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Comparing Measured Impedance by Distance Relay in Presence of Resistive and Inductive Fault Current Limiters

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***Abstract*--Distance relays are widely used as main and back-up protection for transmission lines. Their operation is based on impedance measurement at the relaying point, which can be affected by several factors, including pre-fault line loading and short circuit levels at the line ends. Continues demand for electricity energy leads to increase in short circuit levels along the power systems, which itself causes new problems. One of the proposed solutions for this problem is the utilization of Fault Current Limiter (FCL), which imposes further changes on the measured impedance at the relaying point, in spite of its benefits from the power system operation point of view. This paper studies the effects of superconductor series FCL, both resistive and inductive types, on the measured impedance at the relaying point. In addition to FCL impedance and peak current, its installation point affects the measured impedance. The ideal tripping characteristic would be presented and compared for both resistive and inductive FCLs.**

***Index Terms*--Distance protection, Fault resistance, FCL, Ideal tripping characteristic.**

I. Introduction

THE measured impedance at the relaying point is the basis of distance protection operation. There are several factors affecting the measured impedance at the relaying point. Some of these factors are related to the power system parameters prior to the fault instance, which can be categorized into two groups [1]-[5]. First group is the structural conditions, while the second group is the operational conditions. In addition to the power system parameters, the fault resistance could greatly influence the measured impedance, in such a way that for zero fault resistance, the power system parameters do not affect the measured impedance. In other words, power system parameters affect the measured impedance only in the presence of the fault resistance, and as the fault resistance increases, the impact of power system parameters becomes more severe.

The continuous growth for electrical energy demand leads to increase in short circuit levels in power networks. This is due to introduction of more generators to the power system, using conductors with the higher cross-section, and double or multi circuit lines. Once the short circuit currents levels, the circuit breakers with higher capacity are needed, and the imposed stress on the equipment is increased. Several solutions are presented for this problem, including the use of Fault Current Limiters (FCL), in order to decrease the rated capacity of the circuit breakers and to limit the imposed electromagnetic stress in associated equipment.

Fault current limiting could be provided by various techniques. There are several types of FCL devices such as solid state and superconductor based FCL. In the solid state FCL, the fault current limitation is performed by utilizing power electronics equipments, their required controlling systems, and associated sensors. Here, the controlling system governs the conduction state of the power electronics equipments. On the other hand, superconductor FCL does not have any controlling system, and the fault current limitation is done by inherent characteristic of the superconductor material. There are various types of superconductor FCL such as series resistance, shielded inductance, saturated inductance, and air-gap. The first type has resistive feature while three others are inductive.

Unlike power system parameters, the imposed impedance due to presence of FCL could affect the measured impedance even in the case of zero fault resistance. In the presence of FCL, the conventional distance characteristics are greatly subjected to mal-operation in the both form of over-reaching and under-reaching the fault point. Therefore, the conventional characteristics might not fulfill the protective duties in the presence of FCL.

This paper presents the effects of the installation of a superconducting FCL, both resistive and inductive types, on a transmission line, by means of presenting the measured impedance at the relaying point and the ideal tripping characteristic. In two cases of FCL exclusion and inclusion in fault loop, the measured impedance will be presented and for three installation points, i.e. at near end, mid-point, and far end, the ideal tripping characteristic will be presented and compared for resistive and inductive FCLs.

II. Superconducting FCLs and their Modeling

In the category of superconducting FCLs, the resistive FCL is the simplest to envisage [6]-[7], but its operation cost (cooling requirements) is higher than the inductive types, due to its direct connection to the transmission line. This FCL consists of a superconducting section in series with the power

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line, which switches from zero resistance (or impedance) to a significant resistance (or impedance) when either the critical current, I_C, or the critical magnetic field, H_C, is exceeded within the material.

The resistance of the element during the faulted condition, R_{FCL}, is equal to $R_{FCL} = \rho_n\ l\ /\ A$, where A is given by $I_n\ /\ J_C$. Consequently, $R_{FCL} = \rho_n\ l\ J_C\ /\ I_n$. The length and cross sectional area of the superconducting element can be calculated due to the required degree of the fault current limitation (given values for ρ_n and J_C).

