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The Impact of Current Inversion on Line Protection in High Voltage Transmission Lines with Series Compensation

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***Abstract*—Series capacitors are used in some transmission lines to raise the power transfer limit. If a fault occurs at a location behind which the total reactance is capacitive, the result is current inversion, also known as current reversal. In a current inversion, current leads the voltage instead of lagging it. The probability of current inversion increases with higher levels of compensation. In this paper, the effect of current inversion is studied in distance and differential protection of transmission lines. A 500 kV transmission line is modelled, with compensation levels of 70%, 100% and 140%. Phase to ground faults are applied with fault inception angles of 0°, 60° and 90°. It is shown that current inversion can cause serious problems with distance protection. Differential protection is not severely affected by current inversion. The protection schemes are significantly influenced by parameters of the capacitor bank overvoltage protection components, particularly the metal-oxide varistor.**

***Index Terms*—Series Compensation, Current Inversion, Distance Protection, Differential Protection**

I. INTRODUCTION

In power transmission lines, compensation devices are used to control and change line parameters. They are broadly divided into two categories: series and shunt compensation. The simplest form of series compensation is done by connecting a fixed capacitor in series with the transmission line [1], [2]. Figure 1 shows a single line diagram of a series compensation arrangement in a transmission line. Bus S is the sending and bus R is the receiving end. A series capacitor is shown at the sending end.

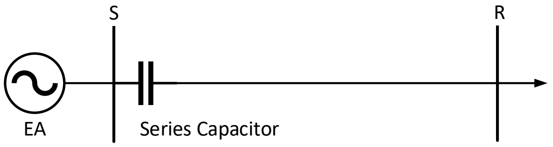

Figure 1. Fixed series capacitor in a transmission line

Series capacitor compensation reduces a line's net impedance, by providing capacitive reactance in series with the line's inductive reactance. The compensation level is defined as the proportion of the line's inductive reactance that is compensated by the capacitive reactance, as expressed by (1),

$$k = \frac{X_C}{X_L} \tag{1}$$

where X_C and X_L are the reactance of the series capacitor and transmission line. It is usually expressed as a percentage.

Reduction of net impedance by series compensation allows the line to carry more current, and therefore more active power [1]. This gives the benefits of higher thermal limits on power transfer, and lower losses. It also gives further benefits for voltage-collapse limit, voltage regulation, reactive power balance and first swing stability [3], [4]. The use of series compensation in the power transmission system has a long history, and it is expected to increase in the future [3], [5].

The benefits of using a series capacitor compensation are accompanied by some challenges in line protection. The introduction of a series capacitor necessarily changes the characteristic of the line. During fault conditions in a series compensated line, some special phenomena can occur, one of which is current inversion or current reversal [1], [2]. Current inversion means that the angle of the current changes abruptly, and leads the voltage instead of lagging it [2], [4]. As shown in Figure 2, in the pre-fault condition the voltage (V_{pre}) leads the pre-fault current (I_{pre}). However, in case of current inversion the fault current (I_{fault}) changes abruptly and leads the fault voltage (V_{fault}). Current inversion happens whenever the line becomes net capacitive from the fault to the source [4]. Therefore, it is dependent on the line parameters, fault type, fault impedance, fault position and source parameters. If X_C, X_S and X_L are the reactances of the capacitor, source and line, then current inversion will occur if the condition in (2) is fulfilled. Here, x is the proportion of the fault distance along the line from the relay.

$$X_C > (X_S + x \cdot X_L) \tag{2}$$

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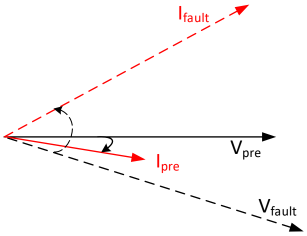

Figure 2. Phasor diagram for current inversion

Traditionally, current inversion has not been a major challenge in line protection. However, with increasing levels of series compensation in the transmission lines, the probability of current inversion increases. Therefore, for high levels of series compensation, it is important to study in detail the effect of current inversion on line protection.

Transmission lines are usually protected using distance or current-differential protection schemes [6]. Distance protection estimates the fault position on the line based on an impedance calculated from voltage and current measurements [6]. In principle, distance protection can work with purely local measurements. Differential protection compares the current measurements from the two ends of the line [6]. In normal conditions, the current going from the sending bus should be equal to the current going in the receiving bus, if the capacitive leakage current can be neglected, but during a fault these two currents mismatch.

