES COMPENSATION OF TRANSMISSION LINES

Series capacitors compensation has been applied mostly to high voltage transmission lines, where the transmission line distances are quite long and where large power transfer over long distance is required [3]. In fact, the installations of series capacitor banks make the design of the protection scheme more complex, and the degree of complexity depends on some factors such as the size of the series capacitor and its location along the transmission line.

### *A. Series Compensation Configuration Model*

Generally, there two types of series compensation can be applied to high voltage transmission lines, Fixed Series Compensation (FSC) or Thyristor Controlled Series Compensation (TCSC) [5],[6],[7].

In this paper, the Fixed Series Compensation **(**FSC) type will be considered. The typical fixed series compensation (FSC) model as shown in figure 1

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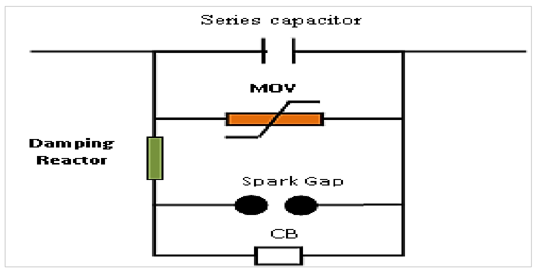


**Fig. 1.** Fixed series capacitor compensation model

The Series capacitors are designed and made up of series and parallel combinations of capacitor elements as required to obtain the desired capacitor bank rating, and to achieve the required reactance value $X_C$ which corresponding to the desired degree of compensation [3].

The Spark gaps are designed to flash over at voltage of 2 to 3 times the rated voltage of the series capacitor bank. When the breakdown voltage of spark gap is reached, spark gap flashes over instantaneously, but it will take time to reach this level of voltage. This time is often longer than the operating tripping time of the distance protection relay [8].

The Metal Oxide Varistor (MOV) is nonlinear resistance**,** which is the main protective element in the series capacitor compensation model. The presence of MOV in parallel with the series capacitor bank will introduce another device of concern. The MOV conduction voltage is approximately 1.5-2.5 times the rated voltage of the series capacitor bank. When the voltage level across the MOV reaches the conduction voltage level, the impedance of the MOV is reduced apparently, causing the series capacitor to be partially bypassed. When the voltage across the MOV decreases below the threshold voltage, the impedance of the MOV becomes high, and the series capacitor reinserted again. Additionally, the bypass circuit breaker is inserted in the scheme to enable bypassing of the series capacitor bank for maintenance or certain operation purposes.

The main purpose of damping reactor or discharge damping is to limit discharge current of a series capacitor bank when spark gap is flashing over or closing of circuit breaker during fault condition.

### *B. Associated Phenomena with Series Compensated Lines*

Most of the long HV transmission lines are protected by using distance protection relays, and the installation of series capacitors in these transmission lines can produce abnormal conditions such as voltage inversions phenomena, current inversions phenomena, and sub-synchronous oscillation phenomena (SSO) [9],[10].

1) **Current Inversion Phenomenon**

Current inversion can occur for a close-in fault, where the fault just after a capacitor bank, as shown in the power system figure 2.

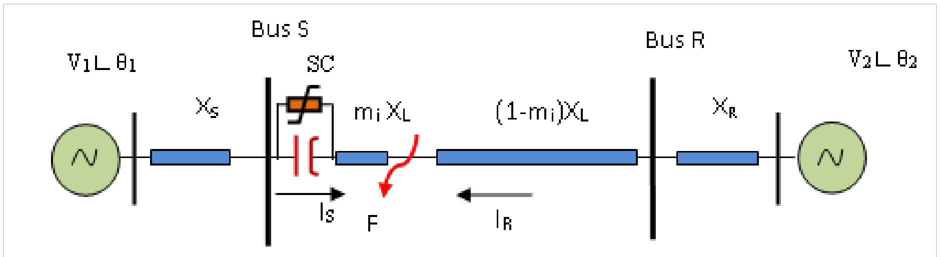


**Fig. 2.** A series compensated line

Current inversion occurs if the series capacitors reactance $X_C$ is greater than the sum of the source inductive reactance $X_S$ and the inductive reactance of the line section to the fault location $m_1X_L$ [9],[10]. Therefore, current inversion occurs if the following condition is fulfilled:

$$X_C > (X_S + m_1X_L) \qquad (1)$$

The Consequent problem of current inversion is directional discrimination issue which effects the performance of directional elements, causing the distance protection relay to operate incorrectly.

2) **Voltage Inversion Phenomenon**

Voltage inversion can occur for a fault near by the series capacitor bank, as shown the power system figure 2. Voltage inversion occurs if the series capacitors reactance $X_C$ is greater than the inductive reactance of the line section to the fault location $m_2X_L$ ,but $X_C$ is smaller than the sum of the source inductive reactance $X_S$ and the inductive reactance of the line section to fault location $m_2X_L$ [9],[10]. Therefore, for voltage transformer VT located behind the SC bank (bus side VT), voltage inversion occurs if the following conditions are fulfilled:

$$X_C > m_2X_L \qquad (2)$$

But,

$$X_C < (X_S + m_2X_L) \qquad (3)$$

The Consequent Problem of voltage inversion is directional discrimination issue.

3) **Sub-Synchronous Oscillation Phenomenon (SSO)**

These oscillations are produced due to the switching and insertion/removal of series capacitor bank during power system faults, which will creating distortion and harmonics in the voltage and current waveforms.