On the other hand, the inductive FCLs are generally categorized into two main types: the screened-core and the saturated-core FCLs.

In the screen-core FCL, the superconducting element is in the form of a cylinder which forms the single turn secondary of an iron cored transformer that a part of the power line is its primary. In superconducting state, the cylinder effectively screens the iron core from the primary, results in low impedance of the line. Once the current (or equally the magnetic field) exceeds a certain level, the superconductor becomes normal, the line impedance increases considerably to that of an iron core transformer with primary of the power line. The other variant of this FCL type, called air-gap FCL, has a superconducting disk inserted into a thin air-gap in an iron core. In superconducting mode, the disk prevents the core to form a complete magnetic circuit; therefore, the impedance is low. On the other hand, as the disk changes to normal, the magnetic loop is completed, leads to increase in the impedance up to that of an iron-cored inductor.

In the saturated core FCL, two iron cores (each one for half of the power frequency) are saturated by a dc magnetic field produced by a superconducting coil wrapped around both cores. As the current exceeds the level, the cores are driven out of saturation, leading to increase in the impedance. In this case there is no need for superconductor to change to the normal state. The required iron for this FCL is approximately twice the previous type, since there are two cores.

Apart from internal structure and parameters of FCL and independent of it type, resistive or inductive, there are two critical parameters about this device from the power system point of view: I_{Peak} and Z_{FCL}. I_{Peak} is the instantaneous magnitude of the current, which leads to the transition from low impedance to limiting mode in FCL. Z_{FCL} indicates the impedance of FCL in the limiting mode, resistive or inductive depending on FCL type.

III. Measured Impedance at Relaying Point

Distance relays operate based on the measured impedance at the relaying point. In the absence of FCL and for zero fault resistance, the measured impedance by a distance relay only depends on the length of the line section between the fault and the relaying points. In Fig. 1 this impedance is equal to pZ_{1L}, where p is per unit length of the line section between the fault and the relaying points, and Z_{1L} is the line positive sequence impedance in ohms.

In the case of a non-zero fault resistance, the measured impedance is not equal to the impedance of the line section between the relaying and fault points. In this case, the structural and operational conditions of the power system affect the measured impedance. The structural conditions are evaluated by short circuit levels at the line ends, S_{SA} and S_{SB}. The operational conditions prior to the fault instance can be represented by the load angle of the line, δ, and the ratio of the voltage magnitude at the line ends, h, totally $E_A\ /\ E_B = he^{-j\delta}$. In the absence of FCL and with respect to Fig. 1 and Fig. 2, the measured impedance by the distance relay can be expressed by the following equations. More detailed calculations can be found in [2].

