VOLTAGE INVERSION DUE TO TCSC PRESENCE ON SECOND CIRCUIT OF DOUBLE CIRCUIT LINE AND DISTANCE RELAY MAL-OPERATION

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ABSTRACT

This paper discusses the distance relay mal-operation in the case of installation of Thyristor Controlled Series Compensator (TCSC) which is categorized as a series connected Flexible Alternating Current Transmission System (FACTS) device, on second circuit of a double circuit transmission line. This is done by presenting the measured impedance at the relaying point in the case of TCSC presence at the near end of the second circuit. Distance relay tripping characteristic is greatly influenced in the presence of TCSC on the transmission line or even in the case of installing TCSC on the near end of the second circuit. Distance relay tripping characteristic depends on many factors including the power system structural conditions and the pre-fault loading, the ground fault resistance, and TCSC compensation degree.

I. INTRODUCTION

The measured impedance at the relaying point is the basis of the distance protection operation. There are several factors affecting the measured impedance. Some of these factors are related to the power system parameters prior to the fault instance, which can be categorized into two groups [1-4]. First group is the structural conditions, represented by the short circuit levels at the line ends, whereas the second group is the operational conditions, represented by the line load angle and the voltage magnitude ratio at the line ends. In addition to the power system parameters, the fault resistance, in the single-phase to ground faults, 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.

In today's power systems, there are some difficulties for constructing new transmission lines, because of the limits in the rights for their paths. This leads to interdiction of double-circuit lines and compensated lines by FACTS devices in to the power systems. In the case of the double-circuit lines, because of the low distance of the conductors of two circuits, two circuits affect each other mutually.

On the other hand, recently FACTS devices are introduced to the power systems to increase the transmitting capacity of the lines and provide the optimum utilization of the system capability. This is done by pushing the power systems to their thermal limits. It is well documented in the literature that the introduction of FACTS devices in power systems has a great influence on their dynamics. As power system dynamics changes, many sub-systems are affected, including the protective systems. Therefore, it is essential to study effects of FACTS devices on the protective systems, especially the distance protection, which is the main protective device at EHV and HV levels.

Unlike power system parameters, the structural and controlling parameters of FACTS devices could affect the measured impedance even in the absence of the fault resistance. In the presence of FACTS devices, the conventional distance characteristic such as Mho and Quadrilateral are greatly subjected to mal-operation in the form of over-reaching or under-reaching the fault point.

It is well-known that in the presence of series capacitors on transmission lines, they would lead to the over-reaching of distance relays located on the adjacent lines. This is true for both fixed and controllable series capacitors. The probability of over-reaching due to presence of TCSC at the near end of the next line is mentioned in [5-6]. In [5-6] only the probability of over-reaching is discussed by means of the simulations and no equations are presented. In the case of double circuit lines, the presence of TCSC on one of the circuits would cause the same problems. Here the measured impedance in the presence of TCSC at the near end of the second circuit of a double circuit line is presented assuming that the protective system operates before TCSC control system.

This paper presents the measured impedance at the relaying point in the presence of TCSC at the near end of the second circuit of a double circuit line. In addition to TCSC compensation degree, the measured impedance depends on the structural and the operational conditions of power system and especially the fault resistance.

II. TCSC MODEL

Thyristor Controlled Series Compensator (TCSC) is placed in the group of thyristor based series connected FACTS devices. As shown in Fig. 1, TCSC consists of a fixed capacitor in parallel with a thyristor controlled reactor [7]. TCSC can be controlled by adjusting the conducting duration of the reactor. TCSC can be modelled as a variable reactance, capacitive or inductive regarding the conducting duration of the reactor, reactance of the reactor, and capacitance of the capacitor. The reactance of TCSC is usually defined on the base of the positive sequence reactance of the line which is given as compensation degree, K_C, as below:

$$Z_{TCSC} = -j\,K_C\,X_{1L} \quad (1)$$

Coefficients C_{1S} and C_{0S} are defined as:

$$C_{1S} = Z_{TCSC} / Z_{1L} \quad (2)$$

$$C_{0S} = Z_{TCSC} /(Z_{0L} - Z_{0M}) \quad (3)$$

III. MEASURED IMPEDANCE

Distance relay operates based on the measured impedance at the relaying point. In the case of faults in the first zone and in the absence of the fault resistance, the measured impedance by a distance relay is the actual impedance of the line section between the fault and the relaying points. According to Fig. 2, 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 at the relaying point is not equal to the mentioned value. In this case, the structural and operational conditions of the power system affect the measured impedance at the relaying point. The operational conditions prior to the fault instance can be represented by the load angle of the line, δ, and the ratio of the magnitude of the line end voltages, h, or totally $E_B / E_A = he^{-j\delta}$. The structural conditions are evaluated by the short circuit levels at the line ends, S_{SA} and S_{SB}. The measured impedance at the relaying point can be expressed by the following equation:

$$Z_A = p\,Z_{1L} + \frac{3R_f}{C_{ld} + 2C_1 + C_0(1+3K_{0L})} \quad (4)$$

The above equation shows that in the case of zero fault resistance, the measured impedance at the relaying point is equal to its exact value and otherwise it deviates from its actual value depending on the fault resistance and the system conditions. As the fault resistance increases, the measured impedance deviates more.

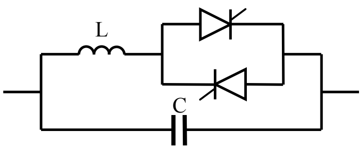

Fig. 1 TCSC circuit arrangement

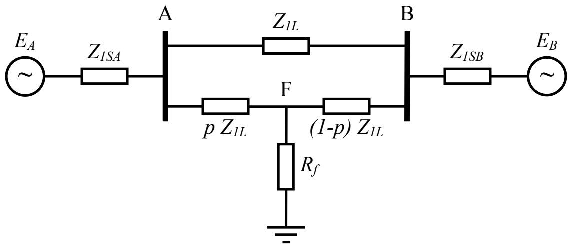

Fig. 2. Equivalent circuit for single-phase to earth fault

As mentioned, the above equation presents the measured impedance for the faults in the first zone, faults on the first circuit. But in the reverse direction, the second circuit of the double circuit line also should be considered, since in this case the second circuit is involved. Fig. 2 can also be utilized in this case by assuming that the faulted circuit is the second circuit and the non-faulted circuit is the first one.

With respect to Fig. 2 and Fig. 3, the measured impedance at the relaying point for the faults on the second circuit can be expressed by the following equations. More detailed calculations can be found in [2], [7-9].

$$Z_{1A} = Z_{1SA} + p\,Z_{1L} / 2 \quad (5)$$

$$Z_{1B} = Z_{1SB} + (1-p)Z_{1L} / 2 \quad (6)$$

$$Z_1 = \frac{Z_{1A}Z_{1B}}{Z_{1A}+Z_{1B}} + p(1-p)Z_{1L} / 2 \quad (7)$$

$$C_{1A} = \frac{Z_{1B}}{Z_{1A}+Z_{1B}} \quad (8)$$

$$Z_{0A} = Z_{0SA} + p(Z_{0L}+Z_{0M}) / 2 \quad (9)$$

$$Z_{0B} = Z_{0SB} + (1-p)(Z_{0L}+Z_{0M}) / 2 \quad (10)$$

$$Z_0 = \frac{Z_{0A}Z_{0B}}{Z_{0A}+Z_{0B}} + p(1-p)(Z_{0L}-Z_{0M}) / 2 \quad (11)$$

$$C_{0A} = \frac{Z_{0B}}{Z_{0A}+Z_{0B}} \quad (12)$$

$$Z_\Sigma = 2Z_1 + Z_0 \quad (13)$$

$$C_1 = \frac{(1-p)(Z_{1SA}+Z_{1L}) + (2-p)Z_{1SB}}{2(Z_{1A}+Z_{1B})} \quad (14)$$

$$C_0 = \frac{(1-p)(Z_{0SA}+Z_{0L}+Z_{0M}) + (2-p)Z_{0SB}}{2(Z_{0A}+Z_{0B})} \quad (15)$$

$$K_{0L} = \frac{Z_{0L}-Z_{0M}-Z_{1L}}{3Z_{1L}} \quad (16)$$

$$K_\delta = \frac{1-he^{-j\delta}}{Z_{1A}he^{-j\delta}+Z_{1B}} \quad (17)$$

$$C_{ld} = (Z_\Sigma + 3R_f)K_\delta / 2 \quad (18)$$

$$C_P = pZ_{1L}[2(2C_1 - C_{1A}) + (2C_0 - C_{0A})(1+3K_{0L})] \quad (19)$$

$$Z_A = p\,Z_{1L} + \frac{C_P + 3R_f}{C_{ld} + 2(C_{1A}-C_1) + (C_{0A}-C_0)(1+3K_{0L})} \quad (20)$$