Previous studies of the effect of series compensation on transmission line protection have focused predominantly on compensation levels of 70% and lower [4], [7]. At low levels of compensation, current inversion does not pose a major issue. However, with increased compensation, current inversion occurs for faults in an increased amount of line, possibly even beyond the receiving end of the compensated line. Therefore, there is a need for studying the effect of current inversion on transmission line protection with higher levels of compensation. The objective this paper is to show the impact of current inversion on distance protection and line differential protection in a long transmission line with high levels of series compensation. Compensation levels of 0%(uncompensated), 70%, 100% and 140% are used in this study. The uncompensated line is included as a reference for comparison. Overcompensated lines, those with more than 100% compensation, are not commonly studied in the literature. However, some transmission utilities already have overcompensated lines in their networks. This often happens due to splitting up an under-compensated line for practical reasons such as connecting new power plants or new loads. For this reason a line with compensation level of 140% is included in the study.

II. METHODOLOGY

The study is conducted by building a model of a 500 kV transmission line in PSCAD/EMTDC [8]. The voltage level of 500 kV is selected as it is a very common voltage level in transmission systems worldwide [1], [2]. The parameters used for the source and receiving ends are shown in Table I. The parameters used for the line are shown in Table II. The conductor data is taken from Svenska kraftnät (Swedish transmission system operator) guideline for transmission line conductors [9].

Table I
SOURCE PARAMETERS

Source	Voltage(kV)	Positive Sequence Impedance (Ω)	Zero Sequence Impedance (Ω)
Sending	$500\angle 25^\circ$	$5\angle 85^\circ$	$15\angle 85^\circ$
Receiving	$475\angle -15^\circ$	$50\angle 85^\circ$	$150\angle 85^\circ$

Table II
TRANSMISSION LINE PARAMETERS

Parameter	Value
Line length	200 km
Conductor	
Type	454,AL59 all aluminium alloy conductor (AAAC)
Geometric mean radius	13.85 mm
DC resistance	0.06532 Ω/km
Strands	61
Strand radius	1.54 mm
Relative permeability	1.0
Sag	12 m
Height	22 m
Sub-conductor	4
Sub-conductor spacing	0.4572 m
Ground wire	
Number	2
Radius	5.5245 mm
DC resistance	2.8645 Ω/km
Relative permeability	1.0
Sag	10 m
Height	10 m
Impedance	
Positive sequence	$0.0172 + j0.285$ Ω/km
Zero sequence	$0.265 + j0.963$ Ω/km
Compensation	
70%	79.8 µF
100%	55.9 µF
140%	39.9 µF

Series capacitors are usually located at a line's terminal or in the middle of the line. Location at a terminal is more common [1], [2]. In the system model used in this study, the capacitor is located at the sending-end bus S, as shown in Figure 1. The relay that is analysed is also at bus S, and the local current and voltage transformers are assumed to be on the bus side of the series capacitor at bus S. Capacitor banks are protected against overvoltage by metal oxide varistors (MOV). The highly non-linear characteristics of MOV allows to protect the capacitor.

The capacitor bank protection configuration used in this study is shown in Figure 3. A bypass circuit breaker, current limiting inductor and resistor are connected in parallel with the MOV. In normal conditions, the line's current flows through the capacitor. During fault conditions with a high voltage across the capacitor, the MOV starts to conduct. The bypass breaker is used to protect the capacitor and MOV. According to pre-set conditions, during a fault, the bypass circuit breaker closes to take the capacitor bank out of the fault loop. If the current through the MOV is very high or if the MOV conducts for a long time (accumulating energy), then the bypass is used to create a short circuit across the capacitor bank. In this paper, for each compensation level, appropriate current and energy levels are set for the MOV for triggering the bypass breaker.

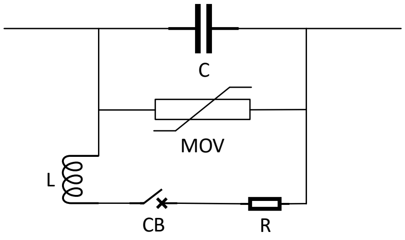

Figure 3. Configuration of the capacitor bank protection

Simulations are run for a fault occurring at different positions along the line. A single-phase to ground fault is chosen, as it is the most common fault in transmission systems [6]. Fault inception angles of 0°, 60° and 90° are used. Series compensation levels of 70%, 100% and 140% are used, and also an uncompensated line for comparison. The scenarios simulated in this paper are shown in the Table III. The simulation results are processed by Matlab programs to show how both distance and differential protection would react. Distance protection evaluation is done by showing the fault trajectory in the R-X plane. Differential protection evaluation is done by showing the fault trajectory of operating current (differential current) versus restraining current, where the restraining current is the average of the current magnitudes at the two terminals of the line.