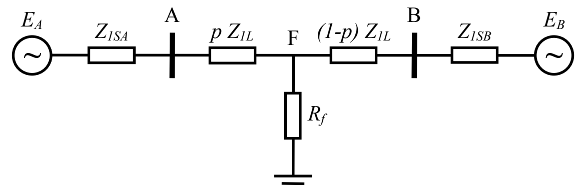


Fig. 1. Equivalent circuit for single phase to ground fault

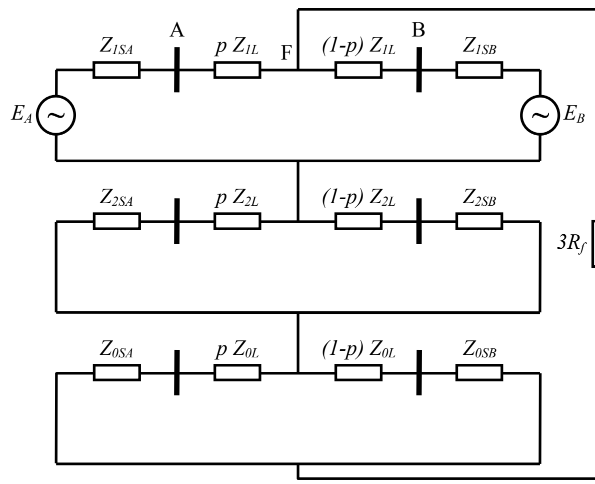


Fig. 2. Equivalent circuit of phase A to ground fault

$$Z_{1A} = Z_{1SA} + p\,Z_{1L} \tag{1}$$

$$Z_{1B} = Z_{1SB} + (1-p)Z_{1L} \tag{2}$$

$$Z_{0A} = Z_{0SA} + p\,Z_{0L} \tag{3}$$

$$Z_{0B} = Z_{0SB} + (1-p)Z_{0L} \tag{4}$$

$$Z_{\Sigma} = 2\frac{Z_{1A}Z_{1B}}{Z_{1A}+Z_{1B}} + \frac{Z_{0A}Z_{0B}}{Z_{0A}+Z_{0B}} \tag{5}$$

$$C_1 = \frac{Z_{1B}}{Z_{1A}+Z_{1B}} \tag{6}$$

$$C_0 = \frac{Z_{0B}}{Z_{0A}+Z_{0B}} \tag{7}$$

$$K_{0L} = \frac{Z_{0L}-Z_{1L}}{3Z_{1L}} \tag{8}$$

$$K_{\delta} = \frac{1-h\,e^{-j\delta}}{Z_{1B}+Z_{1A}h\,e^{-j\delta}} \tag{9}$$

$$C_{ld} = (Z_{\Sigma} + 3R_f)K_{\delta} \tag{10}$$

$$Z_A = p\,Z_{1L} + \frac{3R_f}{C_{ld} + 2C_1 + C_0(1+3K_{0L})} \tag{11}$$

It can be seen that for zero fault resistance the measured impedance at the relaying point is equal to the actual impedance of the line section between the relaying and the fault points.

Once FCL is installed on the line, depending on the presence or the absence of FCL in the fault loop, the measured impedance at the relaying point would change.

A. FCL out of Fault Loop

When FCL is not present in the fault loop (2) and (4) should be modified as:

$$Z_{1B} = Z_{1SB} + (1-p)Z_{1L} + Z_{FCL} \quad (12)$$

$$Z_{0B} = Z_{0SB} + (1-p)Z_{0L} + Z_{FCL} \quad (13)$$

It can be seen when FCL is not present in the fault loop, in spite of its presence on the line, in the absence of the fault resistance the measured impedance is not affected by the power system conditions, or by the presence of FCL.

B. FCL in Fault Loop

Once FCL is present in the fault loop, (1), (3), and (11) should be modified and a new equation is introduced:

$$Z_{1A} = Z_{1SA} + p\,Z_{1L} + Z_{FCL} \quad (14)$$

$$Z_{0A} = Z_{0SA} + p\,Z_{0L} + Z_{FCL} \quad (15)$$

$$C_{Z_{FCL}} = -3C_0 K_{0L} Z_{FCL} \quad (16)$$

$$Z_A = p\,Z_{1L} + Z_{FCL} + \frac{C_{Z_{FCL}} + 3R_f}{C_{ld} + 2C_1 + C_0(1+3K_{0L})} \quad (17)$$

It can be seen that in the absence of the fault resistance, the measured impedance at the relaying point is not equal to the actual impedance of the line section between the relaying and the fault points.

