# The performance of distance protection relay on series compensated line under fault conditions

X.G. Magagula, D.V. Nicolae, A.A. Yusuff

*Department of Electrical Engineering, Tshwane University of Technology*
*Pretoria, South Africa*
magaguxg@eskom.co.za, NicolaeDV@tut.ac.za, YusuffAA@tut.ac.za

***Abstract* — This paper presents the behaviour of the distance protection relays on a series compensated transmission line under fault conditions. Series compensation presents distance protection elements with unorthodox line impedance and as a result the relays may operate incorrectly. Sub-harmonic oscillations and non-linearity of the line impedance are some of the challenges introduced by series compensation of transmission lines. The study is carried out in a Digsilent power factory environment and results pertaining to the response of the distance relay on a 400 kV series compensated line under fault conditions are presented.**

***Index Terms* - Series compensation (SC), Metal Oxide Varistor (MOV), Fault, Distance protection.**

## I. INTRODUCTION

Series compensation is commonly used to increase the power transfer capacity of a transmission line. However, there is a level to which a line can be compensated, since when compensation increases to over 50% of the line impedance it generally has an impact on protection settings co-ordination [1].

During a power system fault condition, the nonlinear behaviour of series capacitor arrangement, the rapidly changing characteristic of circuit impedance and the high frequency noise generated from the nonlinear protective devices of the compensation capacitors affects the typical voltage and current signals that are presented to the relay and thus creates problems for impedance relays [2], [5].

The insertion of series capacitors on a transmission line introduce the phenomenon of voltage inversion, current inversion, sub-harmonic oscillations, non linearity of the line impedance and overreaching of distance elements [2], [13].

One of the main considerations in the design and application of series capacitors is their overvoltage protection. In modern installations, the gap type technology has been replaced with the MOV (Metal Oxide Varistor) technology. The advantage of the MOV is that it does not bypass the capacitor completely during a fault condition and thus makes the reinsertion instantaneous and with minimum transients [3]. However, where there is a fault, MOV can introduce non-linearity.

Recently, the subject of the series compensation has been of great interest to most power system protection researchers and utility engineers. The main task has therefore been an attempt to reproduce some of the internal calculations or algorithms used by distance relays. These algorithms are used to estimate electrical quantities that will be evaluated by the distance relay to decide its operation. Fourier techniques and the line differential equation model are the common algorithms that are generally considered for fault location on series compensated lines research endeavours [11], [12].

In this paper, the study of a power system is performed using Digsilent environment and the results pertaining to the response of the distance relay under a steady state and during a fault condition are presented. Furthermore, the settings of a 400 kV transmission line are considered.

## II. SERIES COMPENSATION THEORY

### *A. Power Transfer*

The use of series capacitors improves the power transfer capability and enhances the voltage profile of the line by reducing the inductive reactance of the line. Consequently, it improves the line loadability as well as the stability margin [2], [4].

A series compensation capacitor bank (SC) installed at the middle of a transmission line is shown in figure 1, where $E_s$, and $E_r$ are the sending end and receiving end respectively. The basic power transfer equation for the simplified system illustrates the power transfer capacity of the transmission line and is depicted in equation 1 and 2.

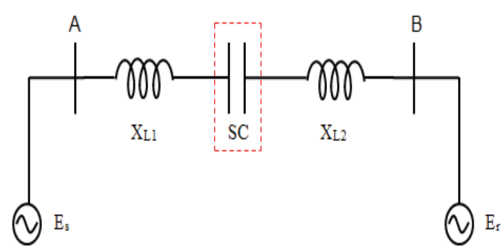


Figure 1: Series compensation

$$P = \frac{E_s \times E_r}{X_t} \times \sin(\delta) \quad (1)$$

$$P = \frac{E_s \times E_r}{X_t - X_{SC}} \times \sin(\delta) \quad (2)$$

$X_t$ is the sum of the source impedance, the inductive reactance ($X_L$) and the line resistance. $X_{SC}$ is the capacitive reactance of the series compensation, ($\delta$) is the transmission angle between the sending and receiving end voltage.