Table III
SCENARIOS

Protection Scheme	Fault Angle	Distance
Distance	0°	1 km
Distance	60°	1 km
Distance	90°	1 km
Distance	0°	150 km
Distance	60°	150 km
Distance	90°	150 km
Differential	0°	1 km
Differential	60°	1 km
Differential	90°	1 km
Differential	0°	150 km
Differential	60°	150 km
Differential	90°	150 km

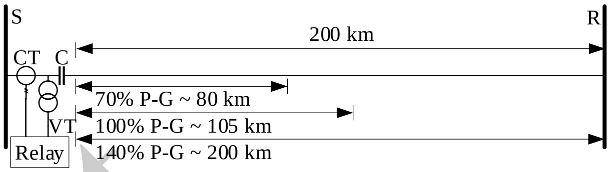

Figure 4. Current inversion prone line segments for phase-ground fault for different compensation levels

III. RESULTS & DISCUSSION

In Figure 4, the line segment where a phase to ground fault results in current inversion at the relay in bus S is shown for different compensation levels. As expected, the line segment affected by current inversion increases with higher compensation levels. In case of the 140% compensated line, a fault at any location along the line will cause a current inversion in the current measured at bus S. It is important to keep in mind that the current-inversion condition will only occur while the fault current is passing through the capacitor. In reality, during a fault, as voltage builds up across the series capacitor, the MOV starts to conduct. Higher current or energy accumulation in the MOV will activate the bypass circuit breaker, effectively taking the capacitor out of the fault loop. The MOV and bypass breaker control in different simulation configurations are designed to operate the bypass circuit breaker in high current and high energy accumulation. In each fault-trajectory figure, bypass circuit breaker conduction is marked separately with dashed lines. The trajectory before the bypass breaker closes is shown with solid lines. This separation helps to show the effect of current inversion, MOV conduction and bypass breaker operation. The fault trajectory for the uncompensated line is also added in each figure for ease of comparison. The time tags associated with each trajectory indicate the trip time. This is the time required after inception of the fault, for the fault trajectory to settle inside the operating region, which is zone 1 for the distance relay, and the trip boundary for the differential relay. After the trajectory enters an operating region, the relay waits 5 ms for tracking the trajectory values; if the values settle to a steady state, then the relay issues a trip signal.

A. Distance Protection

Figures 5, 6 and 7 show the distance relay fault trajectories for a fault 1 km from bus S and the series capacitor for fault inception at 0°, 60° and 90° respectively for different compensation levels. The fault is 1 km from the bus, therefore for all levels of compensation the capacitive reactance is high compared to the sum of the source and line reactance up to the fault, and the condition in (2) is satisfied. Thus, at all levels of compensation, current inversion is experienced by the relay during a solid fault at 1 km from bus S. This

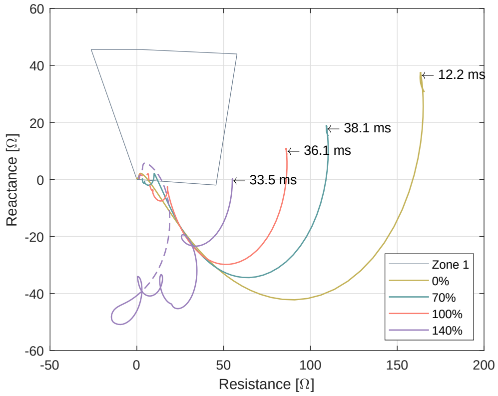

Figure 5. Distance relay fault trajectory for fault at 1 km from bus S, fault inception angle 0°