IV. Effects of Series Superconducting FCLs on Distance Relay Ideal Tripping Characteristic

The impacts of the presence of series superconducting FCL on a transmission line have been tested for a practical system. A 400 kV Iranian transmission line with the length of 300 km has been used for this study. By utilizing the Electro-Magnetic Transient Program (EMTP) [8] various sequence impedances of the line are evaluated according to its physical dimensions. The calculated impedances and the other parameters of the power system are:

Z_{1L} = 0.01133 + j 0.3037 Ω/km
Z_{0L} = 0.1535 + j 1.1478 Ω/km
Z_{1SA} = 1.3945 + j 15.9391 Ω
Z_{0SA} = 7.4540 + j 27.8187 Ω
Z_{1SB} = 0.6972 + j 7.9696 Ω
Z_{0SB} = 3.7270 + j 13.9093 Ω
$h = 0.96$
$\delta = 16^{o}$

In the absence of FCL, Fig. 3 shows the distance relay ideal tripping characteristic, which is the measured impedance at the relaying point as the fault resistance varies from 0 to 200 ohms, while the fault location moves from the near end up to the far end of the line.

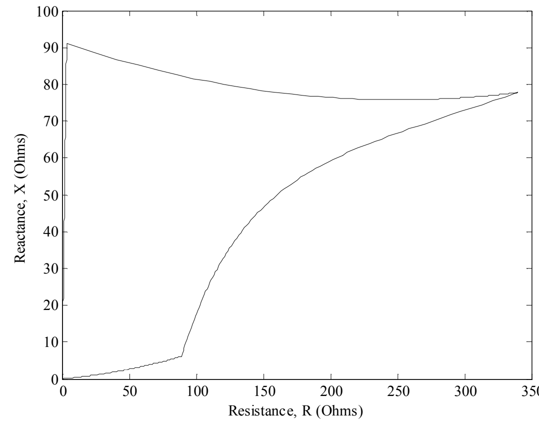


Fig. 3. Distance relay ideal tripping characteristic, without FCL

It can be seen that in the absence of the fault resistance, the measured impedance at the relaying point is the actual impedance of the line section between the relaying and the fault points. Otherwise, the measured impedance deviates from its actual value depending on the fault resistance as well as the power system conditions.

As mentioned, apart from internal structure and parameters of a superconducting FCL, FCL has two critical parameters from the system point of view: Z_{FCL} and I_{Peak}. Here, the effect of these two parameters are investigated on the measured impedance at the relaying point and consequently on the distance relay ideal tripping characteristic. Changes in these parameters would lead to a considerable variation in the measured impedance.

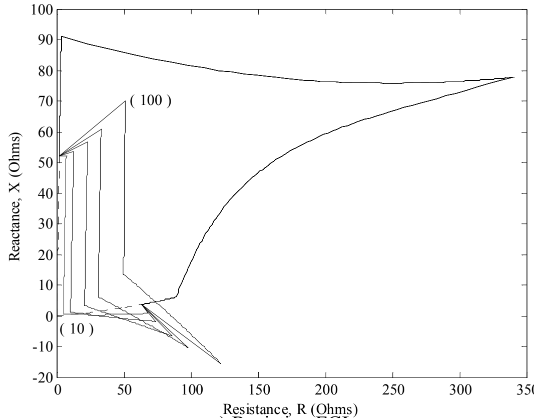
A. FCL at Near End

In this case, FCL is always present in the fault loop. Fig. 4 shows the effect of FCL impedance variation on the ideal tripping characteristic, for both resistive and inductive FCLs. Here, FCL impedance is equal to 10, 20, 40, 60, and 100 ohms, while FCL peak current is 5 kA. The ideal tripping characteristic in the absence of FCL is plotted in dotted form for comparison.

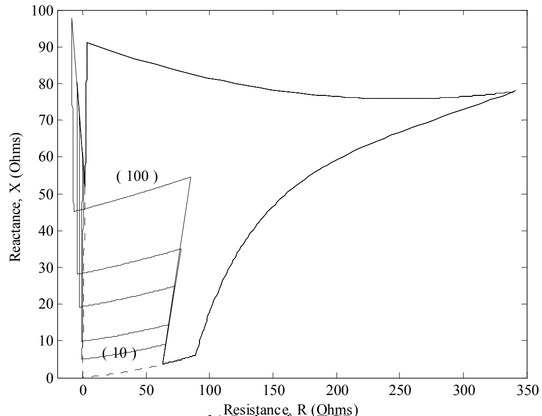
It can be seen that the operation of FCL depends on its peak current and it is independent of FCL type, resistive or inductive, or its impedance.

