MHO Distance Relay of Transmission Line High Voltage using Series Compensation in Algerian Networks

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Abstract: *This paper deal with an analytical and simulation of the application of distance relay for the protection of line transmission high voltage 220 kV employing series capacitors compensating devices. A detailed modelling of series compensated (SC) is proposed and integrated in transmission system. The studies also include different challenges which the protection engineer may face such as current inversion, voltage inversion, non-linearity of the line impedance, … etc. The simulation results show the impact of the series compensating capacitor on distance protection relay during different fault condition*

Keywords: Distance protection, Series Compensation, Numerical relay, Fault, Transmission line.

1. INTRODUCTION

Increased transmittable power, improved system stability, reduced transmission losses, improved voltage profiles and more flexible power flow control are techno-economic reasons behind installing Series Capacitors (SCs) on long transmission lines [1], [2]. SCs and their over voltage protection typically Metal Oxide Varistors (MOV), in spite of their beneficial effects on the power system performance, introduce additional problems and make operating conditions unfavourable for the protective relays that uses conventional techniques [3]. During a power system fault 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 voltage and current signals and thus creates problems with relay functionality [4], [5], [6]. Following paragraph explains the problem in detail. Series compensating capacitors were initially introduced in transmission networks mainly to increase the power transfer capacity of long transmission lines. These series compensating capacitors bring with them significant protection challenges for relay manufacturers, utility engineers and researchers. One approach to studying the performance of advanced protection schemes in the presence of SC is the use of real-time digital simulators. Real-time digital simulation allows actual relay hardware to be tested in a hardware-in-loop arrangement with detailed dynamic models of the protected power system.

Distance protection systems are used in most countries of the world for the protection of high voltage transmission line due to their simple operating principal and capability to work independently under most circumstances [7], [8].

Nowadays numerical distance protection relay based on microprocessor technology is widely used. Systems engineering of electrical power has also been using this technology for over twenty years old. The relay technology has changed dramatically since the advent of microprocessors [8].

In this paper, the setting consideration for a quadrilateral numerical distance relay on a 220 kV transmission line is considered.

2. SERIES COMPENSATION: THEORY AND MODELING

2.1. Principle

Let consider the circuit in figure 1, that represents a typical series compensated radial circuit, where R_L, X_L and X_C are respectively the line resistance, the line reactance and the reactance of the series capacitor. The approximated voltage drop per phase from source to load obtained from phasor diagram is given by:

$$\Delta V = R_L . I_L \cos(\varphi_R) + (X_L - X_C) . I_L \sin(\varphi_R) \quad (1)$$

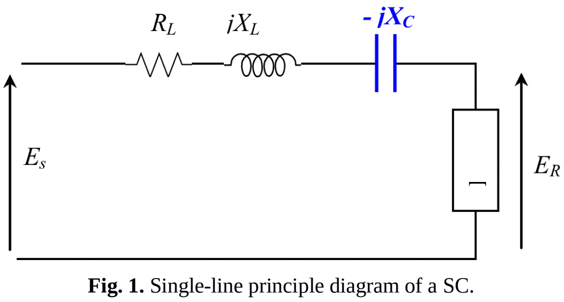


Fig. 1. Single-line principle diagram of a SC.

Manuscript received May 8, 2011.

$$P_R = E_R.I_L \cos(\varphi_R),\quad Q_R = E_R.I_L \sin(\varphi_R) \qquad (2)$$

Therefore:

$$\Delta V = \frac{P_R.R_L + Q_R.(X_L - X_C)}{E_R},\quad \tau = 100.\frac{X_C}{X_L}(\%) \qquad (3)$$

Equation (3) 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 2 shows the influence of the series capacitor on the voltage profile for a radial power distribution line with inductive loads.

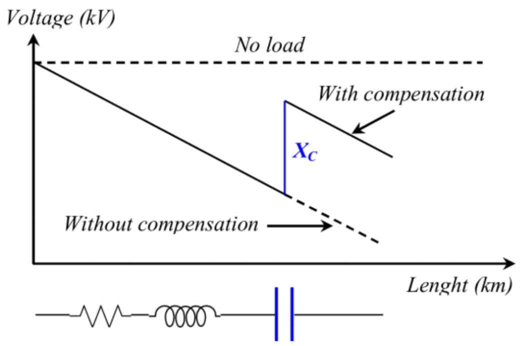


Fig. 2. Voltage profile for a radial circuit with series capacitor.

