Impact of Series Compensation Insertion in Double HV Transmission Line on the Settings of Distance Protection

ZELLAGUI Mohamed, CHAGHI Abdelaziz

Abstract - This paper presents a study of the performance of distance protection relays when series compensation (SC) is inserted on double circuit transmission line high voltage (HV) 400 kV in Algeria (Group Sonelgaz). The relays setting for distance protection is considered as a great challenge to power system protection engineers. Special considerations on the transmission line impedance measurement are necessary in the application of distance protection. The studies also include different challenges which the protection engineer may face such as current and voltage inversion, non-linearity of the line impedance. A detailed modeling of SC is proposed and integrated in transmission system for five case studies in different point locations on transmission line. The proposed results dealing with distance relays protection setting are performed in MATLAB software environment, for different cases.

Index Terms - Distance protection, Double transmission line, High voltage, Fault, Relay, Series compensation.

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1 INTRODUCTION

NOWADAYS the fixed series compensations are commonly used for better utilization on the existing power transmission systems. It is presented as the best choice, because not only does it increase power transmission capacity but also it stabilizes interconnected networks by reducing transmission line impedance. Series compensating capacitors were initially introduced in transmission networks mainly to increase the power transfer capacity of long transmission lines. These series compensating capacitors have brought with them significant protection challenges for relay manufacturers, utility engineers and researchers [1, 2].

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 Protection of SC power transmission lines demands a special care when choosing the protection scheme and numeric protective relay settings, due to the effects on the numeric distance measurements [3]. The dynamic performance of a heavily series compensated network's protection depends on the reliability of the installed relay technology. The transient behavior of a heavily series compensated network during faults is complex to comprehend analytically, but the network needs fast acting protection against faults and abnormal system conditions to maintain power system stability and reliability of supply. The degree of complexity depends on the degree of compensation and the location of the series capacitor. SC introduced additional challenges over well known protection challenges on HV transmission networks. These challenges must be considered carefully when setting numerical distance protection relays.

Protection of the parallel transmission lines is subject to additional problems over that of single circuits. The performance of the relays is affected by the mutual coupling between lines. Due to the mutual coupling effect, the high frequency components induced on the healthy circuit due to a fault on the faulted circuit can be quite significant and thus can lead them into a wrong trip of the healthy circuit [5, 6].

2 FIXED SERIES COMPENSATION

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 [7]:

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

$$P_R = E_R.I_L \cos(\varphi_R) \quad (2)$$

$$Q_R = E_R.I_L \sin(\varphi_R) \quad (3)$$

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Therefore:

$$\Delta V = \frac{P_R.R_L + Q_R.(X_L - X_C)}{E_R} \tag{4}$$

Equation 4 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 voltage at the loads downstream from the series capacitor. Figure 1 shows the influence of the series capacitor on the voltage profile for a radial power distribution line with inductive loads.

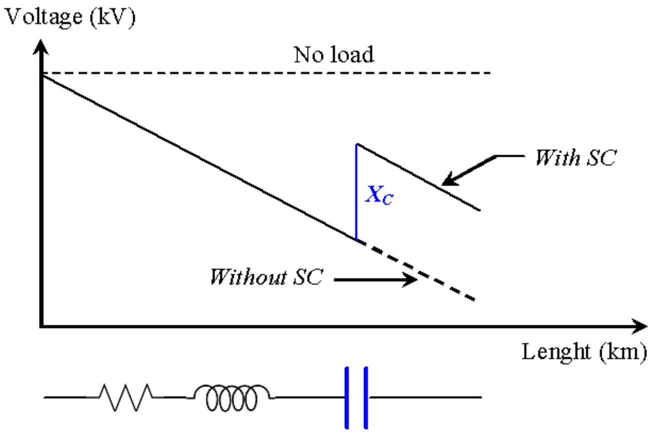


Fig. 1. Voltage profile for a radial circuit with series capacitor.

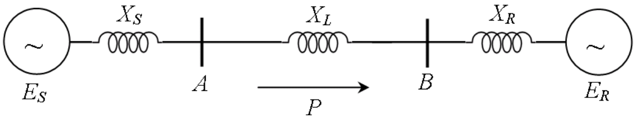
2.1 Power Transfer

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.2.a without series capacitor and figure.2.b with series capacitor.

