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Modified Distance Protection due to Presence of STATCOM on a Transmission Line

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Abstract-- **This paper presents a modified distance protection due to the presence of STATic synchronous COMpensator (STATCOM), one of the shunt connected Flexible Alternating Current Transmission System (FACTS) devices. The presence of STATCOM on a transmission line has a great influence on the measured impedance at the relaying point. The measured impedance itself depends on the power system structural conditions, pre-fault loading, and especially the fault resistance. In the presence of STATCOM, its injected current as well as its installation point affects the measured impedance. Therefore, the conventional distance techniques do not fulfill the protective duties satisfactorily and new approaches are required.**

Index Terms--**Adaptive Distance Protection; FACTS devices; Measured impedance; STATCOM.**

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 [1]-[3], which can be categorized into two groups: structural and operational conditions. In addition to the power system parameters, the fault resistance could greatly influence the measured impedance, in such a way that in the case of zero fault resistance, the power system parameters do not affect the measured impedance. In other words, in the absence of FACTS devices, power system parameters affect the measured impedance only in the presence of the fault resistance, and as the fault resistance increases, the impact of the power system parameters becomes more severe.

In the recent years, FACTS devices are introduced to the power systems to increase the transmitting capacity of the lines and provide the optimum utilization of power systems capability. This is done by pushing the power systems to their thermal limits [4]. It is well documented in the literature that the introduction of FACTS devices into a power system has a great influence on its dynamics. As power system dynamics changes, many sub-systems are affected, including the protective systems. Therefore, it is essential to study the effects of FACTS devices on the protective systems, especially distance protection.

Unlike the power system parameters, the structural and controlling parameters of FACTS devices, as well as their installation position could affect the measured impedance in the case of zero fault resistance. In the presence of FACTS devices, the conventional distance characteristic are greatly subjected to mal-operation in the both form of over-reaching or under-reaching the fault point. Therefore, the conventional characteristics might not fulfil the protective duties in the presence of FACTS devices.

The impact of STATCOM on the measured impedance has been discussed in [4], by assuming the instantaneous operation of its controlling system. Performance of distance relay for the mid-point shunt compensated transmission lines has been investigated in [5]. The impact of shunt connected FACTS devices on distance protection has been studied in [6]. The various distance protection schemes has been compared in [7]-[8] for a mid-point compensated transmission line by means of shunt connected FACTS devises. Furthermore, the effects of series connected FACTS devices, or FACTS devices with the series branch including TCSC, TCPST, and UPFC, on the measured impedance at the relaying point have been presented in [9] and more detailed studies for UPFC have been presented in [10]. In [9]-[10], the protective system operates before the control system of FACTS devices.

The presented solutions in [5]-[8] are based on unit protection or the data exchange between the relays at line ends. The other potential solution for problems caused by introduction of STATCOM on the transmission line could be adaptive distance protection. In the adaptive distance protection, the distance relay reach-point is adapted due to the power system conditions and STATCOM parameters. If the required data is not available, the modified distance relay could perform protective duties not as accurately as the adaptive system, but much better than the conventional protection system.

This paper investigates the measured impedance at the relaying point in the presence of STATCOM. In addition to the power system conditions, the structural and controlling parameters of STATCOM as well as its installation point affect the measured impedance. The measured impedance is presented for the three cases of STATCOM presence at the near end of the line, as well as its exclusion and inclusion in the fault loop. Here, a modified distance protection is presented for distance relays at the ends of the compensated line by STATCOM, based on the power system conditions and STATCOM structural parameters.

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II. STATCOM AND ITS MODELING

Shunt connected FACTS devices are usually utilized to regulate the voltage of their connection point. Static Var Compensator (SVC) is an early type of the shunt connected FACTS devices, which controls its connection point voltage by adjusting its susceptance in order to supply or absorb the required reactive power. Advancement in the power electronic devices, such as Gate Turn Off (GTO) devices, introduced the so-called advanced Static Var Systems (SVS). STATCOM is an example of the advanced SVS, consisting of three-phase sets of several GTO based valve and a dc link capacitor and the associated control system. The control system operates in such a way that its connection point voltage is being regulated according to its controlling strategy within its operational limits. STATCOM consists of a converter which is connected to the line via a shunt coupling transformer [11].