X_T is the total reactance of the line. Assuming constant receiving end apparent power, series capacitor improves power factor seen by the sending end by bringing negative VAR ($-2.X_C.I_L$).

2.2. Power transfer

SC transmission lines utilize series capacitors 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-source power system shown in figure.3.a without series capacitor and figure.3.b with series capacitor. The active power, P transferred by the uncompensated and compensated transmission lines are computed using equations (4) and (5) respectively:

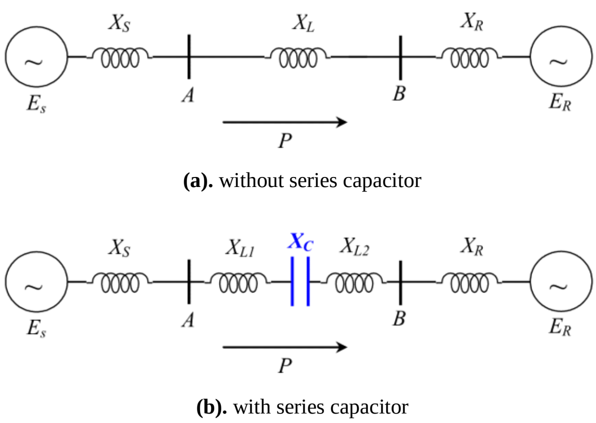


Fig. 3. A two-source power system transmission.

$$P = \frac{E_s \,.\, E_r}{X_T}\sin(\delta) \qquad (4)$$

$$P = \frac{E_s \,.\, E_r}{X_T - X_C}\sin(\delta) \qquad (5)$$

Where, $X_T = X_S + X_L + X_R$ is the total uncompensated reactance and δ is the transmission angle between the sending and receiving end voltages.

The merits of series capacitor compensation can be illustrated by computing power transfer where transmission angle δ is a variable and calculating load bus voltage (V_B) where the load is a variable. This gives a graphical visualization in figure 4. To illustrate further the benefits of series capacitor compensation, consider a given power transfer, P_o shown in figure 4. The power transfer P_o in the compensated line is further away from steady state maximum power transfer capacity, which indicates increased angular and voltage stability margins for the same power transfer level [9], [10]. The use of series capacitors also allows increased power transfer for the same transmission angles δ_o and enhances the voltage profile of the line. Since, series capacitors compensate the inductive reactance of the

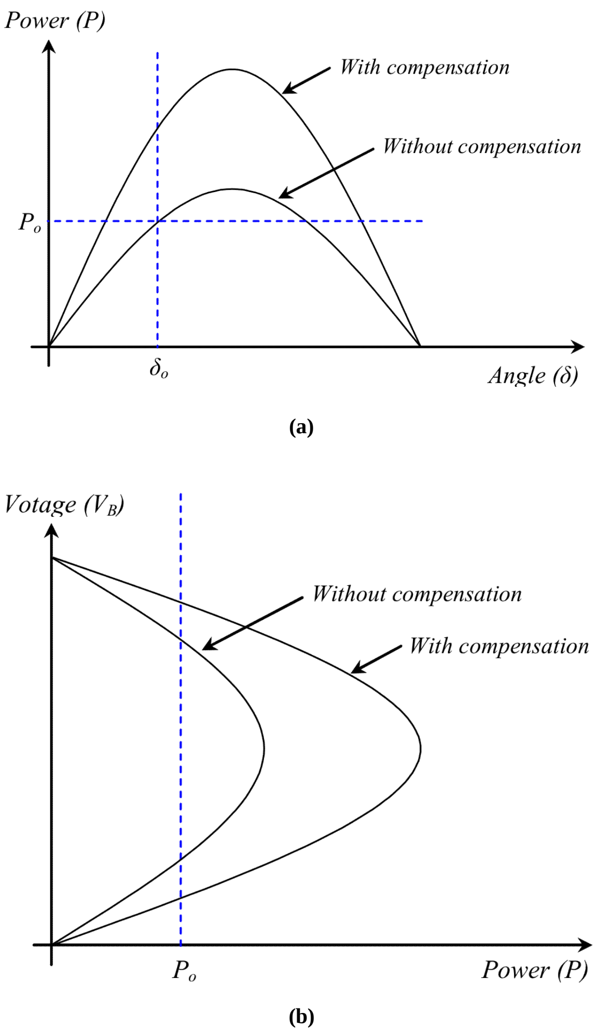


Fig. 4. a). Power-angle curves, **b).** Voltage-power curves.

line, reactive transmission line losses are significantly reduced.