978-1-4799-7498-6/15/$31.00©2015IEEE

Consider a given power transfer, $P_o$ as shown in figure 2. The power transfer in the compensated line is further away from steady state maximum power transfer capacity, which indicates an increase in angular and voltage stability margins for the same power transfer level [2], [4].

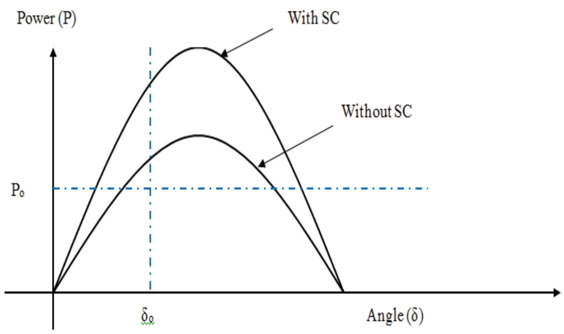


Figure 2: Power-angle curves

In addition, series compensating capacitors allow power transfer at the same voltage level over longer transmission lines than uncompensated lines, this phenomenon is shown in figure 3.

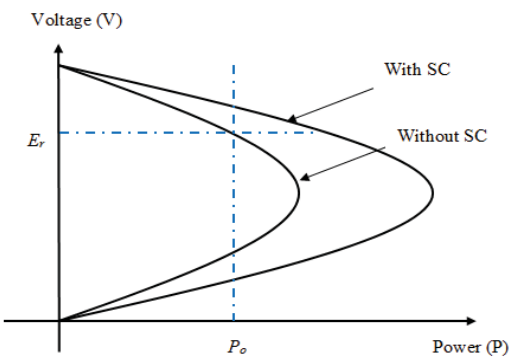


Figure 3: Receiving end voltage power curves

However, series compensation can adversely affect transmission line protection.

*B. Series Capacitor Protection*

It is always necessary to have an overvoltage protection for the capacitors used for series compensation. Overvoltage protection is accomplished by connecting the capacitor bank in parallel with an MOV unit. When the peak voltage reaches the protective level, the MOV conducts, and it limits the voltage across the capacitor. This scheme is shown in Figure 4.

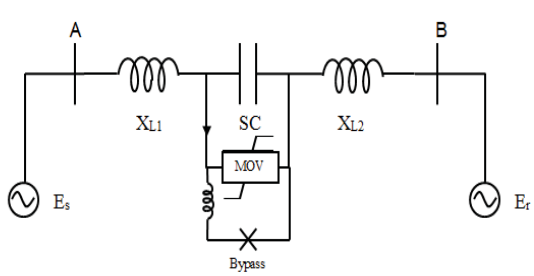


Figure 4: Series compensation with MOV

Under a normal working condition, the MOV presents huge impedance. However, when there is a fault on the transmission line, if the voltage across SC is too high, MOV gets into its nonlinear region as shown in figure 5 [7]. This result in a net impedance that comprises of a non-linear resistor (MOV) in parallel with the capacitive reactance of the series capacitor, the current ($i$) and voltage ($v$) characteristic in a specific range could be described by equation 3.

$$i = P \times \left(\frac{v}{V_{ref}}\right)^{q} \qquad (3)$$

Where $P$ and $V_{ref}$ are coordinates of the knee-point and $q$ is an exponent of the characteristic

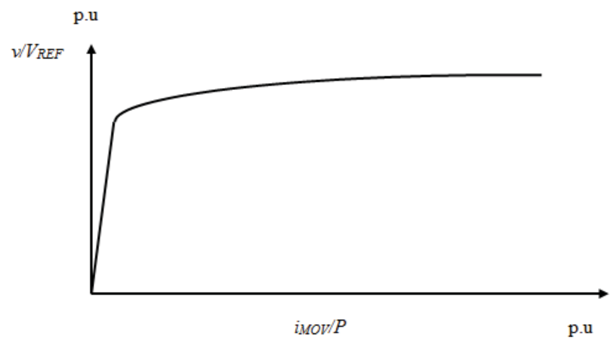


Figure 5: Voltage- Current characteristics of the MOV

The linear impedance of the parallel combination of the capacitor bank and MOV is split into resistive and reactive components terms $R'_c$ and $X'_c$. These are then normalized by dividing the original capacitive reactance, $X_{co}$. The total current through the combination, $I_c$, is also normalized to:

$$I_{pu} = \frac{I_c}{I_{pr}} \qquad (4)$$

Where $I_{pr}$ is the protective level current and is a multiple of the rated capacitor current. $I_{pu}$ represents the normalized current for a particular capacitor bank.