SSO occurs if the series capacitors reactance $X_C$ is smaller than the sum of the source inductive reactance $X_S$ and the inductive reactance of the line section to the fault location m3$X_L$ [1],[9],[10], as shown the power system figure 2. Therefore, SSO occurs if the following condition is fulfilled:

$$X_C < (X_S + m_3X_L) \qquad (4)$$

The resonant condition occurs for any series *LC* circuit, and the natural oscillation frequency may calculated as:

$$f_n = f\sqrt{\frac{X_c}{X_S+m_3X_L}} \qquad (5)$$

Where, $f_n$ is the natural oscillation frequency, and $f$ is the system fundamental frequency.

## III. TESTING AND SIMULATION OF CASE STUDY

The cases study are simulated and tested for different fault types and locations comprising the series capacitor (SC) for different modes with and without MOV with present of distance protection relay. The simulations are conducted by using Matlab/Simulink program. The configuration setting of the series capacitor will be calculated and checked as well the metal oxide varistor (MOV) and the distance protection relay, whereas the Spark gap and the bypass circuit breaker were not considered during the simulations studies. And for the voltage transformer VT, the bus side VT will be used.

This case considers a four buses, 400 kV -50Hz with two sources power system interconnected by HV transmission lines, and the series capacitor bank is considered in the section of the transmission line with 300 km length, as shown in figure 3.

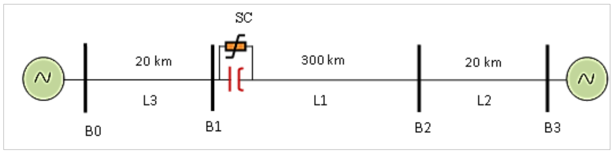


**Fig. 3.** Four buses power system of 400 kv

*A. System Configuration*

1) **High Voltage Network**
The HV Power System is consists of 2 of three-phase sources at both ends, supplying four buses system separated by 3 of three phase transmission lines. The parameters data of the power system are in appendix A1.

2) **Series Compensation Unit**
The Fixed Series Compensation (FSC) is applied in the middle transmission line of 300 km length, with 40% compensation factor (K). The capacitance of the series capacitor per phase is calculated as in appendix A2, where the capacitance setting is $C_S$ = 72.228 μF per phase. The Metal oxide Varistor (MOV) is the main protective element from over-voltages in the series compensation unit. So, the design of the protection voltage level of MOV is calculated as in appendix A3, where $U_{prot}$ = 311.624 kV(ph-n).

3) **Distance Protection Relay Unit**
The distance protection relay with quadrilateral characteristic will be used as shown in figure 4. The setting calculations of the zones reach depend on the rules criteria of calculation as in Appendix A4.

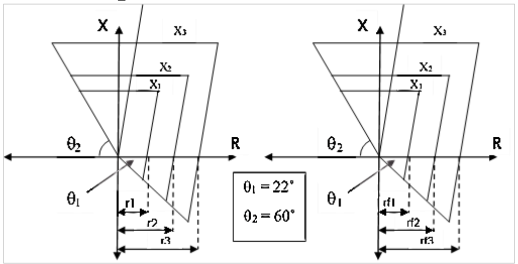


**Fig. 4.** Quadrilateral characteristic for phase & earth faults.

The zones setting calculations in detailed are calculated in appendix A5. The final zones setting of the distance protection relay of case study are in table I.

TABLE 1 THE FINAL ZONES SETTING OF DISTANCE RELAY

| Zones | Setting values (Ω) | | | Tripping time setting | Notes |
|---|---|---|---|---|---|
| | X | r | Rf | | |
| Zone1 | 1 | 5.2 | 5.225 | 100 | $R_E/R_L$ =0.79 |
| Zone2 | 1 | 7.9 | 10.45 | 250 | |
| Zone3 | 2 | 9.5 | 13.06 | 400 | |

*B. Simulations performance and Analysis of Results*

The simulation was performed for two different fault types, the three phase fault (the most severe fault) and the single phase to ground fault (the more probable fault), and with different fault locations along the line, comprising the series capacitor (SC) for different modes without and with MOV.

1) **3 Phase Fault Simulation**

The first simulation was done for 3 phase fault without and with MOV protection, and for different fault location along the compensated line of 300 km. The fault impedance seen by the distance protection relay for some fault locations are shown in table II and III.

TABLE II

FAULT IMPEDANCE SEEN BY DISTANCE RELAY FOR 3 PHASE FAULT-WITHOUT MOV

| Fault Location km | MOV: without — Current inversion, Voltage inversion, SSO& SSO | | | |
|---|---|---|---|---|
| | Z measured Ω (polar) | Z measured Ω (Rect) | Trip Status | Trip time |
| 10 | 10.17∠-89.09 | 0.161 - j 10.17 | reverse | - |
| 30 | 8.293∠-86.12 | 0.561 - j 8.274 | reverse | - |
| 50 | 6.777∠-84.08 | 0.699 - j6.741 | reverse | - |
| 75 | 4.527∠-72.58 | 1.356 - j4.319 | reverse | - |
| 80 | 4.16∠-69.41 | 1.463 - j3.895 | reverse | - |
| 90 | 3.383∠-62.35 | 1.57 - j 2.996 | reverse | - |
| 110 | 1.899∠-33.07 | 1.591 - j 1.036 | reverse | - |
| 115 | 1.698∠-16.7 | 1.626 - j 0.488 | zone 1 | 130 |
| 120 | 1.704∠2.872 | 1.702 + j 0.085 | zone 1 | 165 |
| 200 | 7.863∠68.52 | 2.88 + j 7.317 | zone 1 | 168 |
| 240 | 12.15∠71.76 | 3.802+ j 11.54 | zone 1 | 210 |
| 273 | 15.50∠73.00 | 4.532 + j 14.82 | zone 1 | 275 |
| 280.2 | 16.13∠73.25 | 4.649 + j 15.45 | zone 1 | 400 |
| 300 | 17.97∠73.93 | 4.973 + j 17.27 | zone 2 | 405 |