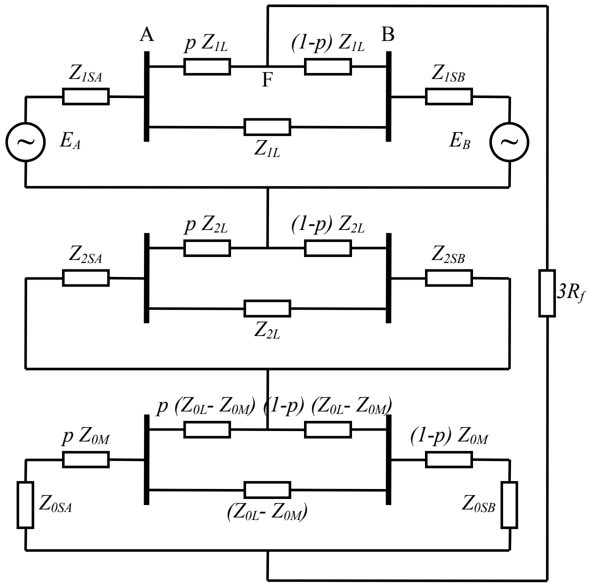

Fig. 3. Equivalent circuit of phase A to earth fault

It can be seen that for zero fault resistance, unlike the case of the first zone, the measured impedance at the relaying point is not equal to the impedance of the line section located between the relaying and the fault points. Here, the power system conditions even affect the measured impedance in the absence of the fault resistance.

Once TCSC is installed at the near end of the second circuit of the double circuit transmission line, some of the above equations would be changed. This variation also depends on TCSC compensation degree. In the following sub-section, TCSC is represented by its compensation degree or coefficients C_{1T} and C_{0T}.

$$Z_{1A} = Z_{1SA} + \frac{p + C_{1S}}{2 + C_{1S}} Z_{1L} \quad (21)$$

$$Z_{1B} = Z_{1SB} + \frac{1 - p}{2 + C_{1S}} Z_{1L} \quad (22)$$

$$Z_1 = \frac{Z_{1A} Z_{1B}}{Z_{1A} + Z_{1B}} + \frac{(1-p)(p + C_{1S})}{2 + C_{1S}} Z_{1L} \quad (23)$$

$$Z_{0A} = Z_{0SA} + \frac{(p + C_{0S})Z_{0L} + [\,p(1 + C_{0S}) - C_{0S}\,]Z_{0M}}{2 + C_{0S}} \quad (24)$$

$$Z_{0A} = Z_{0SA} + \frac{(p + C_{0S})Z_{0L} + [\,p(1 + C_{0S}) - C_{0S}\,]Z_{0M}}{2 + C_{0S}} \quad (25)$$

$$Z_0 = \frac{Z_{0A} Z_{0B}}{Z_{0A} + Z_{0B}} + \frac{(1-p)(p + C_{0S})}{2 + C_{0S}}(Z_{0L} - Z_{0M}) \quad (26)$$

$$C_1 = \frac{(1-p)(Z_{1SA} + Z_{1L}) + (2-p)Z_{1SB}}{(2 + C_{1S})(Z_{1A} + Z_{1B})} \quad (27)$$

$$C_0 = \frac{(1-p)(Z_{0SA} + Z_{0L} + Z_{0M}) + (2-p)Z_{0SB}}{(2 + C_{0S})(Z_{0A} + Z_{0B})} \quad (28)$$

$$C_{ld} = \frac{1 + C_{1S}}{2 + C_{1S}}(Z_\Sigma + 3R_f)K_\delta \quad (29)$$

$$C_{ld_\Delta} = \frac{-C_{1S}}{2 + C_{1S}}(Z_\Sigma + 3R_f)K_\delta \quad (30)$$

$$C_P = (p + C_{1S})Z_{1L}\begin{bmatrix} C_{ld_\Delta} + 2(2C_1 - C_{1A}) + \\ (2C_0 - C_{0A})(1 + 3K_{0L}) \end{bmatrix} \quad (31)$$

$$C_{Z_S} = (C_{0S} - C_{1S})C_0(1 + 3K_{0L})Z_{1L} \quad (32)$$

$$Z_A = (p + C_{1S})Z_{1L} + \frac{C_P + C_{Z_S} + 3R_f}{C_{ld} + 2(C_{1A} - C_1) + (C_{0A} - C_0)(1 + 3K_{0L})} \quad (33)$$