In addition, series compensating capacitors allow power transfer at the same voltage level over longer transmission lines than uncompensated lines. This better utilizes the existing transmission network, which is cost effective and quicker rather than building new or additional parallel lines [11]. Modern HV and EHV transmission lines are series compensated to improve power system performance, enhance power transfer capacity, enhance power flow control and voltage control; decrease transmission losses, environmental impact reduction, decreased capital investment [12].

SC of transmission lines is widely used for very long transmission lines. The literature reveals that heavily-loaded, short transmission lines are also typically series compensated to gain the aforementioned benefits [11]. However, these benefits also bring with them significant transmission line protection challenges, particularly in heavily series compensated networks.

2.3. Series capacitor protection:

The introduction of series capacitors presents a number of technical challenges when setting distance protection relays, because of the combined effects of the series capacitor's compensating reactance and the series capacitor's own protective equipment, on the measured impedance to a short-circuit fault. During a short-circuit fault, the fault current through the capacitor produces overvoltages across the terminals of the series capacitor. Therefore, protection is provided to limit voltage across the series capacitor.

In the mid-1970s a MOV was announced as a means of series capacitor protection, which superseded spark gaps previously used to protect series capacitors [9,10]. The MOV is a nonlinear resistive device, which starts to conduct at specific instantaneous voltage and ceases to conduct when the voltage falls below the same voltage at each half cycle of the power frequency. The result is that there is a non-linearly time-varying degree of series compensation during a fault, due to the non-linear impedance characteristics of the parallel MOV-series capacitor combination.

This non-linear voltage-current characteristic of the MOV allows it to provide overvoltage protection across the capacitor when connected in parallel with it. The MOV holds the voltage across the capacitor within the permissible range of the capacitor by allowing a self-regulating amount of current through itself automatically. This non-linear relationship between the voltage and current is shown in figure 5. The MOV protective voltage is the instantaneous voltage across the series capacitor at a specified current when the MOV starts conducting.

The protective voltage is typically chosen above normal operating conditions, power system swing, and overloads as illustrated in figure 5 [13],[15], [16].

Figure 6 shows the equipment used to protect the series capacitor bank against overvoltages. The MOV itself is protected against excessive absorption of energy by a bypass switch. As the MOV conducts current, energy accumulates within the MOV itself. The MOV has a maximum amount of energy that it can absorb before it breaks down. Hence, the MOV is bypassed at a preset energy level to avoid break down. The bypass breaker operates when the energy absorbed by the MOV is greater than the preset value. This bypasses both the MOV and series capacitors and re-inserts them when the energy falls below the preset value. The impedance seen by the relay transits rapidly from compensated impedance to uncompensated impedance during severe short-circuits faults.

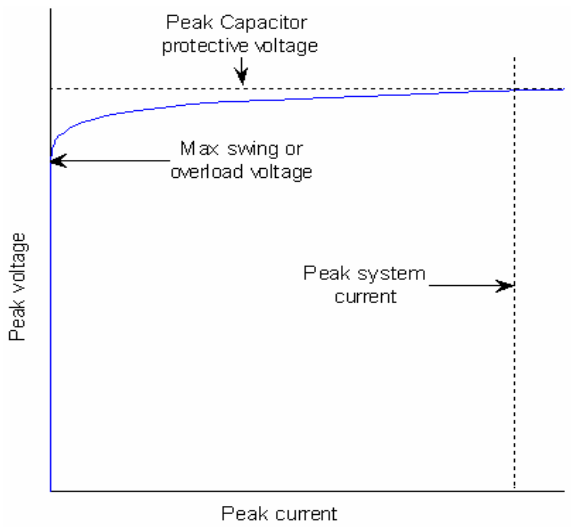


Fig. 5. Voltage-current characteristic of the MOV.

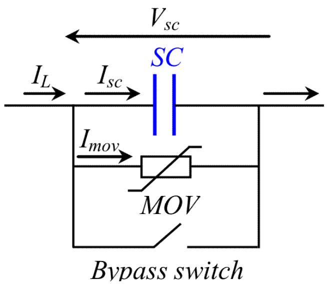


Fig. 6. Protection of the SC bank against overvoltages.