The model of the MOV-Capacitor bank parallel combination under short-circuit currents is given by equation 5 and 6.

$$Rc' = Xco(0.0745 + 0.49e^{-0.243Ipu} - 35.0e^{-5.0Ipu} - 0.6e^{-1.4Ipu}) \qquad (5)$$

$$Xc' = Xco(0.1010 - 0.005749Ipu + 2.088e^{-0.8566Ipu}) \qquad (6)$$

Equation 5 and 6 are used only when the current through the bank exceeds 98% of $I_{pr}$. Below this level there is essentially no MOV conduction so $X_{co}$ represents the bank impedance. The resistive loss in (Rc′) is also an approximation to the MOV energy absorption. [6]

The benefits of MOV protection schemes include: instantaneous and automatic re-insertion, and restoration of power transfer that can considerably increase power system transient stability, optimized capacitor design, increased reliability and reduced maintenance [8]. These benefits do not come without transmission line protection challenges.

## III. Protection Challenges

The performance of a series-compensated line protection depends very much on some of the followings: system configuration, line loading, potential transformer location, polarization of the relay, technology and integration of line protection, teleprotection schemes, autoreclose, and etcetera.

Additionally, there are other classical challenges such as, voltage inversion, current inversion and MOV effect [2],[10],[11].

The line A-B′ shown in figure 6 represents the impedance of a transmission line without series compensation, C-D indicates the capacitive reactance as introduced by series capacitors, D-B shows the new line impedance as seen by a distance relay at point A. During a fault condition, the impedance seen by the relay at A may be anywhere along the radius, which will result in B″.

The varying magnitudes of fault currents cause the impedance of the line to be approximated along the circular locus as indicated in figure 6. The conduction of the MOV introduces resistance into the circuit, at a fault current value of approximately 1.9 p.u. The resistance introduced into the circuit by the MOV may be at its peak, represented by the radius of the circular locus shown in figure 6. This maximum resistance introduced into the circuit is equal in magnitude to approximately a third of the reactance of the capacitor [1].

This means that the resistance decreases again. As the energy level in the MOV exceeds a set threshold, the bypass breaker closes, causing both the capacitor bank and the MOV to be bypassed. The fault impedance therefore now consists of only the line impedance up to the point of fault. Thus, the behaviour of the MOV and capacitor is dynamic and cannot be predicted. It is necessary to ensure a complete coverage of the line when the capacitor is not bypassed.

This implies that if the fault current is inadequate for the MOV to conduct, a fault just beyond the capacitor bank will present itself on line A-B. Therefore, the Zone 1 reach of the relay at A, looking towards B, must be reduced to avoid over reaching into the adjacent lines [7].

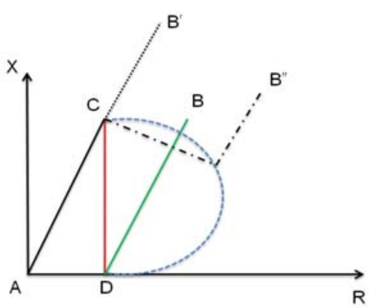


Figure 6: Line impedance

## IV. DISTANCE PROTECTION PRINCIPLE

The basic principle of transmission line protection is distance protection, which involves the division of the measured voltage phasor at the relaying point by the measured current phasor. The apparent impedance calculated is compared with the reach point impedance. If the measured impedance is less than the reach point impedance, it is assumed that a fault exists on the line between the relay and the reach point [1].

A careful application of the reach settings and tripping times for the various zones of measurement enables correct co-ordination between distance relays on a power system. Basic distance protection will consist of instantaneous directional Zone 1 protection and one or more time delayed zones [1].