In the case of resistive FCL and for zero fault resistance, vertical lines, as FCL resistance increases the measured resistance increases as well as the measured reactance. On the other hand, for faults at the near end, horizontal curves, as FCL resistance increases the measured resistance increases while the measured reactance decreases. The measured reactance for the faults on the near end of the line is capacitive.

In the case of inductive FCL and zero fault resistance, as FCL inductance increases the measured resistance decreases, while the measured reactance increases. On he other hand, for faults at the near end, horizontal curves, as FCL inductance increases the measured resistance decreases for low fault resistance and increases for high fault resistances, while the measured reactance increases. The measured resistance in the case of near to zero fault resistances is negative.

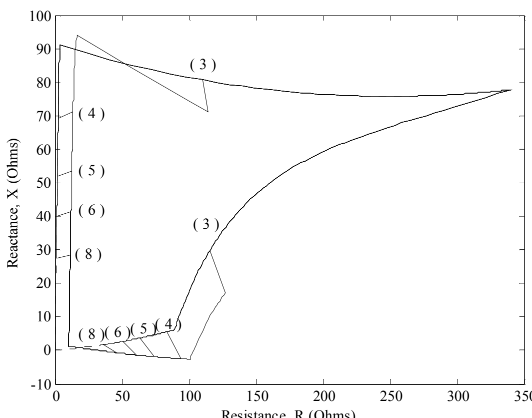


a) Resistive FCL

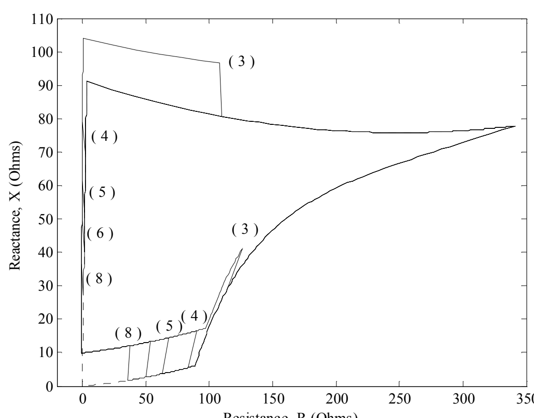


b) Inductive FCL

Fig. 4. Ideal tripping characteristic, FCL at near end, I_{peak} = 5 kA



a) Resistive FCL



b) Inductive FCL

Fig. 5. Ideal tripping characteristic, FCL at near end, Z_{FCL} = 20 Ω

On the other hand, Fig. 5 shows the effect of FCL peak current variation on the ideal tripping characteristic, for both resistive and inductive FCLs. Here, FCL peak current is equal to 3, 4, 5, 6, and 8 kA, while FCL impedance is equal to 20 ohms. The ideal tripping characteristic in the absence of FCL is plotted in dotted format for comparison.

Here, it also can be seen that the operation of FCL depends on its peak current and it is independent of FCL impedance.

In the case of resistive FCL and for zero fault resistance, the measured resistance increases as well as the measured reactance. On the other hand, for faults at the near end or the far end, the measured resistance increases while the measured reactance decreases. But, in the case of inductive FCL and zero fault resistance, the measured resistance decreases while the measured reactance increases. Otherwise, for faults at the near end, as FCL inductance increases the measured resistance decreases for low fault resistances and increases for high fault resistances, while the measured reactance increases.

It can be concluded that as FCL peak current decreases, the region in which FCL operates to limit the fault current is extended; but when FCL operates, the measured impedance depends on FCL impedance.

B. FCL at Mid-Point

In this case, FCL is out of the fault loop for the faults on the near half of the line, while it is present in the fault loop in the case of the faults on the far half of the line. Fig. 6 shows the effect of FCL impedance variation on the ideal tripping characteristic, for both resistive and inductive FCLs.