Goldsworthy [13] has introduced an equivalent series capacitive reactance and resistance of a MOV protected series capacitor as a function of normalized line current based on the capacitor's protective level current. The equivalent model is depicted in figure 7.

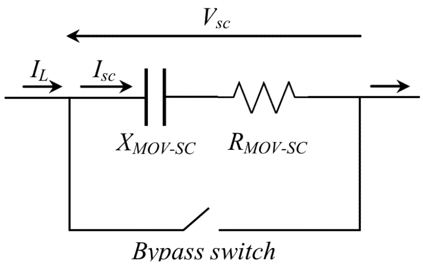


Fig. 7. Equivalent model.

The MOV-protected series capacitor equivalent model parameters under short-circuit currents can be determined by following equations (6) and (7) [17]:

$$R_{MOVSC} = X_{SC}\left(0,0745 + 0,49e^{-0,243.I_{pu}} - 35.e^{-5.I_{pu}} - 0,6e^{-1,4.I_{pu}}\right) \quad (6)$$

$$X_{MOVSC} = X_{SC}\left(0,1010 - 0,005749.I_{pu} + 2,088.e^{-0,8566.I_{pu}}\right) \quad (7)$$

Where, I_{pu} is fault current expressed in per unit of capacitor protective level current.

3. DISTANCE PROTECTION: PRINCIPLES AND SETTING

Distance protection is so called because it is based on an electrical measure of distance along a transmission line to a fault. The distance along the transmission line is directly proportional to the series electrical impedance of the transmission line. Impedance is defined as the ratio of voltage to current. Therefore, distance protection measures distance to a fault by means of a measured voltage to measured current ratio computation.

3.1. Measurement principles

The numerical distance protections relay uses to locate a fault on a distance measurement between the fault and the point where it is installed. It is determined through a measurement of X_d which ranges from 0,33 to 0,42 Ω per kilometer depending on the type of high-voltage line. This measure must be of a directed character. By taking into account the reactive part of the impedance Z_d between the fault point and the relay, can liberate the distance measurement from the R_F, in the presence of a fault as shown in figure 8.

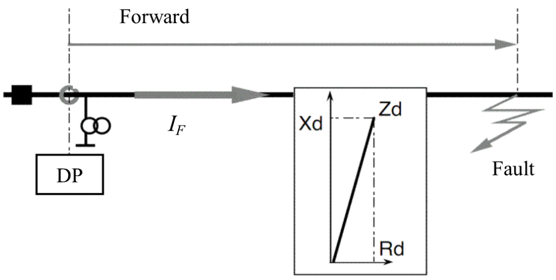


Fig. 8. Distance protection in the presence of fault.

3.2. Relation between times - distance

Time selectivity protection is given by the staggered trip time depending on the distance between measurement point and the fault.

Following the philosophy of setting the NDP in Sonelgaz group, three zones (Z_1, Z_2 and Z_3) have to be chosen as shown in figure.9. The first zone covers about 80% the protected line AB and tripped circuit breaker in t_1, the second zone extends 100% of the line protected AB+20% of the adjacent line is shorter and tripped circuit breaker in the t_2, the third zone extends

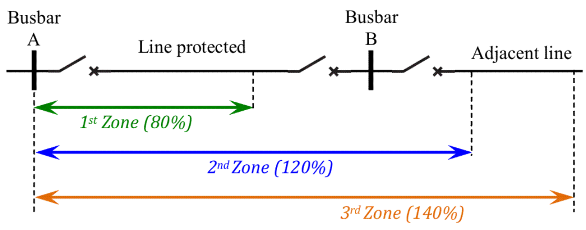


Fig. 9. Settings zones of the distance protection.

of 100% of the line protected AB+40% of the adjacent line is longer and tripped the circuit breaker in the t_3.

The trip delay is not possible for faults surely on the line. It is the role of measurement in the first zone, set at 80% of the reactance of the line. It triggers instantaneous. The trip must be ordered online for failure is the role of other zone settled more than 100% of the line, which then overflows to the first zone line adjacent to the position facing. The outbreak, called 2nd and 3rd stage, must be selectively controlled the 1st stage. The trip time t_1, t_2 and t_3 correspond to these four zones of operation and interval of different selective Δt are indicated in figure 10.