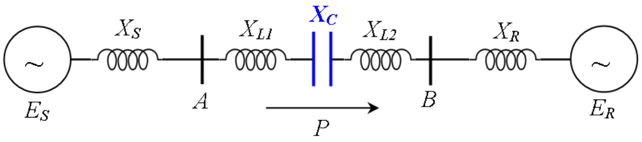
The active power *P* transferred by the uncompensated and compensated transmission lines are computed using equations (5) and (6) respectively:

$$P = \frac{E_s.E_r}{X_T}\sin(\delta) \tag{5}$$

$$P = \frac{E_s.E_r}{X_T - X_C}\sin(\delta) \tag{6}$$



(a)



(b)

Fig. 1. Voltage profile for a radial circuit
a). Without SC, b). With SC.

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. 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 [7]. 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. However, these benefits also bring with them significant transmission line protection challenges, particularly in heavily SC networks

2.2 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. [7, 8, 9]. 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 SC during a fault, due to the non-linear impedance characteristics of the parallel MOV-series capacitor combination [9].

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. Goldsworthy [10] 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 (Fig. 3).

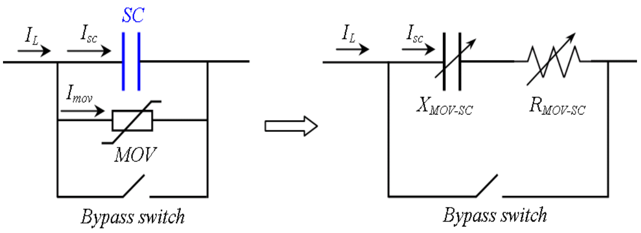


Fig. 3. MOV equivalent model.

3 DISTANCE PROTECTION ZONES AND SETTINGS

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 4.

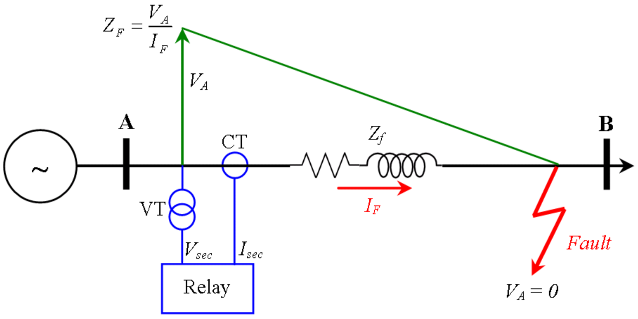


Fig. 4. Principle of operation of distance protection.

The input to the relay point is the phase voltages and line currents transformed with the help of voltage and current transformers. When a fault occurs on the protected line the fault current and voltage is fed to the protection. The voltage would fall towards zero at the point of the fault. The voltage drop along the line is equal to the product of the fault current I_F and the impedance fault Z_F.

3.1 Selectivity Protection

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 distance protection in Sonelgaz group, three zones (Z_1, Z_2 and Z_3) have to be chosen as shown in figure 5. 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 of 100% of the line protected AB+40% of the adjacent line is longer and tripped the circuit breaker in the T_3 are indicated in figure 5.

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 instantaneously. 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.

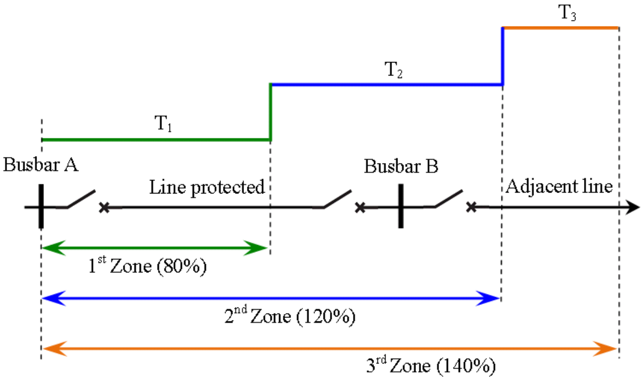


Fig. 5. Settings zones and selectivity.

We place relay side distance protection, 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.