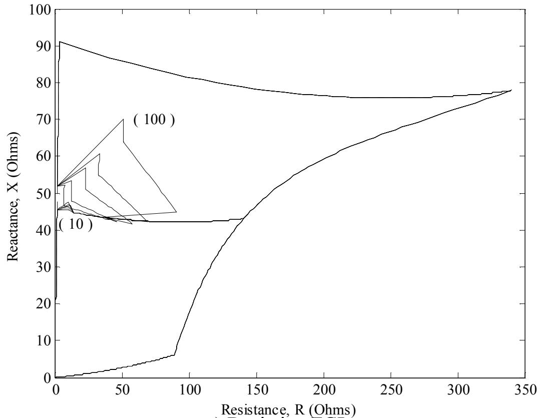
It can be seen that in the presence of FCL at the mid-point the ideal tripping characteristic is split into two parts. The lower part is corresponding to the near half of the line, while the upper part is related to the far half.

In the case of resistive FCL and for zero fault resistance, as FCL resistance increases, the measured resistance increases as well as the measured reactance. Otherwise, in the case of faults at the mid-point, as FCL resistance increases, the measured resistance increases while the measured reactance decreases.

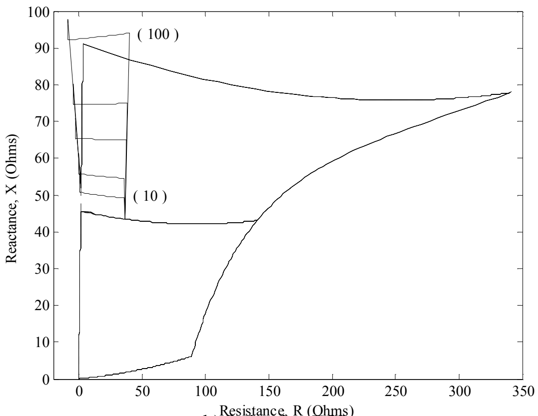
In the case of inductive FCL and zero fault resistance, as FCL inductance increases, the measured resistance decreases while the measured reactance increases. On he other hand, for faults at the mid-point, as FCL inductance increases the measured resistance decreases for low fault resistances and increases for high fault resistances, while the measured reactance increases.

On the other hand, Fig. 7 shows the effect of FCL peak current variation on the ideal tripping characteristic, for both resistive and inductive FCLs.

In the lower part, for zero fault resistance the measured impedance is the actual value. Otherwise, for faults at the mid-point, the measured resistance decreases while the measured reactance increases. In the upper part, for zero fault resistance the measured resistance increases as well as the measured reactance, whereas for faults at the mid-point or the far end, the measured resistance increases while the measured reactance decreases.