A typical setting for distance protection is shown in figure 7. It generally requires that, Zone 1 reach is set at 80% of the line impedance with an instantaneous tripping time, Zone 2 reach is set at least at 120% of the protected line or also set to be equal to the protected line section plus 50% of the shortest adjacent line with a time delay [1].

Zone 3 is applied to provide backup protection for uncleared faults in adjacent line sections. The criterion used is that, the relay should be set to cover 120% of the impedance between the relay location and the end of the longest adjacent line, taking account of any possible fault infeed from other circuits or parallel paths [1].

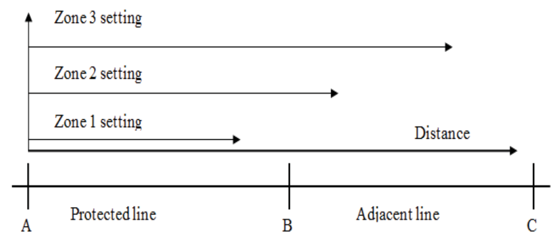


Figure 7: A typical distance protection settings

## V. CASE STUDY: SIMULATION OF A POWER SYSTEM MODEL

The 400 kV three-bus system considered for the study is modelled in the Power Factory DigSilent software is shown in figure 8. The system parameters used in the simulation are given in tables 5, 6, 7 and 8 in the appendix. The transmission line, Zebra, between Bus 1 and Bus 2 is 60% series compensated. The series capacitors are protected by an MOV. A circuit breaker is installed across the series compensator unit to bypass the series capacitors when not needed for simulation purposes.

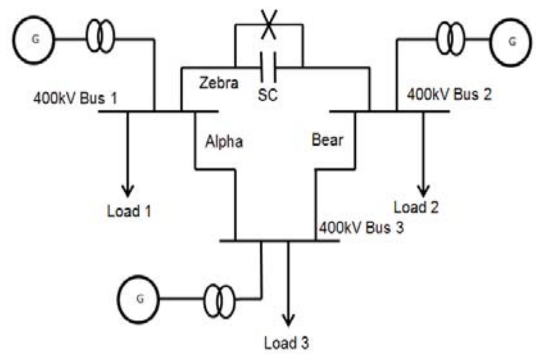


Figure 8: Power system model

### A. POWER FLOW STUDIES

Power flow studies are conducted for two cases, when the transmission line (Zebra) between Bus 1 and Bus 2 has compensation, and when it does not have series compensation.

Table 1: POWER FLOW RESULT FOR AN UNCOMPENSATED LINE

| BUS | MW | Mvar | Loading |
|---|---|---|---|
| Bus 1 (Zebra) | 47.53 MW | - 56.65 Mvar | 14.17 % |
| Bus 1 (Alpha) | 52.47 MW | - 19.03 Mvar | 11.95 % |
| Bus 2 (Zebra) | -47.36 MW | - 54.54 Mvar | 13.87 % |
| Bus 2 (Bear) | -52.26 MW | - 10.83 Mvar | 11.89 % |
| Bus 3 (Alpha) | -52.36 MW | - 33.05 Mvar | 11.95 % |
| Bus 3 (Bear) | 53.36 MW | - 32.44 Mvar | 11.89 % |

Table 2: POWER FLOW RESULT FOR A COMPENSATED LINE

| BUS | MW | Mvar | Loading |
|---|---|---|---|
| Bus 1 (Zebra) | 71.12 MW | - 63.88 Mvar | 18.30 % |
| Bus 1 (Alpha) | 28.88 MW | - 17.15 Mvar | 8.94 % |
| Bus 2 (Zebra) | -70.62 MW | - 47.91 Mvar | 16.41 % |
| Bus 2 (Bear) | -28.81 MW | - 14.12 Mvar | 8.06 % |
| Bus 3 (Alpha) | -28.84 MW | - 36.25 Mvar | 8.94 % |
| Bus 3 (Bear) | 28.84 MW | -30.22 Mvar | 8.06 % |

The results of the power flow studies are presented in tables 1 and 2. It is evident from table 1 and table 2 that, the insertion of series compensation will increase the power transfer capacity.