3.2 Setting of Relay

The equation for calculating the impedance of the secondary is without SC is:

$$Z_{LV} = Z_{HV}.l = \left[\left(R_{HV} + jX_{HV}\right).l\right].\frac{k_{VT}}{k_{CT}} \tag{7}$$

With SC, 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:

$$Z_{LV} = Z_{HV}.l = \left[R_{HV}.l + jX_{HV}.l - jX_c\right].\frac{k_{VT}}{k_{CT}} \tag{8}$$

First zone:

Percentage 80% of line protected

$$Z_1 = 0{,}8\ Z_{LV} = R_1 + j.X_1 \quad (9)$$

$T_1 = 0$ seconds (instant).

Second zone:

Percentage 120% of line protected

$$Z_2 = 1{,}2\ Z_{LV} = R_2 + j.X_2 \quad (10)$$

$T_2 = 0{,}30$ seconds.

Third zone:

Percentage 140% of line protected

$$Z_3 = 1{,}4\ Z_{LV} = R_3 + j.X_3 \quad (11)$$

$T_3 = 1{,}50$ seconds.

4 DISTANCE RELAY PROBLEMS

The phenomena that influence the performance of distance protections in series compensated systems are described as follows.

4.1 Current and Voltage Inversion

Voltage reversal effect is presented when the apparent impedance between the relay location and the fault point, within the protected line, is mainly capacitive, as a result of the capacitor bank influence. Under these conditions the voltage seen by the protection will be in antiphase to the source voltage as may be observed in figure 6. On the other hand, the current reversal phenomenon is presented when the total impedance between the source and the fault point is mainly capacitive [11].

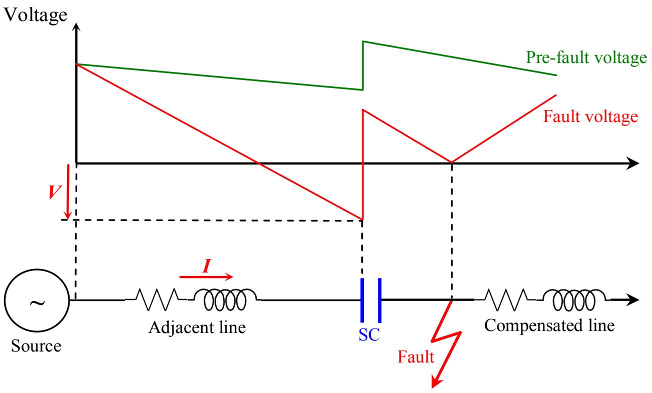


Fig. 6. Voltage profile considering series capacitor effect.

4.2 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.

4.3 Protection Challenges

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 7 on the R-X plane. The RF 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 [11].

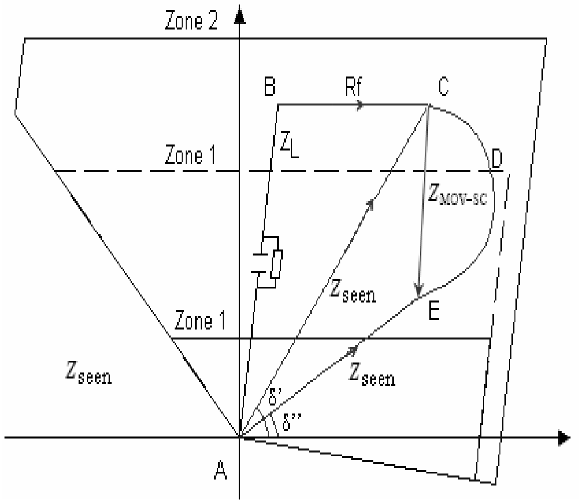


Fig. 7. The effect of R_F and series capacitor on the impedance seen by the relay.

4.3 Impact on Double Circuit Lines

For the impedance measurement, the current measured does not reflect the effect of mutual coupling and depending on the direction of the current flow in the circuit the relay's measured impedance could underreach or overreach. Reversal Current occurs when the current in the healthy line can reverse for a time of short period.