IV. IMPACT OF TCSC ON DISTANCE RELAY TRIPPING CHARACTERISTIC

The impacts of the presence of TCSC on the near end of the second circuit, which might lead to mal-operation, have been tested for a test system. A 400 kV transmission line with the length of 200 km has been utilized. Various sequence impedances of the line are:

$R_{1L} = 2.680$ Ω
$X_{1L} = 62.28$ Ω
$R_{0L} = 30.20$ Ω
$X_{0L} = 233.1$ Ω
$R_{0M} = 9.160$ Ω
$X_{0M} = 50.08$ Ω

The structural conditions of the system are:

$R_{1SA} = 8.561$ Ω
$X_{1SA} = 20.241$ Ω
$R_{0SA} = 23.459$ Ω
$X_{0SA} = 108.31$ Ω
$R_{1SB} = 8.360$ Ω
$X_{1SB} = 15.570$ Ω
$R_{0SB} = 17.530$ Ω
$X_{0SB} = 70.759$ Ω

In the absence of TCSC, Fig. 4 shows the measured impedance at the relaying point for the fault resistances between 0 and 200 ohms and the fault point variation from the near end of the second circuit up to its far end. The characteristic impedance of first circuit is shown in Fig. 4 to make it possible to observe the impedance deviation, especially in the absence of the fault resistance. The quadrilateral characteristic is also plotted in Fig. 4 to show that in the absence of TCSC, in spite of measured impedance great deviation, distance relay would not mal-operate. In this figure, the ratio of the voltage magnitudes is 0.96, and the load angel is equal to 16°. The quadrilateral characteristic is set to 80% of the line impedance. In Fig. 4, the dotted region is the tripping characteristic. The measured impedance in the case of zero fault resistance has a quasi-oval shape.

Fig. 5 is the close look of Fig. 4. It can be seen that in the absence of TCSC, there is no over-lapping between the first line quadrilateral characteristic and the tripping characteristic for the faults on the second circuit. Therefore, in these conditions the distance relay would not mal-operate.

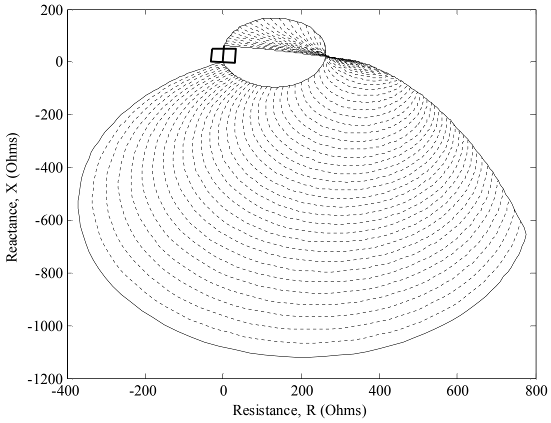

Fig. 4. Tripping characteristic for second circuit, without TCSC

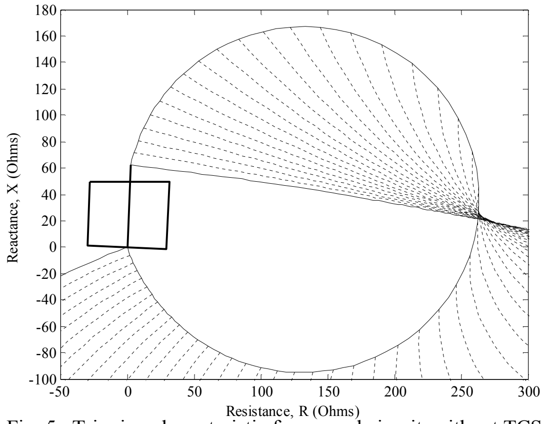

Fig. 5. Tripping characteristic for second circuit, without TCSC, close look

Fig. 6 shows the tripping characteristic for a negative load angle. Here, the load angle is equal to –16° and the ratio of the voltage magnitudes is 1.04.