## B. RELAY RESPONSE

The ABB REL 561 numeric relay model is used in the case study on both ends of the Zebra transmission line, and its dynamic response during fault conditions is evaluated. The performance of the relay during fault conditions is investigated for conditions where the line is uncompensated as well as when it is compensated.

(i) Three phase faults for an uncompensated line

The response of the distance protection relay is evaluated at various distances when the transmission line Zebra does not have a series-compensation. Faults are instantiated at 15%, 50% and 85% of the line total length. The result is presented in table 3. The tripped zone and the tripping time are listed in the table

Table 3: TRIPPING ZONES AND RESPONSE TIME

| Fault position (%) | Relay 1 response | | Relay 2 response | |
|---|---|---|---|---|
| | Trip zone | Trip Time | Trip zone | Trip Time |
| 15 % | Zone 1 | 0.016 s | Zone 2 | 0.416 s |
| 50 % | Zone 1 | 0.016 s | Zone 1 | 0.016 s |
| 85 % | Zone 2 | 0.416 s | Zone 1 | 0.016 s |

Figure 9 and Figure 10 depict the trajectory impedance seen by the distance relay 1 and relay 2 respectively during a three-phase faults instantiated on the Zebra line. It is evident from the Tripping time in Figure 9 that for a fault within 80% of the protected line, Relay 1 tripped in zone 1 in 0.126s. However, Relay 2 tripped in zone 2 in 0.532.s for a similar fault. This is evident in the tripping time shown in Figure 10.

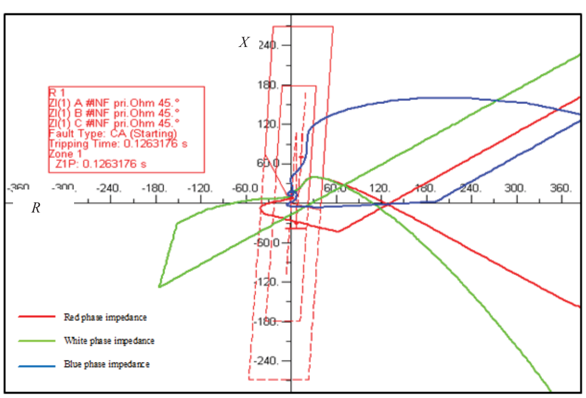


Figure 9: Trajectory impedance seen by the relay 1

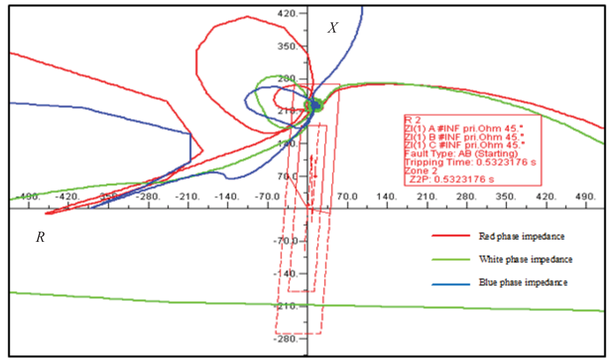


Figure 10: Trajectory impedance seen by the relay 2

The study showed that the conventional method of applying distance protection on a transmission line yield desired protection response during fault condition particularly if the series compensation is out of service. However, there is a need to study how the introduction of series compensation will impact the response of the distance relay.

(ii) Three phase faults for a compensated line

The simulation is repeated for the case when the transmission line Zebra has a series-compensation. Table 4 summarizes the response of the distance protection relay for faults introduced at 15%, 50% and 85% along the length of the line.