TABLE III

FAULT IMPEDANCE SEEN BY DISTANCE RELAY FOR 3 PHASE FAULT-WITH MOV

| Fault Location km | MOV: with Current inversion / Voltage inversion / SSO & SSO | | | |
|---|---|---|---|---|
| | Z measured Ω (polar) | Z measured Ω (Rect) | Trip Status | Trip time |
| 10 | 4.515∠-34.23 | 3.737 - j 2.54 | reverse | - |
| 20 | 4.553∠-27.01 | 4.057 - j 2.068 | reverse | - |
| 30 | 4.623∠-20.11 | 4.341 - j 1.589 | zone 1 | 165 |
| 50 | 4.829∠-7.262 | 4.791 - j 0.61 | zone 1 | 165 |
| 60 | 4.972∠-1.278 | 4.971 - j 0.111 | zone 1 | 165 |
| 65 | 5.051∠1.606 | 5.049 + j 0.145 | zone 1 | 165 |
| 100 | 5.742∠19.97 | 5.397 + j 1.961 | zone 1 | 165 |
| 200 | 9.013∠61.72 | 4.27 + j 7.937 | zone 1 | 170 |
| 240 | 12.26∠71.86 | 3.819+ j 11.65 | zone 1 | 180 |
| 273 | 15.52∠72.80 | 4.588 + j 14.82 | zone 1 | 230 |
| 280.2 | 16.13∠73.24 | 4.651 + j15.45 | zone 1 | 390 |
| 300 | 17.97∠73.93 | 4.974+ j 17.27 | zone 2 | 370 |

The next simulation is done to draw and trace the trajectory of the measured fault impedance seen by the distance protection relay for some fault locations without and with MOV, and presented in figures 5 to 10.

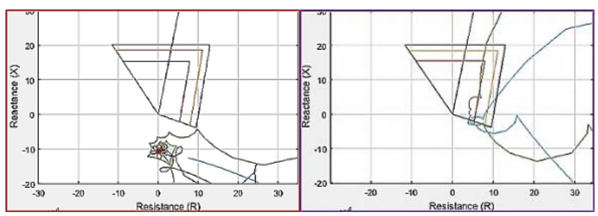


**Fig. 5.** Fault location at 10 km without and with MOV

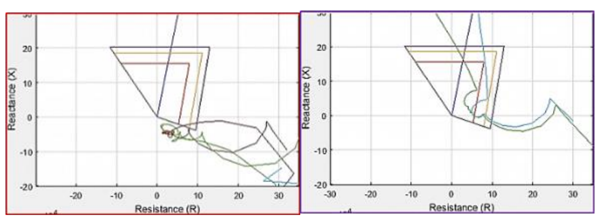


**Fig. 6.** Fault location at 70 km without and with MOV

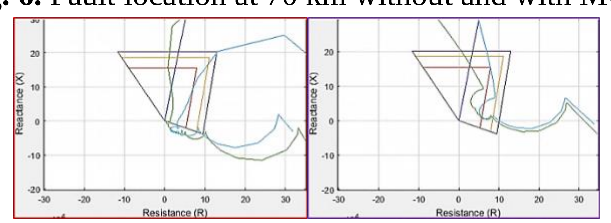


**Fig. 7.** Fault location at 90 km without and with MOV

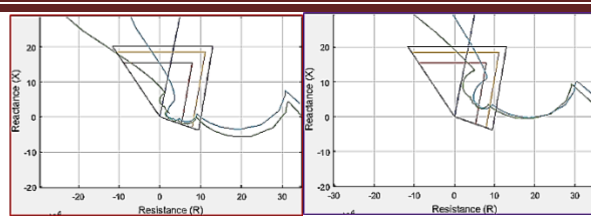

**Fig. 8.** Fault location at 130 km without and with MOV

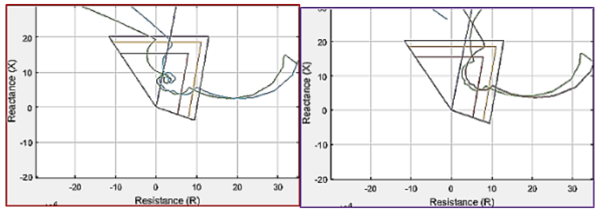

**Fig. 9.** Fault location at 200 km without and with MOV

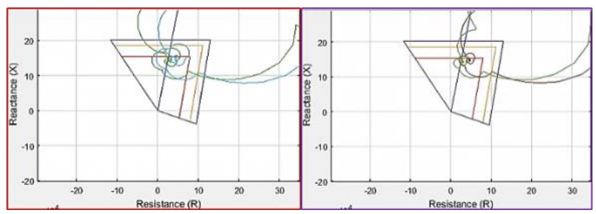

**Fig. 10.** Fault location at 273 km without and with MOV

The next simulation is performed to trace the waveforms of the voltages and the currents which are measured by the distance protection relay for some fault locations to check the presence of the different special phenomena.

a) SC without MOV

The simulation is created for fault locations at (50, 100, and 200) km as shown in the figures 11 to 13.