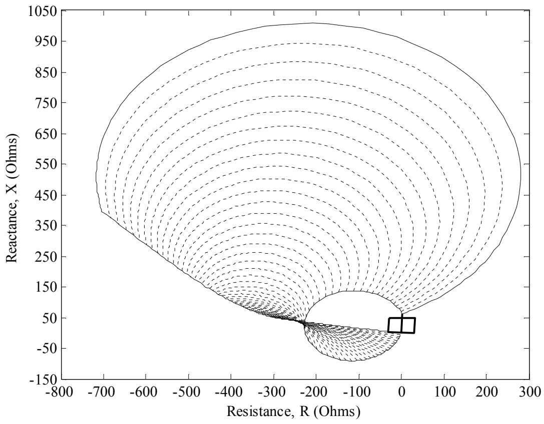

Fig. 6. Tripping characteristic for second circuit, without TCSC, negative load angle

It can be seen that, for the negative load angle, the tripping characteristic is changed considerably, but it is still somehow similar to that of the previous case. It can be said that the tripping characteristic turns 180°.

Fig. 7 is the close look of Fig. 6. It can be seen that in the absence of TCSC, a little over-lapping, at the left lower part of the quadrilateral characteristic, could be observed. Therefore, the probability of the mal-operation is very low.

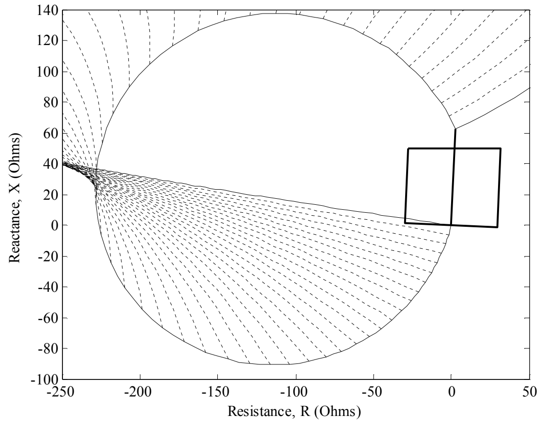

Fig. 7. Tripping characteristic for second circuit, without TCSC, negative load angle, close look

Fig. 8 shows the effect of TCSC compensation degree variation on the measured impedance at the relaying point for positive load angle, with the same parameters as Fig. 4. Here the compensation degree takes the values –0.1, 0.0, 0.1, 0.2, and 0.3. For better observation, the doted lines are omitted and only the outer boundary of the tripping characteristic is shown where only the close look of the tripping characteristic is presented.

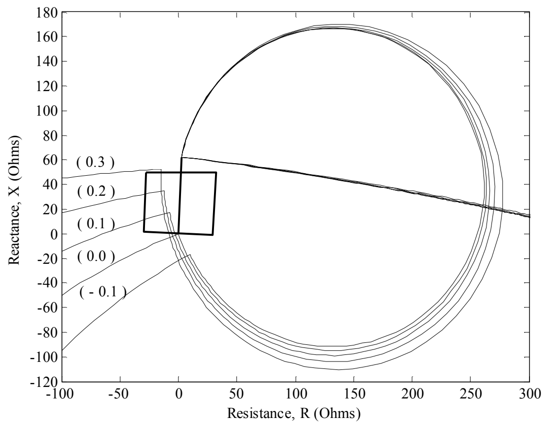

Fig. 8. Tripping characteristic, TCSC at near end of second circuit, positive load angle, effects of compensation degree variation, close look

It can be seen that for the inductive mode of TCSC, the distance between the lower boundary of the quadrilateral and the tripping characteristic of the faults on the second circuit is more than that of in the absence of TCSC. On the other hand, as the compensation degree increases, in the capacitive mode, the tripping characteristic expands and the distance between the tripping and the quadrilateral characteristics becomes less and the tripping characteristic enters the quadrilateral characteristic. As the compensation degree increases, the over-lap between the tripping and quadrilateral characteristics also increases considerably up to the compensation degrees around 0.3, and then it decreases slowly.

Fig. 9 shows the effect of TCSC compensation degree variation on the measured impedance for negative load angle, with the same parameters as Fig. 6. Here also the compensation degree takes the values –0.1, 0.0, 0.1, 0.2, and 0.3.