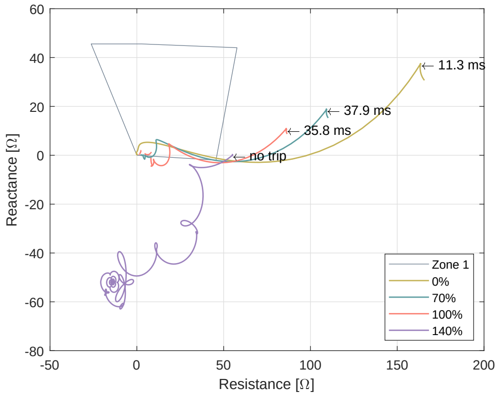

Figure 6. Distance relay fault trajectory for fault at 1 km from bus S, fault inception angle 60°

is observed from the solid lines in the fault trajectory in both Figure 5, 6 and 7. The fault trajectories in all figures go in the capacitive region in the R-X plane. The dashed portion of trajectory represents the bypass breaker being in the closed state, removing the capacitor from the fault loop. After the bypass breaker closes, all fault trajectories converge to the same as for the uncompensated line. The delay for breaker closing depends on MOV settings. The exception in these three figures is the 140% compensated case with 60° and 90° inception angle. The higher compensation leads to a high capacitive reactance, and in these cases, the fault current is very low and does not pass through the MOV. If the MOV voltage threshold is reduced to make it more sensitive, the normal load current would start flowing through the MOV which is undesirable. The trip time is longer for all compensated cases compared to the uncompensated line. The trajectories for compensated lines settle in zone 1 when the bypass breaker closes. For 60° and 90° inception angles the fault trajectories enter the zone 1 briefly, then exit it. Trip time for the compensated cases is dependent on the MOV's limits of current and energy.

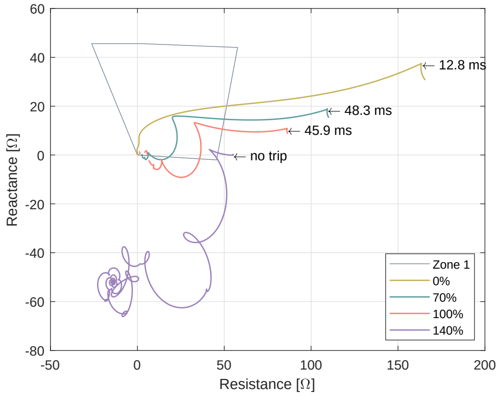

Figure 7. Distance relay fault trajectory for fault at 1 km from bus S, fault inception angle 90°

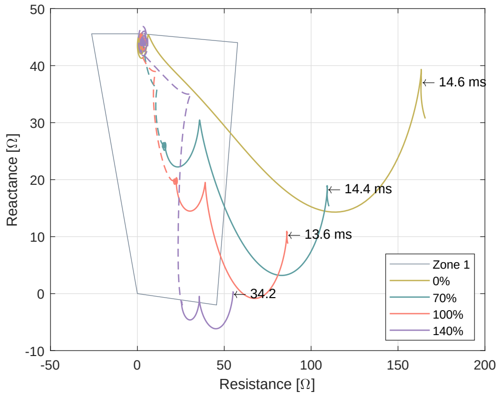

Figure 8. Distance relay fault trajectory for fault at 150 km from bus S, fault inception angle 0°

Figures 8, 9 and 10 show the distance relay trajectory in the R-X plane for faults far from bus S (150 km). The uncompensated line trajectory in Figure 10 takes a longer time due to the inception angle. In all cases, 70% and 100% compensated lines do not experience a current inversion, so their trajectories enter zone 1 before the bypass breaker closes. The trip times for these two cases are similar to the uncompensated line. However, the 140% compensated line experiences current inversion and the trajectory only moves in zone 1 with the bypass breaker operation. This causes a longer trip time. All trajectories converge to the uncompensated line with the bypass operating. However, some oscillation of the fault trajectories of the compensated lines can be observed. Zone 1 is set to 80%: the fault at 150 km is at the end of zone 1, but such oscillations can make distance relay over-reach or under-reach. This is a further problem with distance protection in compensated lines.