Table 4: TRIPPING ZONES AND RESPONSE TIME

| Fault position (%) | Relay 1 response | | Relay 2 response | |
|---|---|---|---|---|
| | Trip zone | Trip Time | Trip zone | Trip Time |
| 15 % | Zone 1 | 0.016 s | Zone 1 | 0.016 s |
| 50 % | Zone 1 | 0.016 s | Zone 1 | 0.016 s |
| 85 % | Zone 1 | 0.016 s | Zone 1 | 0.016 s |

Figure 11 and 12 depicts the X-R characteristics of Relay 1 and Relay 2 respectively. They are the trajectories of impedance seen by both relays

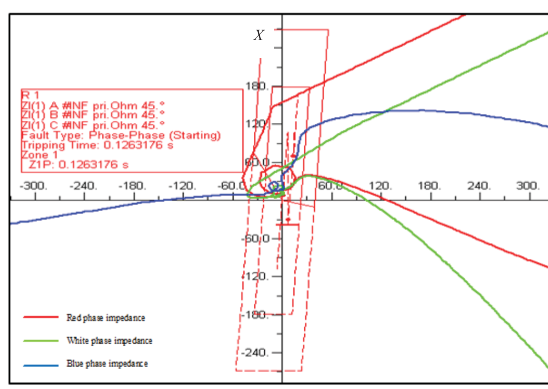


Figure 11: Trajectory impedance seen by the relay 1

When a three-phase fault is instantiated on the protected line at various locations along the line it is evident that both relays at the terminals of the transmission line will see the fault within Zone 1 regardless of the fault location along the line.

The introduction of series compensation on the transmission lines will definitely affect the impedance seen by the distance protection relay and as a result, the functionality of the relay may be affected.

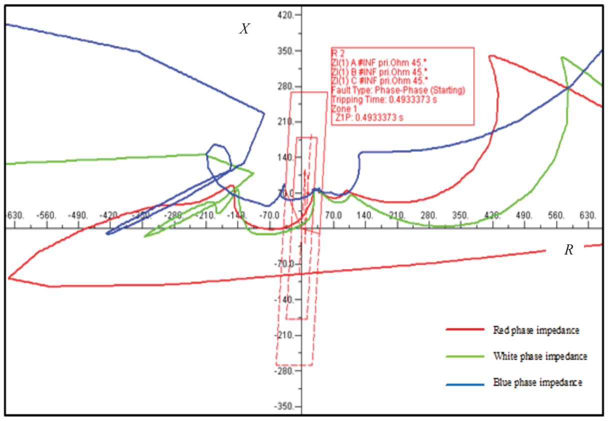


Figure 12: Trajectory impedance seen by the relay 2

## C. MOV EFFECT

During steady state fault calculations, the impedance of the MOV installed on series capacitors is not included in the impedance matrix due to their non-linear voltage-current characteristic. Figures 13, 14, 15 and 16 show the response of the MOV and the capacitor bank during a fault on the transmission line.

The MOV conducts only when the fault current is high enough to produce a voltage that exceeds the MOV protective level voltage across the parallel combination of the capacitor bank and the MOV. This does not occur throughout the entire cycle of the fault current and the MOV conducts only during this portion of the fault current cycle, when the instantaneous values of the current result in voltage drop across the capacitor higher than MOV protective level voltage. It is important to note that the peak value of the capacitor current ($I_{sc}$) does not change significantly, however, the RMS value is reduced substantially.

The amount of resistance that the MOV will introduce into the circuit is a nonlinear function of fault current, since some of the current is by-passed by the MOV and does not flow through the series capacitor. The effective reactance of the capacitor during faults will be reduced.

The linearized relationships between the effective reactance and the resistance of an equivalent series model, is given in equation 5 and 6.