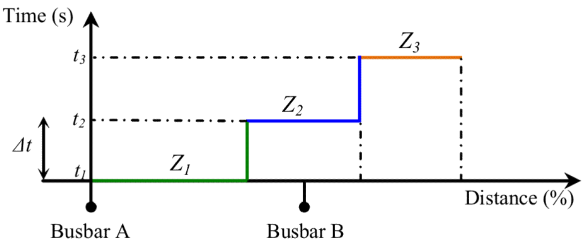


Fig. 10. Time selectivity for the distance protection.

3.3. Representation of the impedance operation

We place relay side NDP, the impedance of the relay is invariant whatever the type of fault: the characteristic is fixed. The relationship between it and the voltage, current is invariant, fixed by the constructor. However, the relationship between the impedance measurement and the direct impedance may vary with the type of fault if the relationship is strictly used in the corresponding for fault, direct representation of the impedance may change depending on the type fault.

Four types of characteristics of the curve $X=f(R)$ is: MHO, quadrilateral, polygonal and elliptical, but the relay digital NDP is based on two types first.

3.4. Numerical distance protection

The discreet signal processing and the numerical mode of measurement allow a higher accuracy and shorter tripping times with exact filter algorithms and the application of adaptive processes. Intelligent evaluation routines furthermore allow improved selectivity, even during complex fault situations. Over and above this the cost/performance ratio was dramatically improved [17].

The modern devices are multifunctional and thereby can implement the protection functions as well as additional function for other tasks such e.g. operational measurements and disturbance recordings. Only one device for main and one device for backup protection (when applied) are therefore required at each line end. By means of the integrated self-monitoring the transition from the expensive maintenance to the more cost effective condition maintenance and testing is achieved.

The numerical devices also allow for the operation with PC or the integration into network control system, via serial interfaces. Thereby several new aspects arise for the configuration, installation and maintenance.

3.5. Setting

The equation for calculating the impedance of the secondary is:

$$Z_{LV} = Z_{HV}.l = \left[\left(R_{HV} + jX_{HV}\right).l\right].\frac{k_{VT}}{k_{CT}} \qquad (8)$$

With, l: the total length of the line.

3.5.1. Without series compensation

Table I: The relay setting without SC.

	1^{st} *zone*	2^{nd} *zone*	3^{rd} *zone*
Percentage	80	120	140
X_i	$0{,}8.X_{LV}$	$1{,}2.X_{LV}$	$1{,}4.X_{LV}$
R_i	$0{,}8.R_{LV}$	$1{,}2.R_{LV}$	$1{,}4.R_{LV}$
Time (sec)	0,00	0,30	1,50

3.5.2. With series compensation

To determine the optimum reach of first zone, the decrease of the series reactance of the transmission line, caused by the capacitors inclusion, should be considered:

$$Z_L - j.X_C \qquad (9)$$

$$Z_{LV} = Z_{HV}.l = \left[R_{HV}.l + jX_{HV}.l - jX_c\right].\frac{k_{VT}}{k_{CT}} \qquad (10)$$

Table II: The relay setting with SC.

	1^{st} *zone*	2^{nd} *zone*	3^{rd} *zone*
Percentage	80	120	140
X_i	$0{,}8.X_{LV}$	$1{,}2.\ X_{LV}$	$1{,}4.X_{LV}$
R_i	$0{,}8.R_{LV}$	$1{,}2.R_{LV}$	$1{,}4.R_{LV}$
Time (sec)	0,00	0,30	1,50

4. PROTECTION CHALLENGES

The performance of the series compensated line protection depends very much on some of the followings subjects: system configuration, line loading, potential transformer location, polarization of the relay, technology and integration of line protection, teleprotection schemes, autoreclose, etc. Additionally, the protection engineer may face different challenges for this particular application, which can be mentioned as follows:

4.1. Current inversion

A classical problem that may occur in the protection of series compensated lines is the current inversion. The current inversion shall happen when the reactance of the series capacitor is bigger than the reactance of the source, if internal faults in the line are considered. This will cause difficulty for the distance protection to clearly identify the correct direction of the fault.

4.2. Voltage inversion

Another classic problem is the voltage inversion. The voltage inversion shall happen when the reactance of the series capacitor is bigger than the line reactance up to the point of fault. This will cause again difficulty for the distance protection to clearly identify the correct direction of the fault.