STATCOM can be modeled as a shunt branch consisting of an impedance, due to the coupling transformer, and a voltage source, which is in phase with the voltage of its connection point, so it can only inject or absorb reactive power according to the magnitude of voltage source.

III. MEASURED IMPEDANCE AT RELAYING POINT

Distance relays operate based on the measured impedance at the relaying point. In the absence of STATCOM 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.

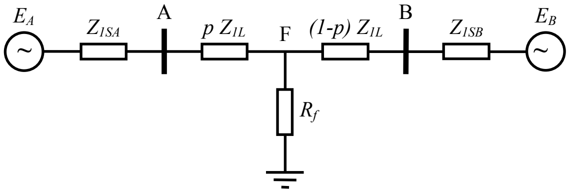

Fig. 1. Equivalent circuit for single phase to ground fault

In the case of a non-zero fault resistance, the measured impedance is not equal to the mentioned value. 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 ratio of the magnitude of the line end voltages, h, or $E_B / E_A = he^{-j\delta}$. In the absence of STATCOM and with respect to Fig. 1 and Fig. 2, the measured impedance can be expressed by the following equations. More detailed calculations can be found in [2].

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

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

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

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

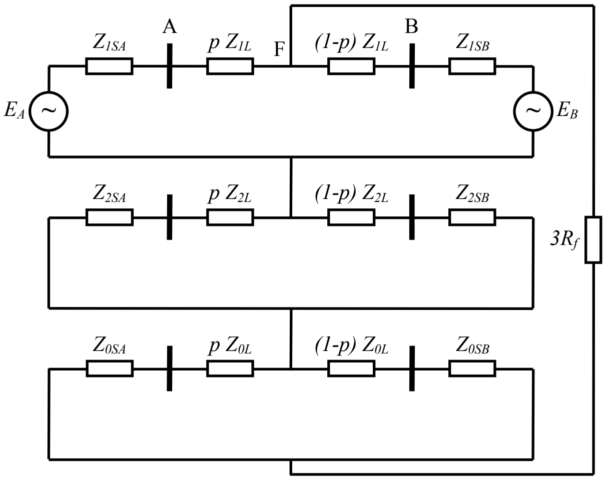

Fig. 2. Equivalent circuit of phase A to ground fault

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

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

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

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

$$K_{ld} = \frac{1-he^{-j\delta}}{Z_{1A}he^{-j\delta}+Z_{1B}} \tag{9}$$

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

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

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

Once STATCOM is installed on the transmission line, depending on its presence at the near end, its exclusion or inclusion in the fault loop, the measured impedance would change. STATCOM is installed at the length of i per unit from the relaying point. The following equations introduced due to STATCOM presence on the line, independent of its exclusion or inclusion in the fault loop.

$$Z_{1AI} = Z_{1SA} + i\,Z_{1L} \tag{12}$$

$$Z_{1BI} = Z_{1SB} + (1-i)Z_{1L} \tag{13}$$

$$Z_{1AF} = Z_{1SA} + pZ_{1L} \tag{14}$$

$$Z_{1BF} = Z_{1SB} + (1-p)Z_{1L} \tag{15}$$

$$Z_{1IF} = |i-p|Z_{1L} \tag{16}$$

$$Z_{0AI} = Z_{0SA} + i\,Z_{0L} \tag{17}$$

$$Z_{0BI} = Z_{0SB} + (1-i)Z_{0L} \tag{18}$$

$$Z_{0AF} = Z_{0SA} + pZ_{0L} \tag{19}$$

$$Z_{0BF} = Z_{0SB} + (1-p)Z_{0L} \tag{20}$$

$$Z_{0IF} = |i-p|Z_{0L} \tag{21}$$

A. STATCOM at Near End

Once STATCOM is at the near end of the line, definition of Z_{1SA}, Z_{0SA}, h, and δ are modified as:

$$Z_{1SA_{new}} = \frac{Z_{Sh}Z_{1SA}}{Z_{Sh}+Z_{1SA}} \tag{22}$$

$$Z_{0SA_{new}} = \frac{Z_{Sh}Z_{0SA}}{Z_{Sh}+Z_{0SA}} \tag{23}$$

$$E'_A = \frac{Z_{Sh}E_A + Z_{1SA}E_{Sh}}{Z_{Sh}+Z_{1SA}} \tag{24}$$

$$h_{new} = h/\left|E'_A\right| \tag{25}$$

$$\delta_{new} = \delta + \angle E'_A \tag{26}$$

B. STATCOM out of Fault Loop

Once STATCOM is out of the fault loop, (1)-(4), and (9)-(10) should be modified and a new equation is introduced:

$$Z_{1A} = Z_{1AF} \tag{27}$$

$$Z_{1B} = Z_{1IF} + \frac{Z_{Sh}Z_{1BI}}{Z_{Sh}+Z_{1BI}} \tag{28}$$

$$Z_{0A} = Z_{0AF} \tag{29}$$

$$Z_{0B} = Z_{0IF} + \frac{Z_{Sh}Z_{0BI}}{Z_{Sh}+Z_{0BI}} \tag{30}$$

$$Den = Z_{1BI}[Z_{1AF}E_{Sh} + Z_{1IF}] + Z_{Sh}[Z_{1AF}he^{-j\delta} + Z_{1BF}] \tag{31}$$

$$K_{ld} = Z_{1BI}(1-E_{Sh}) + Z_{Sh}(1-he^{-j\delta}) \tag{32}$$

$$C_{ld} = (Z_{\Sigma} + 3R_f)K_{ld}/Den \tag{33}$$

Here, the measured impedance in the case of zero fault resistance is equal to the impedance of the line section between the relaying and the fault points.

C. STATCOM in Fault Loop

When STATCOM is in the fault loop, (1)-(4) should be modified; (9)-(10) are changed to (32)-(33); and some new equations are introduced:

$$Z_{1A} = Z_{1IF} + \frac{Z_{Sh}Z_{1AI}}{Z_{Sh}+Z_{1AI}} \tag{34}$$

$$Z_{1B} = Z_{1BF} \tag{35}$$

$$Z_{0A} = Z_{0IF} + \frac{Z_{Sh}Z_{0AI}}{Z_{Sh}+Z_{0AI}} \tag{36}$$

$$Z_{0B} = Z_{0BF} \tag{37}$$

$$C_{1A} = \frac{Z_{Sh}}{Z_{Sh}+Z_{1AI}} \tag{38}$$

$$C_{0A} = \frac{Z_{Sh}}{Z_{Sh}+Z_{0AI}} \tag{39}$$

$$\begin{aligned} Den = {} & Z_{1AI}[Z_{1IF}\,he^{-j\delta} + Z_{1BF}\,E_{Sh}] \\ & + Z_{Sh}[Z_{1AF}\,he^{-j\delta} + Z_{1BF}] \end{aligned} \tag{40}$$

$$K_{ld_{\Delta}} = Z_{1AI}[E_{Sh} - he^{-j\delta}] - Z_{1BI}[1-E_{Sh}] \tag{41}$$

$$C_{ld_{\Delta}} = (Z_{\Sigma} + 3R_f)K_{ld_{\Delta}}/Den \tag{42}$$

$$C_{Sh} = Z_{1IF}[C_{ld_{\Delta}} + 2C_1(1-C_{1A}) + C_0(1-C_{0A})(1+3K_{0L})] \tag{43}$$

$$Z_A = pZ_{1L} + \frac{C_{Sh}+3R_f}{C_{ld} + 2C_1C_{1A} + C_0C_{0A}(1+3K_{0L})} \tag{44}$$

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 STATCOM ON DISTANCE RELAY IDEAL TRIPPING CHARACTERISTIC

The impacts of the presence of STATCOM 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) [12] various sequence impedances of the line are evaluated according to its physical dimensions. The calculated impedances and the other parameters of the system are:

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

In the absence of STATCOM, Fig. 3 shows the ideal tripping characteristic of the distance relay, 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. The quadrilateral characteristic covering 80% of the line and the impedance of the transmission line, Z_{1L}, are shown in Fig. 3. In addition the dotted line is the measured impedance for the faults at the reach-point while the fault resistance varies from 0 to 200 ohms.

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 up to the fault point. In other words, the left side of the ideal tripping characteristic is the impedance of the transmission line.