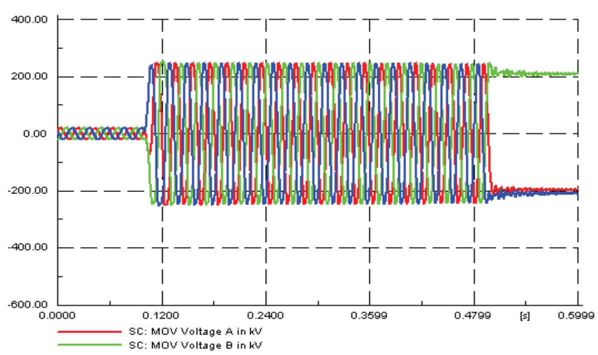


Figure 13: Voltage across the MOV

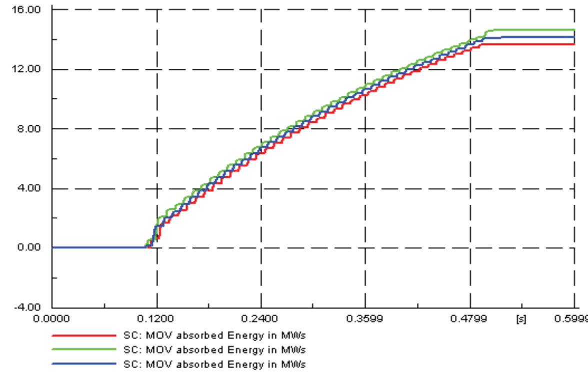


Figure 14: Energy in the MOV

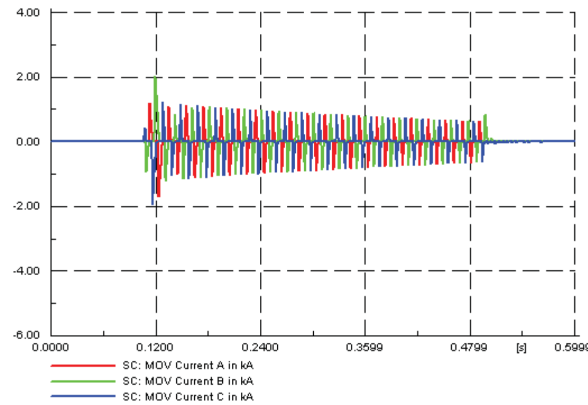


Figure 15: Current flowing through the MOV

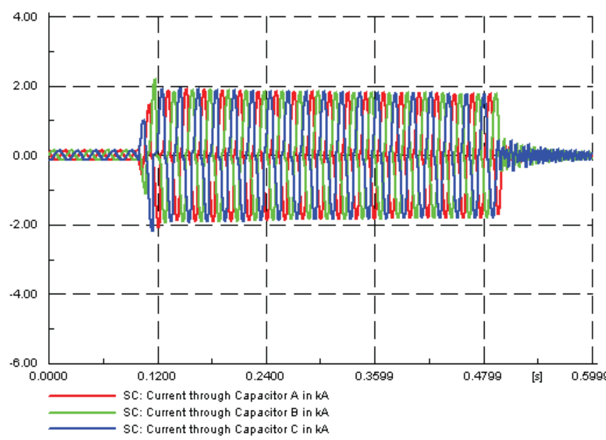


Figure 16: Current flowing through the capacitor bank

## VI. PROPOSED SOLUTION

One of the ways to mitigate the impact of series-compensation and the non-linearity of MOV resistance on the performance of distance relays could be by switching off the Zone 1 and increasing the time delay settings of Zone 2 in an adaptive manner. This technique will require a near real time estimation of the transmission line parameters and power flow.

The use of an ultra high speed protection schemes, could be also used, provided such schems can estimate the fault location before the MOV gets to its non-linear region.

() VII. CONCLUSIONS

The impact of series-compensation on the dynamic behaviour of the distance protection under fault conditions is presented in this paper. The functionality of the distance protection element is disturbed by the introduction of series compensation on transmission lines. MOV introduces a non-linear resistance into the transmission line impedance and thus a distance protection relay sees unorthodox impedance. This may cause impedance relay to mal-operate if an appropriate measure is not put in place. The development of the concept of ultra-high speed protection will greatly assist in dealing with series compensated network distance protection relay settings.

## APPENDIX

The network parameters used are given below:

Table 5: GENERATOR PARAMETERS

| GENERATOR | MVA | kV | PF | Xd (p.u) | Xq |
|---|---|---|---|---|---|
| GEN 1 | 689 | 20 | 0.96 | 2.637 | 2.5 p.u |
| GEN 2 | 689 | 20 | 0.96 | 2.637 | 2.5 p.u |
| GEN 3 | 689 | 20 | 0.96 | 2.637 | 2.5 p.u |

Table 6: TRANSFORMER PARAMETERS

| TRANSFORMER | MVA | HV (kV) | LV (kV) | Vector Group | % Z |
|---|---|---|---|---|---|
| TRFR 1 | 700 | 400 | 20 | YNd1 | 12.1 |
| TRFR 2 | 700 | 400 | 20 | YNd1 | 12.1 |
| TRFR 3 | 700 | 400 | 20 | YNd1 | 12.1 |