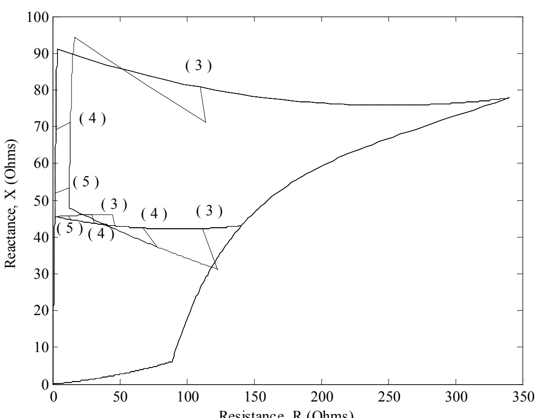


a) Resistive FCL

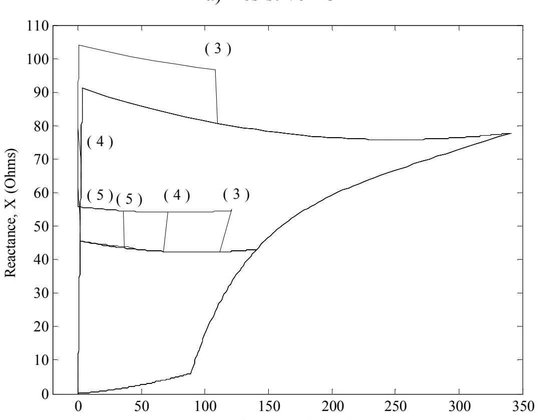


b) Inductive FCL

Fig. 6. Ideal tripping characteristic, FCL at mid-point, I_{peak} = 5 kA



a) Resistive FCL



b) Inductive FCL

Fig. 7. Ideal tripping characteristic, FCL at mid-point, Z_{FCL} = 20 Ω

In the case of inductive FCL and in the lower part, for zero fault resistance the measured impedance is the actual value. Otherwise, for faults at the mid-point, the measured resistance increases as well as the measured reactance. In the upper part, for zero fault resistance the measured resistance decreases while the measured reactance increases, whereas for faults at the mid-point or the far end, the measured resistance decreases for low fault resistances and increases for high fault resistances, while the measured reactance increases.

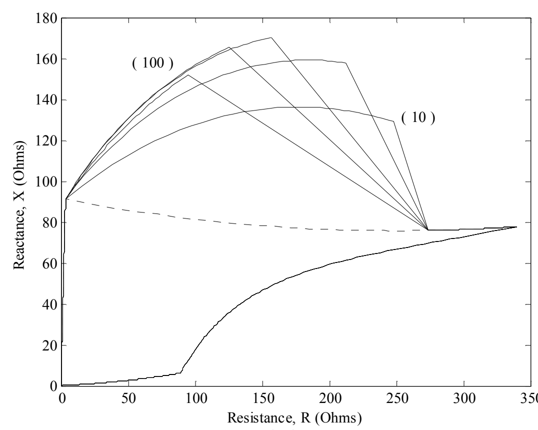
In the case of FCL peak currents of 6 and 8 kA, FCL has no operation, since the flowing current through FCL is less than theses magnitudes. Here, the distance ideal tripping characteristic does not change in spite of the presence of FCL.

It can be concluded that as FCL peak current increases, the region in which FCL operate to limit the fault current decreases and then vanishes.

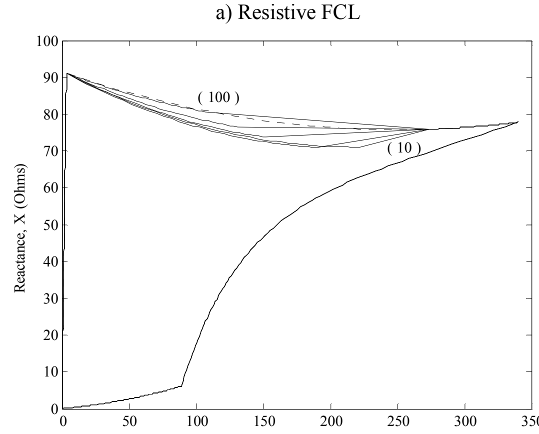
C. FCL at Far End

In this case, FCL is always out of the fault loop. Fig. 8 shows the effect of FCL impedance variation on the ideal tripping characteristic.

In the case of resistive FCL and zero fault resistance, the measured impedance is the actual impedance of the line section between the fault and the relaying points. On he other hand, for faults at the far end, as FCL resistance increases the measured resistance decreases while the measured reactance increases. As the FCL resistance increases, the increase in the measured reactance increase and then decreases.