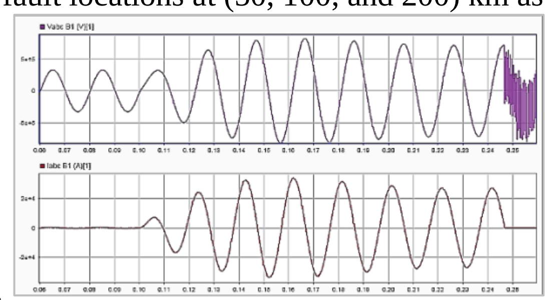

**Fig. 11.** Fault location at 50 km

The previous figure is showing the waveforms of voltage and current during current inversion phenomenon, where the fault voltage $V_1$ lags the pre-fault voltage, and the fault current $I_1$ leads the pre-fault current.

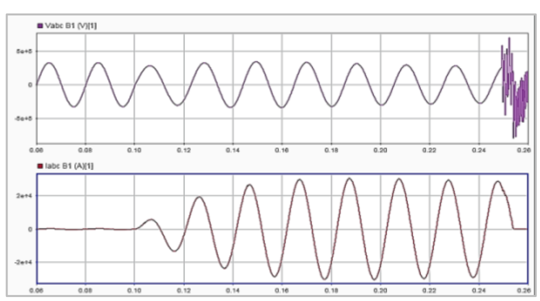

**Fig. 12.** Fault location at 100 km

The previous figure is showing the waveforms of voltage and current during voltage inversion phenomenon, where the fault voltage $V_1$ lags the pre-fault voltage, and the fault current $I_1$ lags the pre-fault current.

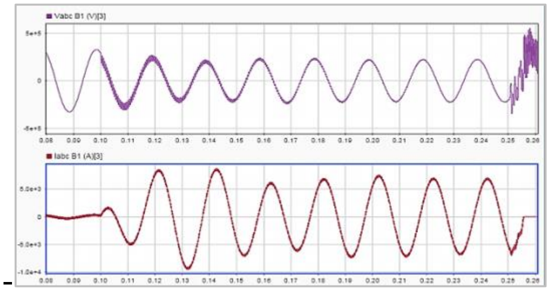

**Fig. 13.** Fault location at 200 km

The previous figure is showing the distortion of fault voltage $V_1$ waveform and fault current $I_1$ waveform during SSO phenomenon.

b) SC with MOV

The simulation was performed for fault location at 1 km just behind the series capacitor unit to check the presence of current inversion, as shown in figure 14.

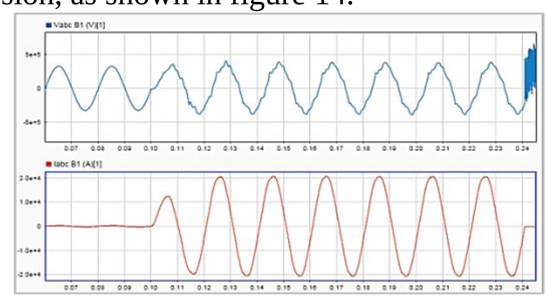

**Fig.14.** Fault location at 1 km.

Figure 14 is showing that the occurrence of current inversion phenomenon is not existent, and this situation is considered as voltage inversion phenomenon, where the fault voltage $V_1$ lags the pre-fault voltage and the fault current $I_1$ lags the pre-fault current.

So, the same previous simulations were performed for all the fault location points of the table II and table III to check the presence of the different special phenomena.

2) **Single Phase to Ground Fault Simulation**

The second simulation was done for single phase to ground fault without and with MOV protection.

The fault impedance seen by the distance protection relay during some fault locations on the compensated line for both modes of MOV protection are shown in table IV and table V.

TABLE IV
FAULT IMPEDANCE SEEN BY DISTANCE RELAY FOR 1 PHASE TO GROUND FAULT-WITHOUT MOV

| Fault Location km | MOV: without<br>Current inversion Voltage inversion SSO & SSO | | | |
|---|---|---|---|---|
| | Z measured Ω (polar) | Z measured Ω (Rect) | Trip Status | Trip |
| 10 | 6.551∠-75.08 | 1.87-j 6.33 | reverse | - |
| 20 | 5.693∠-67.57 | 2.172 - j5.262 | reverse | - |
| 30 | 5.228∠-51.59 | 3.248 -j 4.096 | reverse | - |
| 45 | 4.186∠-37.63 | 3.814 -j 2.94 | reverse | - |
| 50 | 4.765∠-30.85 | 4.091 -j 2.443 | reverse | - |
| 70 | 4.488∠-19.5 | 4.23 -j 1.498 | zone 1 | 110 |
| 80 | 4.717∠-8.499 | 4.665 -j0.6971 | zone 1 | 120 |
| 90 | 4.637∠-3.218 | 4.63 –j 0.2603 | zone 1 | 120 |
| 95 | 4.825∠1.365 | 4.823 +j 0.1149 | zone 1 | 120 |
| 110 | 4.531∠9.577 | 4.468 +j 0.7538 | zone 1 | 120 |
| 200 | 10.77∠69.51 | 3.772 +j10.09 | zone 1 | 180 |
| 273 | 15.83∠70.96 | 5.163 +j14.96 | zone 1 | 270 |
| 282.9 | 16.31∠71.30 | 5.23 +j15.45 | zone 1 | 480 |
| 300 | 17.05∠71.68 | 5.36 +j 16.18 | zone 2 | 400 |