This occurs when a fault clears sequentially on one circuit of a double circuit line with sources at both ends of the circuit. If a permissive overreach or blocking type communication aided distance scheme is used, unwanted tripping of current breaker on the line can occur. The distance relay will under-reach if a fault occurs on a line that lies beyond the remote terminal end of a parallel line circuit. The relay only sees 50 % of the total fault current for a fault in the adjacent line section. Besides this the relay sees the impedance of the affected section as twice the correct value. It is not necessary to adjust second zone impedance setting to compensate since minimum reach of zone 2 is to the end of protected line section and under-reach effect only occurs for the fault in the following line section. Conversely, under-reach effect must be allowed in zone 3 impedance calculation since zone 3 is to provide back-up protection to the adjacent line [12].

5 CASE STUDY: SETTING AND DISCUSSION

When overhead lines follow parallel path, a mutual, inductive coupling of the current paths exists. In the case of transposed lines, this effect in the positive and negative sequence system may be neglected for all practical purposes (mutual reactance less than 5% of the self impedance). This implies that during load conditions and for all short-circuits without earth, the lines may be considered as independent. For this summated current, a fictitious summation conductor is placed at the geometrical centre of the phase-conductors models the three-phase system as shown in Figure. 8.

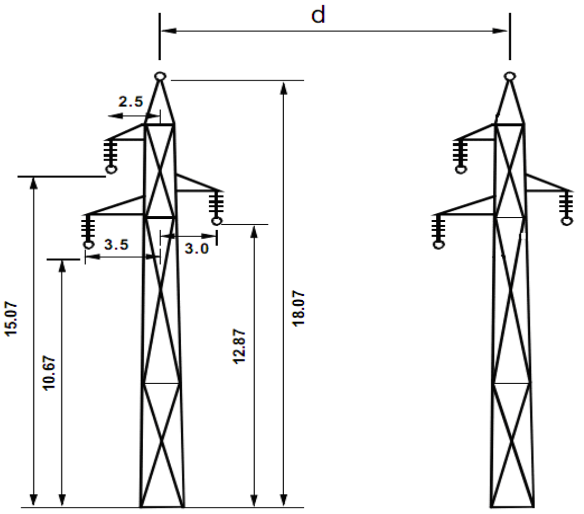


Fig. 8. Geometry for double transmission line studied.

The data for the 400 kV, 129 km double transmission line studied in this case are summarized in the Annex. The relays setting with and without fixed SC simulated in MATLAB software environment are presented.

5.1 Case N°1: Without Series Compensation

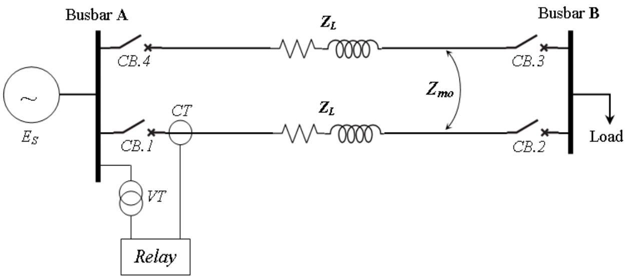


Fig. 9. Double transmission line without SC.

The proposed relay settings for zone protection (Z_1, Z_2 and Z_3) without SC on transmission line high voltage protected summarized in table 1.

TABLE 1
SETTING RELAY WITHOUT SC.

Zone	X_i (Ω)	R_i (Ω)	Time (sec)
1st Zone	24,7066	1,3594	0,00
2nd Zone	37,0599	2,0390	0,30
3rd Zone	43,2365	2,3789	1,50

5.2 Case N°2: With Line-end Series Compensation

Figure 10 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.

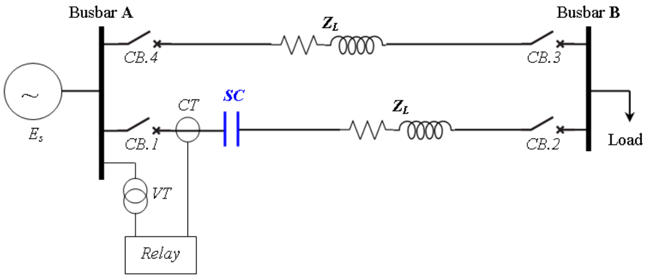


Fig. 10. Line transmission with sending end line SC.

The proposed relay settings for zone protection with line end SC is summarized in table II:

TABLE 2
Setting Relay With Line End SC.