a) Resistive FCL

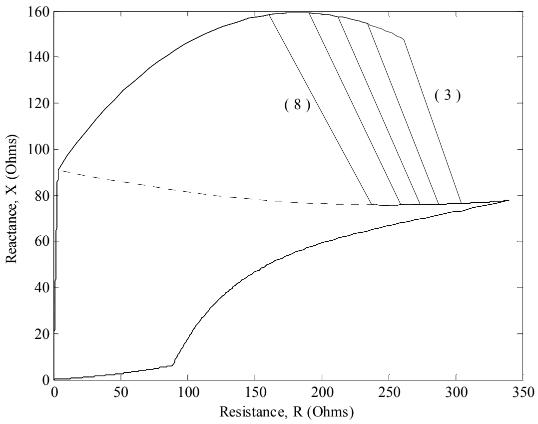


b) Inductive FCL

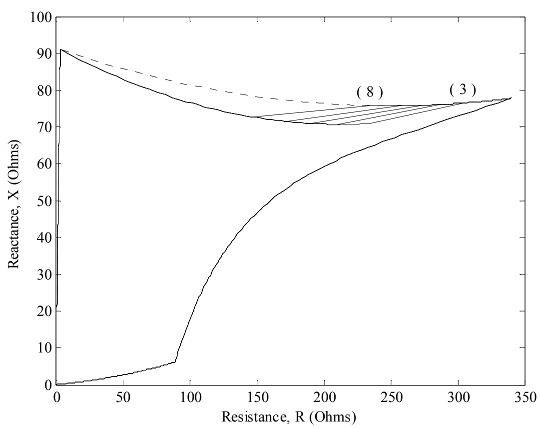
Fig. 8. Ideal tripping characteristic, FCL at far end, I_{peak} = 5 kA

In the case of inductive FCL and zero fault resistance, the measured impedance is the actual impedance of the line section between the fault and the relaying points. On he other hand, for faults at the far end, as FCL inductance increases, the measured resistance increases and then decreases, while the measured reactance increases.

On the other hand, Fig. 9 shows the effect of FCL peak current variation on the ideal tripping characteristic.



a) Resistive FCL



b) Inductive FCL

Fig. 9. Ideal tripping characteristic, FCL at far end, Z_{FCL} = 20 Ω

In the case of zero fault resistance, the measured impedance is the actual impedance of the line section between the fault and the relaying points. On the other hand, for faults at the far end, the measured resistance decreases while the measured reactance increases for restive FCL and once inductive FCL operates to limit the fault current, the measured resistance decreases as well as the measured reactance. It can be concluded that as FCL peak current decreases, the region in which FCL operates to limit the fault current is extended; but when FCL operates, the measured impedance depends on FCL impedance.

V. Conclusion

The operation of FCL depends on its peak current and it is independent of FCL type or impedance. It can be concluded that as FCL peak current decreases, the region in which FCL operates to limit the fault current is extended; but when FCL operates, the measured impedance at the relaying point depends on FCL type and impedance. As FCL impedance increases, in both resistive and inductive types, the deviation of the measured impedance also increases.

Therefore, when FCL is applied on a transmission line to limit the short circuit current, the measured impedance and consequently the distance protection are affected. It is necessary to consider this fact, when providing protective system for the line with FCL.

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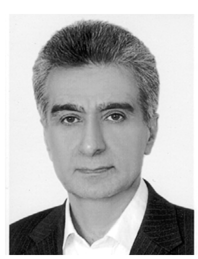
VII. Biographies

Hossein Shateri (M'07) was born in 1979 in Karaj, Iran. He received his BSc and MSc from Iran University of Science and Technology in Tehran in 2001 and 2003, respectively all in electrical Engineering. He is currently working towards a PhD degree in the Department of Electrical Engineering at Iran University of Science and Technology (IUST) in Tehran, Iran since Sep. 2004. He has published over 120 papers in international conferences and journals. H. Shateri is a Member of the Institution of Electrical and Electronic Engineers (IEEE) and a Member of the Institution of Engineering Technology (IET). His field of interest includes Power System Protection, and Distribution Systems Protection and Automation.



Sadegh Jamali, was born in 1956 in Tehran, Iran. He received his BSc from Sharif university of Technology in Tehran in 1979, MSc from UMIST, Manchester, UK in 1986 and PhD from City University, London, UK in 1990, all in Electrical Engineering. Dr. Jamali is currently an Associate Professor in the Department of Electrical Engineering at Iran University of Science and Technology in Tehran. Dr. Jamali is a Fellow of the Institution of Engineering Technology (IET) and the IET Council Representative in Iran. His field of interest includes Power System Protection and Distribution Systems.