Table 7: TRANSMISSION LINE PARAMETERS

| LINE | km | kA | $Z_1$ (Ω) | $R_1$ (Ω) | $X_1$ (Ω) | $R_0$ (Ω) | $X_0$ (Ω) |
|---|---|---|---|---|---|---|---|
| Zebra | 375 | 0.75 | 224.14 | 13.66 | 223.72 | 118.72 | 561.86 |
| Alpha | 180 | 0.75 | 107.59 | 6.55 | 107.39 | 56.99 | 269.69 |
| Bear | 150 | 0.75 | 89.66 | 5.46 | 89.49 | 47.49 | 224.74 |

Table 8: LOAD PARAMETERS

| LOAD | MW | Mvar | MVA |
|---|---|---|---|
| LOAD 1 | 500 | 20 | 500.4 |
| LOAD 2 | 650 | 30 | 650.69 |
| LOAD 3 | 600 | 50 | 602.1 |

## REFERENCES


[1] Plumtre, F., Nagpal, M., Chen, X. & Thompson, M. 2009. Protection of EHV Transmission Lines With Series Compensation: BC Hydro's Lessons Learned. Schweitzer Engineering Laboratories, Inc.

[2] Zellagui, M. & Chaghi, A. 2011. Impact of Series Compensation on the MHO Disatnce Relay in Algerian 220kV Transmission Line.Electrical and Electronics Vol. 2.No. 6.

[3] Nekoubin, A. 2011. Simulaion of Series Compensated Transmission Lines Protected with MOV. World Academy of Science, Engineering and Technology 58.

[4] Zellagui, M. & Chaghi, A. 2011. Impact of Series Compensation Insertion in Double HV Transmission Line on the Settings of Distance Protection.Scientific& Engineering Research Electrical Vol. 2.No. 8.

[5] Nkwetta, D.N., Van Thong, V. & Belmans, R. 2006. Protection of Transmission Lines using Series Compensation Capacitors in Cameroon - Southern Interconnected System. Belgium: 3rd IEEE Benelux Young Researchers Symposium in Electrical Power Engineering.

[6] Sadeh, J., Hadjsaid N., Ranjbar, A.M. & Feuillet, R. 2000.Accurate Fault Location Algorithm for SeriesCompensated Transmission Lines. IEEE Transaction on Power Delivery Vol. 15. No.3

[7] Kasztenny, B. 2001. Distance Protection of Series Compensated Line – Problems and Solutions. Spokane: 28th Annual Western Protective Relay Conference.

[8] Sidhu, T.S. & Khederzader, M. 2006. Series Compensated Line Protection Enhancement by Modified Pilot Relaying Schemes. Transaction on Power Delivery Vol. 21. No.3

[9] Abdelaziz, A.Y., Ibrahim, A.M., Mansour, M.M. &T alaat, H.E. 2005. Modern approaches for protection of series compensated transmission lines. Cairo: Electric Power Systems Research.

[10] Castro, R.A. & Pineda, H.A. 2006. Protection System Considerations for 400 kV Series Compensated Transmission Lines of the Central Western Network in Venezuela. Venezuela: IEEE PES Transmission and Distribution Conference and Exposition Latin America.

[11] Santos, L.F. & Silveira, P.M. 2006. Evaluation of Numerical Distance Protection Algorithms for Series Compensated Transmission Lines. Venezuela: IEEE PES Transmission and Distribution Conference and Exposition Latin America.

[12] Saha, M.M, Rosolowki, E. & Izykowski, J. 2003. ATP-EMTP Investigation of a New Distance Protection Principle for Series Compensated Lines. New Orleans: International Conference on Power Systems Transients.

[13] Shah, A.B., Sood, V.K. & Saad, O. 2009. Mho Relay for Protection of Series Compensated Transmission Lines. Japan: International Conference on Power Systems Transients.

[14] Phadke A.G. & Thorp, J.S. 2009 Computer Relaying for Power Systems. England: wiley.