TABLE V
FAULT IMPEDANCE SEEN BY DISTANCE RELAY FOR 1 PHASE TO GROUND FAULT-WITH MOV

| Fault Location km | MOV: with<br>Current inversion Voltage inversion SSO & SSO | | | |
|---|---|---|---|---|
| | Z measured Ω (polar) | Z measured Ω (Rect) | Trip Status | Trip time |
| 10 | 3.87∠-35.05 | 3.168 -j 2.223 | reverse | - |
| 20 | 3.826∠-29.13 | 3.343 -j 1.863 | reverse | - |
| 30 | 3.77∠-22.75 | 3.477 -j 1.458 | reverse | - |
| 40 | 2.931∠-8.645 | 2.897 -j 0.440 | zone 1 | 165 |
| 50 | 3.019∠0.011 | 3.019 -j 0 | zone 1 | 165 |
| 55 | 3.069∠4.144 | 3.061 +j 0.2218 | zone 1 | 165 |
| 110 | 4.158∠44.63 | 2.959 +j 2.921 | zone 1 | 175 |
| 200 | 10.77∠69.51 | 3.769 +j 10.08 | zone 1 | 180 |
| 273 | 15.83∠70.96 | 5.163 +j 14.96 | zone 1 | 270 |
| 282.9 | 16.31∠71.30 | 5.23 +j 15.45 | zone 1 | 480 |
| 300 | 17.05∠71.68 | 5.36 +j 16.18 | zone 2 | 400 |

The next simulation was performed to draw and trace the trajectory of the measured fault impedance seen by the distance protection relay for some fault locations without and with MOV, and presented in figures 15 to 20.

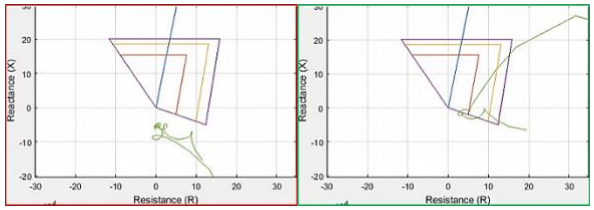


**Fig. 15.** Fault location at 10 km without and with MOV

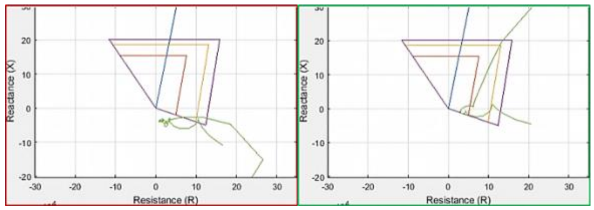


**Fig. 16.** Fault location at 30 km without and with MOV

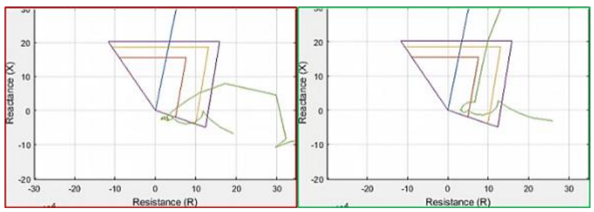


**Fig. 17.** Fault location at 50 km without and with MOV

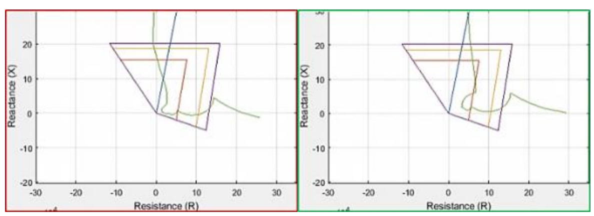


**Fig. 18.** Fault location at 90 km without and with MOV

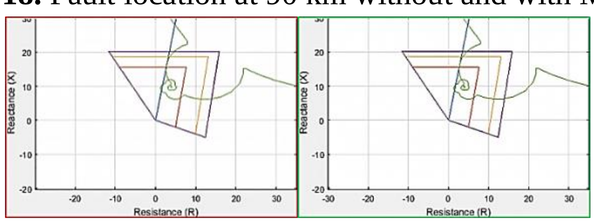


**Fig. 19.** Fault location at 200 km without and with MOV

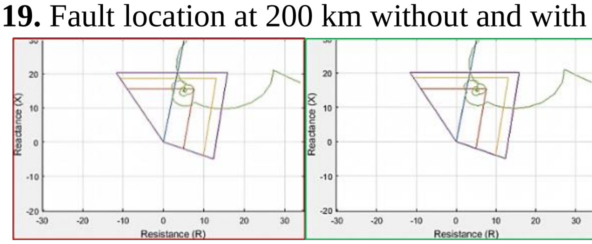


**Fig. 20.** Fault location at 273 km without and with MOV

The next simulation was performed to trace the waveforms signals of voltages and currents which are measured by the distance protection relay for some fault locations to check the presence of the different special phenomena.

a) SC without MOV

The simulation was done for fault location at (30, 75, and 150) km, as shown in the figure 21 to figure 23.