4.3. Non-linearity of the line impedance

In order to protect the series capacitor bank against transient over-voltages, the MOV is typically used. During the normal condition of the power system the MOV is not conducting. When a fault occurs the current in the series capacitor will increase, and so the voltage as well. When this voltage increases, the MOV starts conducting in order to protect the series capacitor. However, it should be noted that the MOV presents a non-linear behaviour, and the distance protection will see the measured impedance as a combination of RLC parameters. It must be mentioned that this behaviour depends very much on the level of fault current.

4.4. Protection challenges of SC network

A series compensating capacitor reduces the net fault impedance for all faults behind it; consequently such a fault appears closer to the relay depending on the amount of series compensation, fault current and the fault location. A comprehensive depiction of the effect of fault resistance and the MOV-series capacitor impedance characteristic on a distance relay is illustrated in figure 11 on the R-X plane.

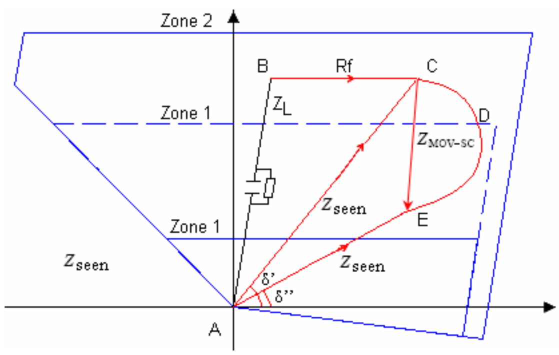


Fig. 11. The effect of R_F and MOV and series capacitor on the impedance seen by the relay.

The R_F shifts the impedance seen by the relay to the right and lowers the fault impedance angle to δ'. The MOV and series capacitor combination also reduces the impedance seen by the relay and lowers the fault impedance angle further to δ''. This shifting of the fault impedance seen by the relay could affect the relay's performance.

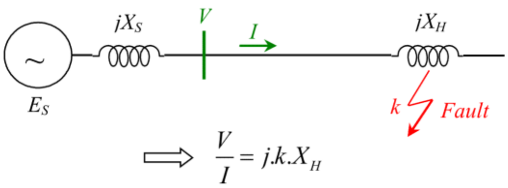
The first challenge is the dynamic changes that occur in the total impedance presented by the series capacitor and its protection devices. The unknown state of the series capacitor, whether it is in service, by-passed, or partly in service and partly by-passed, complicates the reach settings of zone 1 elements. If the capacitor is in service, over-reaching occurs and if the capacitor is by-passed, under-reaching occurs depending on the assumption made when setting zone elements.

The second challenge is the effect of series capacitor location and degree of compensation. The series capacitor can practically be located at the middle of the line, or at the line terminals. It is apparent that for a high degree of compensation and a fault close to the series capacitor, the net reactance seen by a relay could be capacitive. Since the relays are designed for inductive reactance, the relay would see such a fault in the reverse direction.

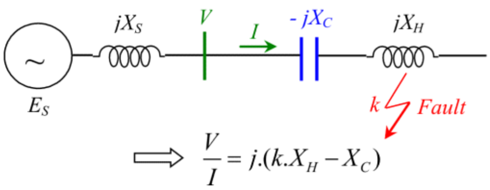
The third and obvious challenge is that the impedance seen by the relay is smaller than would be the case in an uncompensated line, and is no longer a true measure of distance to a fault, so that the relay overreaches the fault. These problems are compounded by the action of the devices used to protect the series capacitors themselves which dynamically alter the effective degree of series compensation during a fault [12]. Hence, restriction of the reactive and resistive reach of zone 1 is necessary (as illustrated by the dotted versus solid zone 1 polygons).

4.5. Effect of SC on impedance measurement

An important consideration is choice of the location of the voltage signal (or the potential source) on which the impedance measurement is based. With the compensation located at a terminal, the potential source for the impedance measurement could be obtained from either side of the series capacitor, i.e. the



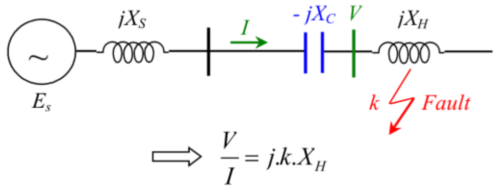
a). Inductive system.



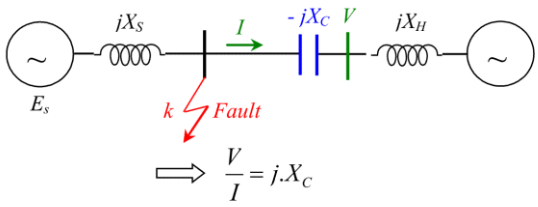
b). Capacitive system.