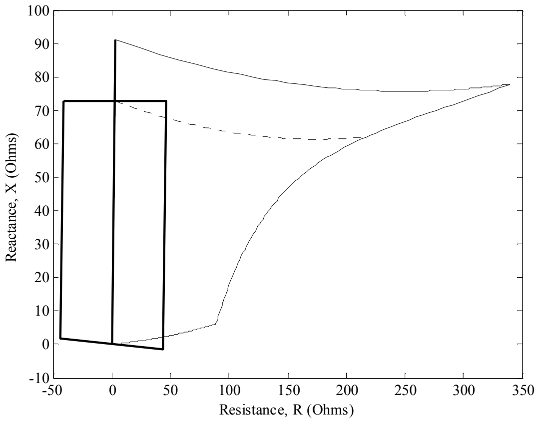

Fig. 3. Ideal tripping characteristic, without STATCOM

Usually STATCOM regulates its connecting point voltage according to its controlling strategy. Therefore, the amount of STATCOM injected or absorbed reactive power would vary as the power system loading is changed. But in this study the operational conditions of the power system are assumed to be constant and it is assumed these conditions are achieved by the different STATCOM operational parameters. Here, STATCOM current is utilized to describe its operational condition.

The ideal tripping characteristic in the case of STATCOM installation on near end, mid-point, and far end of line are investigated in [13]. In the case of STATCOM at the line ends, it does not affect the measured impedance for zero fault resistance. Therefore, only the case of STATCOM at the mid-point is investigated.

Fig. 4 shows the effect of STATCOM installation at the mid-point of the transmission line on the measured impedance at the relaying point. Here, the injected current of STATCOM is equal to 0.0, 0.5, and 1.0 per unit in both leading and lagging modes. In Fig. 4 the tripping characteristic without STATCOM is also shown in the dashed form for comparison.

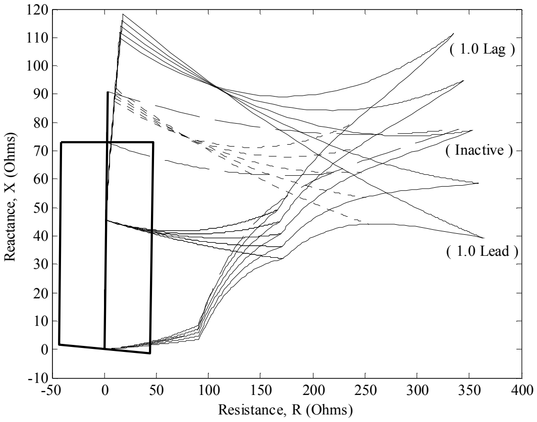

Fig. 4. Ideal tripping characteristic, STATCOM at mid-point

In the presence of STATCOM at the mid-point, tripping characteristic is split into two adjoined parts. The lower part is for the faults on the near half of the line, while the upper part is corresponding to the faults on the far half. The lower boundary of the upper part and the upper boundary of the lower part are just the same.

In the presence of an inactive STATCOM on the line and in the lower part, the measured resistance increases slightly, while the measured reactance decreases slightly. In the upper part, the measured resistance increases slightly, and in the case of the measured reactance, for the faults close to the mid-point it decreases slightly while for the faults close to the far end it increases more considerably, especially for low fault resistances.

In the case of Leading STATCOM and in the lower part, as STATCOM compensation current increases, the measured resistance increases slightly, while the measured reactance decreases more considerably. On the other hand, in the upper part, as STATCOM compensation current increases, the measured resistance increases slightly. In the case of the measured reactance, it decreases for the faults close to the mid-point; and for the faults close to the far end, it increases for low fault resistances while it decreases in the case of high fault resistances.

In the case of lagging STATCOM and in the lower part, as STATCOM compensation current increases, the measured resistance decreases slightly, while the measured reactance increases more considerably. On the other hand and in the upper part, as STATCOM compensation current increases, the measured resistance decreases slightly. The measured reactance increases for the faults close to the mid-point; and for the faults close to the far end, it decreases for low fault resistances while it increases in the case of high fault resistances.

It can be seen that in the presence of STATCOM at the mid-point of the transmission line, the measured impedance for the reach-point, 80% of the line, increases considerably compared with its actual value. Therefore, it can be concluded that in the presence of STATCOM, the length of the line covered in the first zone of the conventionally set distance relay decreases considerably.

V. ADAPTIVE DISTANCE PROTECTION IN PRESENCE OF STATCOM

Knowing the structural and operational conditions of the power system, as well as the structural and controlling parameters of STATCOM, the measured impedance for a solid fault at the reach-point can be calculated. The required information could be provided via SCADA system, after each updating. There is no need for online data from the other side of the line, as it is required in unit protection based approaches. Once the measured impedance at the relaying point for a solid fault at the reach-point has been calculated, the quadrilateral characteristic would be adopted due to this value. Therefore, distance relay would operate correctly and its covering region in the first zone does not reduce.