B. Differential Protection

The same fault scenarios are also used to evaluate current differential protection. Comparison graphs of operating current (I_o) versus restraining current (I_r) are used in evaluating dif-

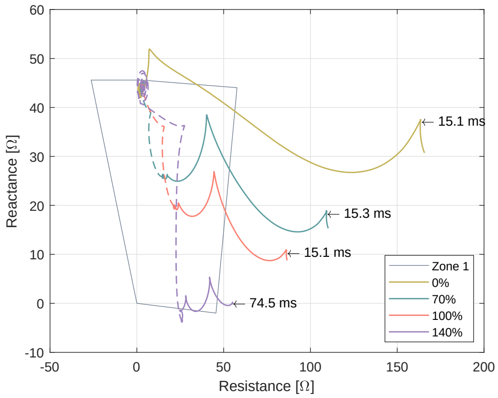

Figure 9. Distance relay fault trajectory for fault at 150 km from bus S, fault inception angle 60°

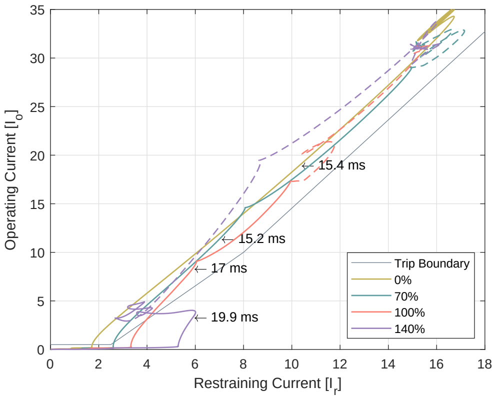

Figure 11. Differential relay fault trajectory for fault at 1 km from bus S, fault inception angle 0°

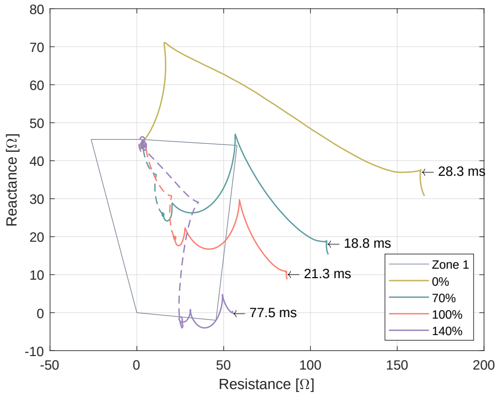

Figure 10. Distance relay fault trajectory for fault at 150 km from bus S, fault inception angle 90°

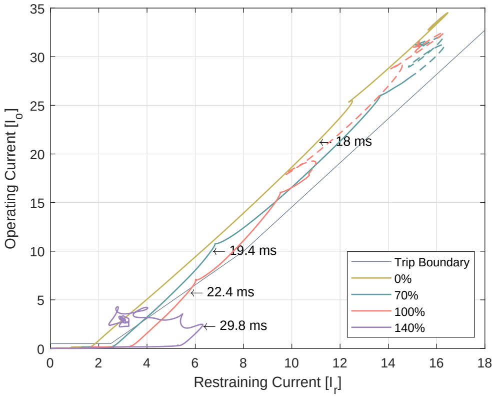

Figure 12. Differential relay fault trajectory for fault at 1 km from bus S, fault inception angle 60°

ferential protection. A generic three-stage trip boundary is used to measure trip times for different cases. Figures 11, 12 and 13 show the operating and restraining current trajectories for a fault at 1 km from bus S, with fault inception angles of 0°, 60° and 90° respectively. All fault trajectories converge in a similar region after the bypass circuit breaker closes and removes the capacitor from the fault loop. Trip times generally tend to increases with compensation level. The fault at 1 km from the capacitor results in high currents. Unlike distance protection, all trajectories enter the operating region (left side of the trip boundary) before the bypass breaker operates. With 140% compensation and 60° and 90° inception angle, the bypass breaker is not activated, and the trajectory therefore takes a longer time to cross the trip boundary. However, there is no case of failure to trip with the differential protection. Some oscillating behaviour is observed with higher compensation levels, which also (depending on the setting) can cause a delay in the differential relay's operation. Current inversion happens in all the compensated lines with a fault 1 km from bus S, but in the differential relay it does not cause a failure to trip. Depending on the setting higher levels of compensation can cause delay in relay operation. This is largely due to the big difference between the source and receiving end impedances of the system. The source impedance is much lower than the receiving end impedance, therefore, fault currents from both ends vary in magnitude. For this reason, regardless of the level of compensation, settings can be made for differential relays to operate.