Fig. 12. Impedance measurement with bus side potential source.

bus side or the line side of the capacitor. Figures.12 and 13 compare the steady state measurements of impedance, as represented by ***V/I***, with the potential source on the bus side of the capacitor in figure 12 and on the line side in figure 13. In each of the cases illustrated in figures 12 and 13, the one line diagrams depict three-phase faults in system without load flow. Three phase faults, zero load flow as well as reactive impedances are assumed in these examples in order to simplify the representation [18].



a). Forward fault.



b). Reverse fault.

Fig. 13. Impedance measurement with line side potential source.

5. CASE STUDIES, SETTINGS AND RESULTS

The data for the 220 kV line studied in this case are summarized in the Annex. The following settings programmed distance relay MHO:

5.1. Without series compensated

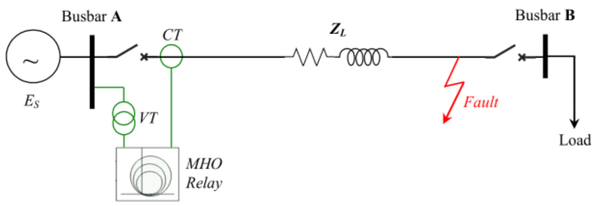


Fig. 14. Simplified power system model.

The proposed relay settings without SC are summarized in table III.

Table III: The relay setting without SC.

	1st zone	*2nd zone*	*3rd zone*
X (Ω)	51,0873	76,6309	89,4027
R (Ω)	13,2000	19,8000	23,1000
Time (sec)	0,00	0,30	1,50

5.2. With line-end series compensated

Figure 15 shows a line with sending end line compensation. For high current faults, the capacitor spark gap flashes and removes the capacitor from service. The relay measures the correct line impedance for a line-end fault (dashed line in Fig. 15). The dashed

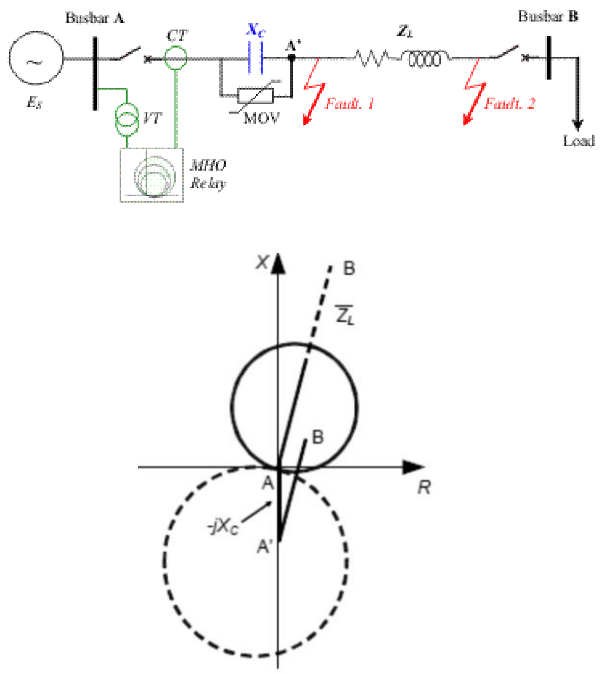


Fig. 15. Line transmission with sending end line compensation.

circle is the characteristic of a Zone 1 MHO element set to cover 90 percent of the line when the capacitor is out of service.

The proposed relay settings with SC are summarized in table IV.

Table IV: The relay setting with line end SC.

	1^st^ zone	*2^nd^ zone*	*3^rd^ zone*
X (Ω)	48,5418	72,8127	84,9482
R (Ω)	13,2000	19,8000	23,1000
Time (sec)	0,00	0,30	1,50

5.3. With mid-point line series compensated

The traditional solution is to set the MHO element to cover 90 percent of the line when the capacitor is in service (solid circle in figure 16). However, the zone 1 instantaneous coverage drops to approximately 50 percent of the line length for current faults (capacitor out of service) [20].

The effect of series capacitors on distance elements is more critical for capacitors located at the line ends than for mid line capacitors. Line-end capacitors do not only affect distance estimation [20]. They also affect directional discrimination because of voltage inversion. Mid-line capacitors do not affect directional discrimination unless the level of series compensation is very high.