Zone	X_i (Ω)	R_i (Ω)	Time (sec)
1st Zone	21,6666	1,3594	0,00
2nd Zone	32,4999	2,0390	0,30
3rd Zone	37,9165	2,3789	1,50

5.3 Case N° 3: With Mid-point Line Series Compensationws

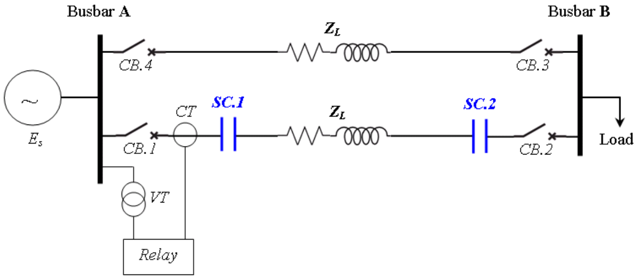


Fig. 12. Transmission line with both end SC line.

The proposed relay settings for zone protection with both end SC line is summarized in table 3.

TABLE 3
SETTING RELAY ITH BOTH END SC LINE.

Zone	X_i (Ω)	R_i (Ω)	Time (sec)
1st Zone	18,6266	1,3594	0,00
2nd Zone	27,9399	2,0390	0,30
3rd Zone	32,5965	2,3789	1,50

5.4 Interpretation

Resistance value setting for the three protection zones (Ri) is constant because any change on the line for the different cases studied. For the first and third case study the reactance value setting (X_i) for the three protection zones is the same because the value is the same X_{SC}.

The selected delay is fixed for different case a study is by select Sonelgaz Groups.

5 CONCLUSION

This paper evaluates the performance of a relay model and distance protection on a 400 kV double circuit transmission line in Algeria (Group Sonelgaz). A detailed model of an SC is presented. A calculation procedure of the apparent impedance of the series capacitor is outlined and explained.

This article is addressing the change settings distance relay protection with different point location on transmission line 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.

6 Appendix

Apprendix A: Double Transmission Line Study

Voltage = 400 kV
Number of circuit = 2
Frequency = 50 Hz
Length = 129 km
Cross section = ACSR, 954 MCM
R_1 = 0,03293 Ω/km
X_1 = 0,3184 Ω/km
R_0 = 0,2587 Ω/km
X_0 = 1,1740 Ω/km
R_{om} = 0,2262 Ω/km *
X_{om} = 0,7568 Ω/km *
B_1 = 3,5700 μmhos/km
B_o= 2,1680 μmhos/km
B_{om} = 0,5762 μmhos/km*

* Mutual zero sequence quantities between the two circuits.

Apprendix B: Series Compensation

$X_{MOV\text{-}SC}$ = 9,5 Ω
$R_{MOV\text{-}SC}$ is neglect
Q_{sc} = 50,52 Mvar

Apprendix C: The Protection System

C.1. Voltage Transformer

Primary voltage = $400000/\sqrt{3}\ V$
Secondary voltage = $100/\sqrt{3}\ V$
Voltage transformer ratio = 4000
Rated output = 100 VA
Class of precision = 3P10

C.2. Current Transformer

Primary current = 1600 A
Secondary current = 1 A
Current transformer ratio = 1600
Rated output = 60 VA
Class of precision = 5P20

7 NOMENCLATURE

X_T : Total uncompensated reactance
X_C : Series capacitor's compensation reactance
X_S : Source reactance at the sending end
E_S : Source voltage at the sending end
X_R : Source reactance at the sending end
E_R : Source voltage at receiving end
R_{MOVSC} : Equivalent series resistance
X_{MOVSC} : Equivalent series reactance

Z_{MO} : Mutual impedance
$V_{L1, L2, L3}$: Line voltage
$I_{L1, L2, L3}$: Currents on line
l : Total length of the line
X_i : Reactance of the zone i
R_i : Resistance of the zone i
T_i : Time zone i
k_{VT} : Voltage transformer ratio
k_{CT} : Current transformer ratio
R_{HV}, X_{HV} : Primary resistance and reactance
R_{LV}, X_{LV} : Secondary resistance and reactance
R_F : Fault resistance
I_F : Fault current.

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BIOGRAPHY

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