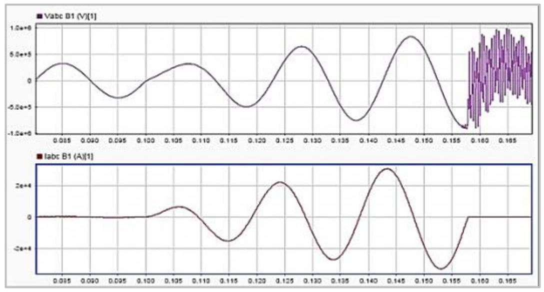

**Fig. 21.** Fault location at 30 km

Figure 21 is showing the waveforms of voltage and current during current inversion phenomenon, where the fault voltage $V_1$ lags the pre-fault voltage, and the fault current $I_1$ leads the pre-fault current.

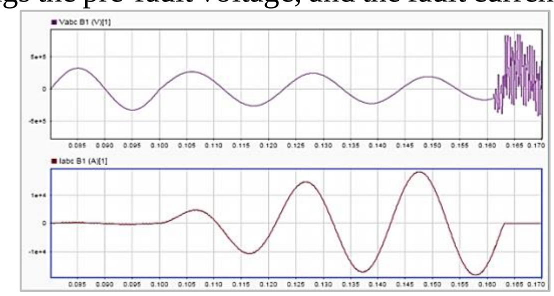

**Fig. 22.** Fault location at 75 km

The previous figure is showing the waveforms of voltage and current during voltage inversion phenomenon.

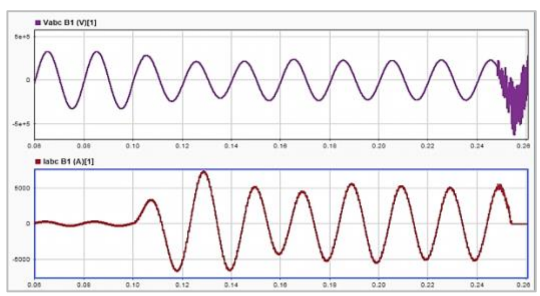

**Fig.23.** Fault location at 150 km

The previous figure is showing the distortion of fault voltage $V_1$ waveform and fault current $I_1$ waveform during SSO phenomenon.

b) SC with MOV

The simulation was done for fault location at 1 km just behind the series capacitor unit to check the presence of current inversion, as shown in figure 24.

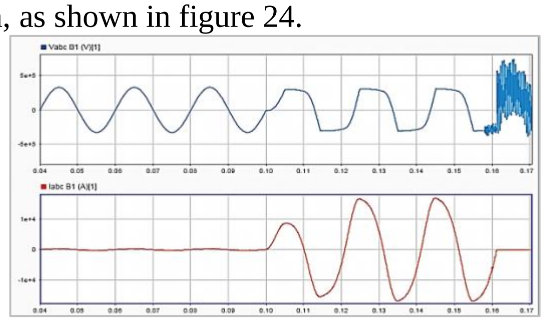

**Fig.24.** Fault location at 1 km.

In the previous figure, the occurrence of current inversion phenomenon is not existent, and this situation is considered as voltage inversion phenomenon, where the fault voltage $V_1$ lags the pre-fault voltage and the fault current $I_1$ lags the pre-fault current.

So, the same previous simulations were performed for all the fault location of the table IV and table V to check the presence of the different phenomena.

3) **Analysis of Results**

The results are analysed to investigate the occurrence and behaviour of the special phenomena, so the analysis as followed:

a) For 3 phase fault

- It can be observed that the occurrence locations of special phenomena along the compensated line in case of series capacitors without MOV protection as:
  0 Km ≤ Current Inversion occurrence ≤ 75 km.
  75 km <Voltage Inversion occurrence ≤ 115 km.
  75 km < SSO occurrence ≤ 300 km
  But, in case of series capacitors with MOV protection:
  Current inversion occurrence is not existent.
  0 km ≤ Voltage Inversion occurrence ≤ 60 km.
  0 km ≤ SSO occurrence ≤ 300 km
  The occurrence of current inversion phenomenon is not existent in case of SC with MOV simulation, because the 3-phase short circuit current closed to the SC is high (the capacitors will be partially bypassing).
- The fault impedances seen by the distance relay without and with MOV are nearly the same for the fault location ≥ 240 km.
- Another issue should be analyzed which is occurred during the previous simulations is the over-reaching of the distance protection relay due to the effect of SSO phenomenon, the following equations 6 and 7 are calculating the over-reaching values in percentage.

$$Over-reaching\ value(X\%) = \frac{X_{set} - X_m}{X_{set}} * 100\% \quad (6)$$

Where: $X_{set}$ is the actual reactance to the fault location (reach setting), and $X_m$ is the measured fault reactance for the same fault location.

$$Over-reaching\ value(X\%) = \frac{Z_{set} - Z_m}{Z_{set}} * 100\% \quad (7)$$

Where, $Z_{set}$ is the actual impedance to the fault location (reach setting), and $Z_m$ is the measured fault impedance for the same fault location.