In the case of the conventional distance protection, setting the first zone of the relay at 80% of the line length, the first zone would be a quadrilateral as follows. The upper side is parallel with R axis and its reactance is equal to the reactance of the reach-point. The left and right sides are parallel with the impedance of the reach-point with the distance of 0.6 of the magnitude of the reach-point impedance. The lower side crosses the impedance of the reach-point at the origin and makes a right angle with it.

In the proposed adoptive distance protection, setting the first zone of the relay at 80% of the line length, the first zone would be a quadrilateral as follows. The upper side is parallel with R axis and its reactance is equal to the reactance of the calculated impedance for a solid fault at the reach-point. The left and right sides are parallel with the impedance of the calculated impedance for the solid fault at the reach-point with the distance of 0.6 of the magnitude of the reach-point impedance, i.e. $0.8Z_{1L}$. The lower side crosses the calculated impedance for the solid fault at the reach-point at the origin and makes a right angle with it.

Fig. 5 shows the ideal tripping characteristic in the presence of STATCOM at the mid-point. Here, the injected current of STATCOM is equal to 0.0 and 1.0 per unit in both leading and lagging modes. The conventional quadrilateral characteristic and the impedance of the line are plotted with solid lines. The adopted quadrilateral characteristic is shown with dotted line. The ideal tripping characteristic in the absence of STATCOM is plotted with dashed line for comparison. The measured impedance for faults at the reach-point is shown for all cases.

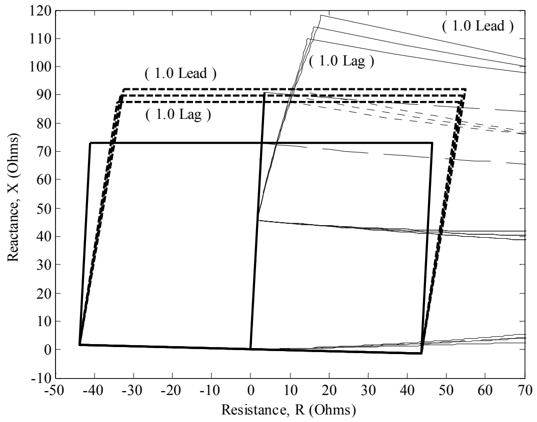

Fig. 5. Adoptive distance protection, STATCOM at mid-point

It can be seen that in the case of an inactive STATCOM presence at the mid-point, the region covered with the adopted quadrilateral characteristic is more than that of in the case of conventional quadrilateral characteristic. In the case of the adopted quadrilateral exactly 80% of the line is covered in the first zone, and the protected region does not reduce.

In the case of STATCOM presence at the mid-point in the full leading mode, the region covered with the adopted quadrilateral characteristic is considerably more than that of in the case of conventional quadrilateral characteristic. When comparing this region with that of in the case of an inactive STATCOM, only a slight expansion could be observed.

In the case of STATCOM presence at the mid-point in the full lagging mode, the region covered with the adopted quadrilateral characteristic is considerably more than that of in the case of conventional characteristic. When comparing this region with that of in the case of an inactive STATCOM, only a slight shrinking could be observed.

VI. MODIFIED DISTANCE PROTECTION IN PRESENCE OF STATCOM

As mentioned, the adoptive distance protection is based on the information about the power system conditions and STATCOM parameters. If the required information is not available, the adoption procedure could not be performed. In this case, distance relay should utilize a fixed pre-determined characteristic. This characteristic could be a conventional quadrilateral characteristic, but the modified characteristic is a better alternative. Here, it is suggested that the adopted characteristic in the case of an inactive STATCOM is selected as the modified characteristic. When the required information is not available, this characteristic would be activated.

The lack of information would be in two stages of lack of STATCOM information and lack of the whole system information. The modified distance protection is investigated in the both stages of information unavailability.

A. Lack of STATCOM Information

In this case, the information about STATCOM is not available but the information of the power system is known. Fig. 6 shows the close up of ideal tripping characteristic around quadrilateral characteristic in the presence of STATCOM at the mid-point of the line. Here, the injected current of STATCOM is equal to 0.0 and 1.0 in the both leading and lagging modes. The conventional quadrilateral characteristic is shown by dotted line; and the modified characteristic and the impedance of the line are plotted with solid lines. The measured impedance for faults at the reach-point is shown for all cases.