Table V: The relay setting with mid-line SC.

	1^st^ zone	*2^nd^ zone*	*3^rd^ zone*
X (Ω)	48,5418	72,8127	84,9482
R (Ω)	13,2000	19,8000	23,1000
Time (sec)	0,00	0,30	1,50

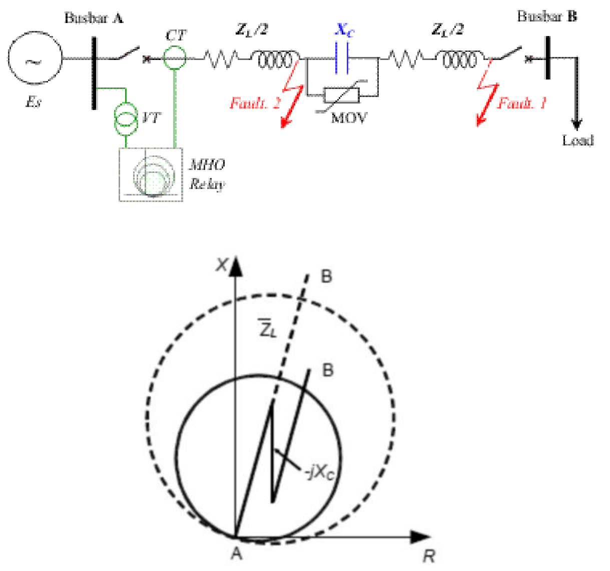


Fig. 16. Line transmission with mid- point line compensation.

We note that no change of setting protection on the MHO protection relay because the total impedance does not change the first zone.

6. CONCLUSION

This paper presents firstly a detailed model of a series capacitor used in power system. A calculation procedure of the apparent impedance of the series capacitor is outlined and explained. This article is addressing the change settings MHO distance relay protection with different point location on transmission 220 kV line high voltage such as sending end line and mid-point line series compensation.

As can be seen the effect of series capacitors on distance elements is more critical for capacitors located at the sending end line than the mid-point.

MONOCULTURES

X_T : Total uncompensated reactance
X_C : Series capacitor's compensation reactance
X_S : Source reactance at sending end
E_S : Source voltage at sending end
X_R : Source reactance at sending end
E_R : Source voltage at receiving end
$P_{W\text{-}SC}$: Power transfer with series capacitor
$P_{W/O\text{-}SC}$: Power transfer without series capacitor
R_{MOVSC} : MOVSC equivalent series resistance
X_{MOVSC} : MOVSC equivalent series reactance
$V_{L1, L2, L3}$: Line voltage
$V_{1, 2, 0}$: Symmetrical voltages
$I_{L1, L2, L3}$: Currents on line
$I_{1, 2, 0}$: Symmetrical currents
Z_i : Impedance of the zone i
t_i : Time zone i
k_{VT} : Voltage transformer ratio
k_{CT} : current transformer ratio
k_o : Ground impedance factors, equal to $(Z_0 - Z_1)/Z_1$
R_{HV}, X_{HV} : Primary resistance and reactance

R_{LV}, X_{LV} : Secondary resistance and reactance
R_F : Fault resistance
I_F : Fault current.

ANNEXES

Appendix A: TRANSMISSION Line Study

Nominal voltage: $U_n = 220$ *kV,*
Nominal frequency: $f = 50$ *Hz,*
Total length of the line: $l = 300$ *km,*
Line resistance: $R_L = 0{,}121$ *Ω/km,*
Line inductive reactance: $X_L = 0{,}423$ *Ω/km,*
Line capacity reactance: $X_{CL} = 0{,}0453$ *Ω/km.*

Appendix B: Series Compensation

Nominal voltage: $U_n = 220$ *kV,*
Maximum voltage: $U_{max} = 240$ *kV,*
Capacity reactance: $X_{sc} = 7{,}00$ *Ω,*
Capacity: $C_{sc} = 0{,}000455$ *F/phase,*
Reactive power: $Q_{sc} = 20{,}743$ *kVar*.

Appendix C: The Protection System

Primary current: $I_{CT1} = 2000$ *A,*
Secondary current: $I_{CT2} = 1$ *A.*
Primary voltage: $V_{VT1} = 220000$ *V,*
Secondary voltage: $V_{VT2} = 100$ *V.*
Type of extinction: *SF6,*
Nominal current: *2500 A.*

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