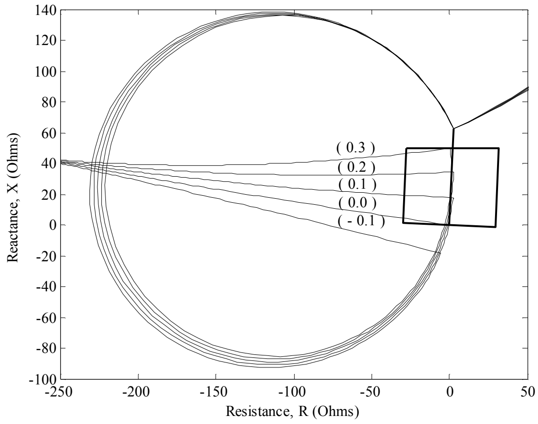

Fig. 9. Tripping characteristic, TCSC at near end of second circuit, negative load angle, effects of compensation degree variation, close look

It can be seen that for the inductive mode of TCSC, the distance between the lower boundary of the quadrilateral and the tripping characteristics increases. On the other hand, as the compensation degree increases, in the capacitive mode, the tripping characteristic expands and approaches toward the quadrilateral characteristic and even enters into it. As the compensation degree increases, the over-lap between the tripping and quadrilateral characteristics also increases considerably up to the compensation degrees around 0.3, and then this area decreases slightly.

Comparing the positive and the negative load angles, it can be seen that, in the case of positive load angles the overlapping region is smaller than that of for the negative load angles.

V. CONCLUSION

This paper evaluates the measured impedance at the relaying point in the presence of TCSC at the near end of the second circuit of a double circuit line. In the absence of TCSC, the measured impedance for the faults on the second circuit does not locate in the first zone of the other circuit, but in the presence of TCSC, the measured impedance might locate in the first zone, leading to distance relay mal-operation. The distance relay mal-operation depends on many parameters including: TCSC compensation degree and TCSC operating mode, capacitive or inductive, power system conditions and the fault resistance magnitude. The distance relay might mal-operate only in the case of TCSC in the capacitive mode.

As mentioned, the presence of a series capacitor is necessary for the distance relay mal-operation. But it is not the only affecting factor in distance relay mal-operation. Among the operational conditions, load angle has a great role in distance relay mal-operation.

It can be seen that in the presence of TCSC at the near end of the second circuit in a double circuit line, the distance relay greatly is subjected to mal-operation, and it is essential to consider this fact in providing the protective system. Since the deviation of the measured impedance is not constant, because of the various including parameters, adaptive methods should be utilized.

REFERENCES

1. Zhang Zhizhe, and C. Deshu, An adaptive approach in digital distance protection, IEEE Trans. Power Delivery, vol. 6, no. 1, pp. 135-142, Jan. 1991.
2. Y. Q. Xia, K. K. Li, and A. K. David, Adaptive relay setting for stand-alone digital distance protection, IEEE Trans. Power Delivery, vol. 9, no. 1, pp. 480-491, Jan. 1994.
3. S. Jamali, A fast adaptive digital distance protection, in Proc. 2001 IEE 7th International Conference on Developments in Power System Protection, DPSP 2001, pp. 149-152.
4. Khalil El-Arroudi, Geza Joos, and Donald. T. McGillis, Operation of impedance protection relays with the STATCOM, IEEE Trans. Power Delivery, vol. 17, no. 2, pp. 381-387, April 2002.
5. Wang Weiguo, Yin Xianggen, Yu Jiang, Duan Xianzhong, and Chen Deshu, The Impact of TCSC on Distance Protection Relay, in Proc. 1998 IEEE International Conference on Power System Technology, POWERCON '98, vol. 1, pp. 382-388.
6. M. Khederzadeh, The Impact of FACTS Devices on Digital Multifunction Protective Relays, in Proc. 2002 IEEE Conference and Exhibition on Transmission and Distribution, Asia Pacific IEEE/PES, vol. 3, pp. 2043-2048.
7. Yi Hu, D. Novosel, M.M. Saha, V. Leitloff, An adaptive scheme for parallel-line distance protection, IEEE Trans. Power Delivery, vol. 17, no. 1, pp. 105-110, Jan. 2002.
8. Yi Hu, D. Novosel, M.M. Saha, V. Leitloff, Improving parallel line distance protection with adaptive techniques, in Proc. 2000 Power Engineering Society Winter Meeting, vol. 3, pp. 1973-1978, Jan. 2000.
9. A.G. Jongepier, L. van der Sluis, Adaptive distance protection of a double-circuit line, IEEE Trans. Power Delivery, vol. 9, no. 3, pp. 1289-1297, July. 1994.