The reactance setting of zone1 (at 273 km) is 15.45 Ω, and the measured fault reactance at the same location is 14.82 Ω, so:

$$\text{Over} - \text{reaching value (X\%)} = \frac{15.45 - 14.82}{15.45} * 100\% \quad = 4.08\%$$

And from Appendix A6, the actual $Z_{set}$ (at 273 km) is $16.16\angle 73^\circ\Omega$, and the measured fault impedance $Z_m$ at the same location is $15.5\angle 73^\circ\Omega$, so:

$$\text{Over} - \text{reaching value (Z\%)} = \frac{16.16 - 15.5}{16.16} * 100\% = 4.08\%$$

The main cause of over-reaching condition is the effect Sub-Synchronous Oscillation phenomenon (SSO) on the measurement of distance protection relay due to the distortion of the voltage and current waveforms, and these oscillations increase the operating time of distance relay which is reached to 400 msec (at zone1 border).

b) For Single phase to ground Fault

- It can be observed that the occurrence locations of special phenomena along the compensated line in case of series capacitors without MOV protection as:
  0 Km ≤ Current Inversion occurrence ≤ 45 km.
  45 km <Voltage Inversion occurrence ≤ 90 km.
  45 km ≤ SSO occurrence ≤ 300 km
  But, in case of series capacitors with MOV protection:
  Current inversion occurrence is not existent.
  0 km ≤ Voltage Inversion occurrence ≤ 50 km.
  0 km ≤ SSO occurrence ≤ 300 km
  The occurrence of current inversion phenomenon is not existent in case of SC with MOV simulation, because the single phase to ground fault current closed to the SC is high (the capacitors will be partially bypassing).
- The fault impedances seen by the distance relay without and with MOV are nearly the same for the fault location ≥ 200 km.
- The reactance setting of zone1 (at 273 km) is 15.45 Ω, and the measured fault reactance at the same location is 14.96 Ω, so:

$$\mathrm{Over-reaching\ value\ (X\%)} = \frac{15.45 - 14.96}{15.45} * 100\% = 3.17\%$$

And from Appendix A6, the actual $Z_{set}$ (at 273 km) is $16.16\underline{|73^{\circ}}\Omega$, and the measured fault impedance $Z_m$ at the same location is $15.83\underline{|70.96^{\circ}}\Omega$, so:

$$\mathrm{Over-reaching\ value\ (Z\%)} = \frac{16.16 - 15.83}{16.16} * 100\% = 2.04\%$$

Due to the effect of SSO phenomenon, the operating time of distance relay is increased which is reached to 480 msec (at zone1 border).

4) **Adjustment of The Characteristic Directionality**

The directionality angle $\theta_1$ and $\theta_2$ are modified ($\theta_1$=45º and $\theta_2$=60º) to enforce the distance relay to see most of these reverse faults within zone1. After the adjustment, the system was retested & checked, and it was found:

- When SC without MOV protection:
  - For 3 phase fault, the first 100 km of the line is still out of zone1 (reverse direction).
  - For 1 phase to ground fault, the first 30 km of the line is still out of zone1 (reverse direction).
- When SC with MOV protection (the usual operation mode): All kinds of faults located on the first zone setting are seen by the distance relay within zone 1.

## IV. Conclusion

The conclusions of this paper can be summarized as following:

- When the SC bank is installed at one end of a transmission line, the fault loop seen by the distance relay during faults contains the line impedance to fault point, and the equivalent impedance of the SC/MOV parallel combination (non-linear behavior & main effective).
- The installation of series capacitor bank on a transmission line will produce some special phenomena such as Current Inversion, Voltage Inversion and Sub-Synchronous Oscillation SSO.
- The Voltage transformer was installed at bus-side VT for SC bank. It is observed that the current inversion phenomenon could not occur together with the voltage inversion phenomenon, and the current inversion could not occur together with the SSO phenomena at the same time. But, the voltage inversion and SSO phenomena could be occurred together at the same time.

- The phenomena associated by SC bank with MOV protection is less effective on distance relay performance than without MOV protection.
- The consequent problem of current inversion and voltage inversion phenomena is directional discrimination issues.
- The related problem of the SSO phenomenon is the over-reaching of zone1 of the distance protection relay, where the over-reaching value reached to 4.08% in case of 3phase fault and 3.17% in case of single phase to ground fault, with high tripping time reached to 400 msec and 480 msec respectively.
- The Adjustments of the quadrilateral characteristic directionality of the distance protection relays is just an effort to eliminate some faults which seen by the distance relay as a negative faults due to current inversion and voltage inversion phenomena. But actually, these phenomena need a complete mitigation technique to overcome the associated problems of these abnormal phenomena.

## APPENDIX

Appendix A1**:** The HV Power System is consists of 2 of three phase sources at both ends (with 20GVA 3-phase short-circuit level, with X/R ratio =10), and the parameters of the transmission lines as shown in next table.

| No | Parameters | Data value |
|---|---|---|
| 1 | Lines Length TL1,TL2,TL3 | 300 km- 20 km- 20 km |
| 2 | System voltage V | 400 Kv |
| 3 | System frequency f | 50 Hz |
| 4 | Positive seq. resistance $R_1$ | 0.063 Ω/km |
| 5 | Zero seq. resistance $R_0$ | 0.212 Ω/km |
| 6 | Positive seq. inductance $L_1$ | 0.001169 H/km |
| 7 | Zero seq. inductance $L_0$ | 0.00337 H/km |
| 8 | Positive seq. capacitance $C_1$ | 0.001 μF/km |
| 9 | Zero seq. capacitance $C_0$ | 0.0045 μF/km |
| 10 | Positive seq. Impedance $Z_1$ | $0.3728\lfloor\underline{80.24}$: (0.063+ j0.3672) Ω/km |
| 11 | Zero seq. Impedance $Z_0$ | $1.080\lfloor\underline{78.65}$: (0.212+j1.0591)Ω/km |

Appendix A2**:** Calculation of the capacitance of the series capacitor per phase:

$X_L=(2\pi fL)$*line length $=(2*\pi*50*1.169*10^{-3})*300$

$X_L= 110.17565\ \Omega$ per phase, and the required capacitor reactance for 40% compensation factor will be:

$X_C = 0.4 * 110.17565 = 44.07\ \Omega$ per phase.