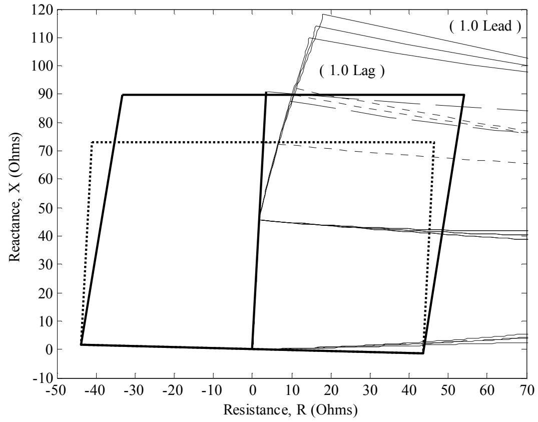

Fig. 6. Modified distance protection, STATCOM at mid-point, STATCOM information unavailability

It can be seen that the modified quadrilateral characteristic for STATCOM at the mid-point covers larger region than the conventional quadrilateral characteristic. In the case of the modified quadrilateral characteristic, approximately 80% of the line is covered in the first zone, and the protected region is not reduced as severely as the case of conventional quadrilateral characteristic. In the case of STATCOM in the leading mode, due to ideal tripping characteristic expansion, the covered region decreases slightly, while for lagging STATCOM, due to ideal tripping characteristic shrinking, the covered region increases.

B. Lack of Whole System Information

In this case, the information of the power system, including STATCOM information, is not available. Fig. 7 shows the ideal tripping characteristic in the presence of STATCOM at the mid-point. The first operational condition is the case of increase in the transmitted load trough the line, load angle of 22° and voltage ratio of 0.94. Otherwise, the second operational condition is the case of decrease in the transmitted load, load angle of 10° and voltage ratio of 0.98. The conventional quadrilateral characteristic is shown by dotted line; and the modified characteristic and the impedance of the line are plotted with solid lines.

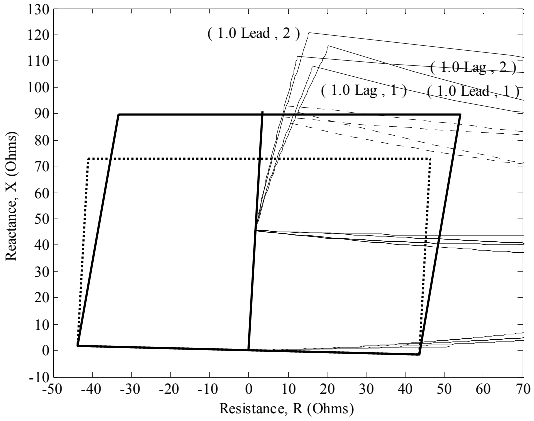

Fig. 6. Modified distance protection, STATCOM at mid-point, whole system information unavailability

It can be seen that in the case of solid faults, the power system conditions does not affects the measured impedance as severely at STATCOM controlling parameters. It can be concluded that the impact of STATCOM controlling parameters on the measured impedance for faults with zero fault resistance is more considerable than the power system conditions. Therefore, the mentioned tips in the previous section are also valid in this case.

VII. CONCLUSION

In the case of STATCOM installation at the mid-point, the measured impedance for the faults at the reach-point deviates considerably from its actual value which leads to decrease in the covered region in the distance relay first zone. In order to solve this problem, the reach-point of the distance relay is adopted due to the power system conditions and STATCOM structural and controlling parameters.

Comparing the adopted quadrilateral characteristic with the conventional one, it can be seen that the adopted quadrilateral characteristic changes considerably, significant increase in the covered region. On the other hand, comparing the adopted quadrilateral characteristics in the various cases, it can be seen that the characteristic does not vary severely due to changes in STATCOM controlling parameters. Therefore, the adopted characteristic for inactive STATCOM could be applied as the modified characteristic in the case of information unavailability.

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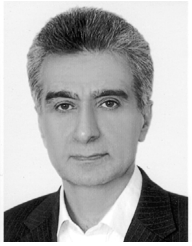
IX. BIOGRAPHIES



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