Figures 14, 15 and 16 show the plots of operating and restraining current for a fault at 150 km from bus S for fault inception angles of 0°, 60° and 90° respectively. At this location, compensation levels of 70% and 100% do not cause current inversion, but at 140% compensation current inversion occurs. The current inversion also does not cause an issue for the differential protection here. Before the bypass circuit breaker is activated, the trajectory oscillates and does not converge to the characteristic of the uncompensated line. Concerning the relay settings used here, fault trajectories for 70% and 100% compensation enter the operating region (cross the trip boundary) before the bypass breaker operates, but for 140% compensation the trajectory crosses the trip boundary after bypass breaker operation. However, this is dependent

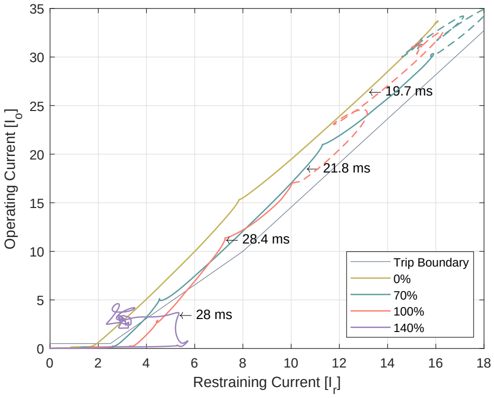

Figure 13. Differential relay fault trajectory for fault at 1 km from bus S, fault inception angle 90°

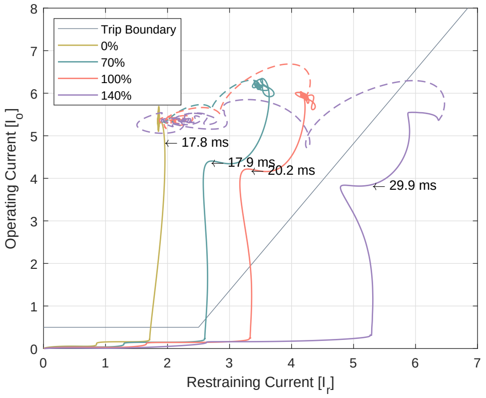

Figure 14. Differential relay fault trajectory for fault at 150 km from bus S, fault angle inception 0°

on the settings chosen in this study. The trip boundary can be modified to take care of this. Trip time is longer for 140% compensation in all cases. The effect of different fault inception angles is not pronounced in differential protection.

IV. CONCLUSION

The simulation results demonstrate the problems of distance protection with higher levels of compensation. The line segment where a fault causes current inversion increases with high levels of series compensation. Without the operation of the bypass circuit breaker, the traditional distance relay has a high probability of failing to pick up faults in case of current inversion conditions. Differential protection is not affected by current inversion conditions to such an extent. Settings for differential relays can be modified to accommodate high levels of series compensation. High levels of compensation cause a delay in operation of both distance and differential relays, but more severely for distance relays. For examples from Figure 10 and Figure 16, the trip time for 140% compensation compared to the uncompensated line is 2.75 time as long for the distance relay, and 1.7 as long for the differential relay. MOV parameter and control of the bypass circuit breaker for

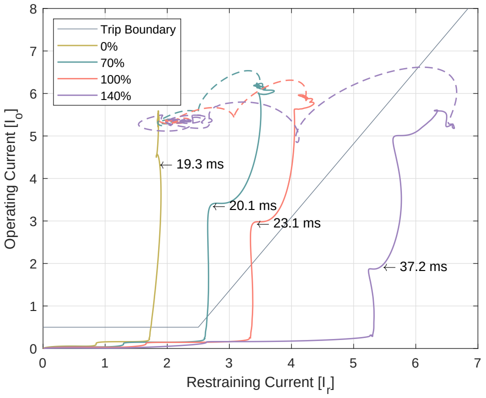

Figure 15. Differential relay fault trajectory for fault at 150 km from bus S, fault angle inception 60°

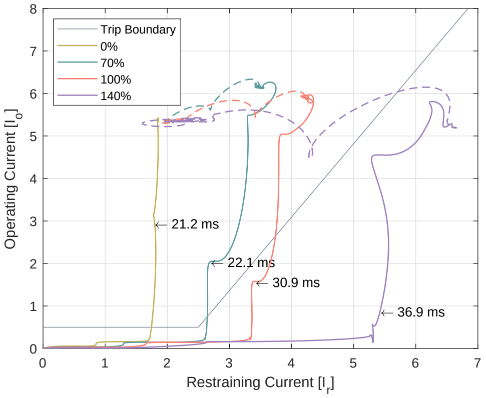

Figure 16. Differential relay fault trajectory for fault at 150 km from bus S, fault angle inception 90°

high levels of compensation should be chosen carefully, as it influences protection schemes.

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