The capacitance can be calculated as $C_S = 72.228\ \mu F$/phase.

Appendix A3: The protection voltage level of MOV can be calculated at 2.5 times of the nominal capacitor voltage, where this nominal capacitor voltage should be taken at the nominal capacitor rating current (2kA rms), and the protection voltage level is calculated by using next equation

$U_{prot} = 2.5\sqrt{2}\ I_{rated}\, X_C$ $U_{prot} = 2.5\sqrt{2} * 2kA * 44.07$

$U_{prot} = 311.624$ kV(ph-n)

Appendix A4: The rules criteria of setting calculation:

Where: $X_{L1}$ is the total reactance of the protected line $TL_1$

$X_{L2}$ is the total reactance of the second line $TL_2$

$X_C$ is the total reactance of the series capacitor bank.

$R_{arc(\varphi-\varphi)}$ is the arc resistance for phase faults, $R_{arc(\varphi-N)}$ is the arc resistance for earth faults, and $R_{tower}$ is the tower footing resistance.

| Zone | Setting Parameters | | |
|---|---|---|---|
| | *X* *Reactance reach* | *r* *for ph.* | *rf* *for* |
| Zo | $X_1 = 85\%(X_{L1} – X_C)$ | $r_1 =$ | $r_{f1} =$ |
| Zo | $X_2 = 100\%\ (X_{L1} –$ | $r_2 = 1.5$ | $r_{f2} = 2$ |
| Zo | $X_3 = 100\%\ (X_{L1} –$ | $r_3 = 1.8$ | $r_{f3} = 2.5$ |

Appendix A5: The zones setting calculation:
$Z_1 = 0.063 + j0.3673 = 0.3728\underline{|80.24^\circ}\ \Omega/km$
$Z_0 = 0.212 + j1.0591 = 1.080\underline{|78.65^\circ}\ \Omega/km$
CTR= 1000/1, VTR= 400/0.11 and CTR/VTR = 0.275
$R_{arc(\varphi-\varphi)} = 12\ \Omega$, $R_{arc(\varphi-N)} = 9\ \Omega$ and $R_{tower} = 10\ \Omega$
Zone 1:
$X_1 = 0.85 *[0.33673*300 – 44.07]*0.275 = 15.45\ \Omega$
$r_1 = 1.6 * 12 * 0.275 = 5.28\ \Omega$
$r_{f1} = [9 + 10] * 0.275 = 5.225\ \Omega$
Zone 2:
$X_2 = [(0.6*0.3673*300) + (0.2*0.3673*20)]*0.275 = 18.58\ \Omega$
$r_2 = 1.5 * 5.28 = 7.92\ \Omega$
$r_{f2} = 2 * 5.225 = 10.45\ \Omega$
Zone 3:
$X_3 = [(0.6 * 0.3673 * 300)+(0.3673 * 20)]*0.275 = 20.20\ \Omega$
$r_3 = [1.8 * 5.28] = 9.504\ \Omega$
$r_{f3} = [2.5 * 5.225] = 13.06\ \Omega$
Zero Sequence Compensation:
$K_0 = \frac{1}{3}\left[\frac{Z0}{Z1} - 1\right] = \frac{1}{3}\left[\frac{(1.080\ \angle 78.65^\circ)}{(0.3728\ \angle 80.24^\circ)} - 1\right]$ $K_0 = 0.634\underline{|-2.41}$
$\frac{RE}{RL} = \frac{1}{3}\left[\frac{R0}{R1} - 1\right] = \frac{1}{3}\left[\frac{0.212}{0.063} - 1\right]$ $\frac{RE}{RL} = 0.79$
$\frac{XE}{XL} = \frac{1}{3}\left[\frac{X0}{X1} - 1\right] = \frac{1}{3}\left[\frac{1.0591}{0.3673} - 1\right]$ $\frac{XE}{XL} = 0.63$

Appendix A6: Calculation of actual $Z_{set}$ of zone1.
The positive sequence impedance of the compensated line is
$Z_1 = 0.063 + j0.3673 = 0.3728\underline{|80.24^\circ}\Omega/km$, CTR/VTR= 0.275
Actual resistance at zone1 border (at 273km):
$R_1 = 0.063 * 273 = 17.2\ \Omega$ (in primary)
$R_1 = 17.2 * 0.275 = 4.73\ \Omega$ (in secondary)
Since, reactance setting of zone1 $X_1 = 15.45\ \Omega$ (in secondary)
$|Z_{set}|$ (at 273km) = $\sqrt{(4.73)^2 + (15.45)^2} = 16.16\ \Omega$
The angle of $Z_{set}$, $\theta = \tan^{-1}\left[\frac{15.45}{4.73}\right] = 73^\circ$
$Z_{set} = 16.16\ \underline{|73^\circ}\ \Omega$

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