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Effects of Instrument Transformers Connection Point on Measured Impedance by Distance Relay in Presence of SSSC

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This paper presents the measured impedance at the relaying point in the presence of a series connected Flexible Alternating Current Transmission System (FACTS) device, i.e. Static Synchronous Series Compensator (SSSC). The presence of SSSC on a transmission line has a great influence on the tripping characteristic of distance relays. The distance relay tripping characteristic itself depends on power system structural and pre-fault operational conditions and, especially, the ground fault resistance. In the presence of SSSC, its controlling parameters, as well as the connection point of the instrument transformers of distance relay affect the tripping characteristic. Here, measured impedance at the relaying point is calculated, due to the concerned parameters.

Keywords: Distance protection; Fault resistance; FACTS devices; Tripping characteristic; SSSC.

INTRODUCTION

The measured impedance at the relaying point is the basis of the 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 [1-4]. The first group is the structural conditions, whereas the second group is the operational conditions. 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 recent years, FACTS devices have been 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 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 the 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 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 characteristics, such as Mho and Quadrilateral, are greatly subjected to mal-operation in the form of over-reaching or under-reaching the fault point. Therefore, the conventional characteristics might not provide the protective functions satisfactorily in the presence of FACTS devices.

Regarding the high levels of currents and voltages in EHV and HV systems, it is essential to provide the current and voltage signals for the protective system via instrument transformers. In the presence of SSSC at the relaying point, the connection point of the voltage transformers can be either in front of or behind SSSC. As the connection point changes,

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considerable variations in the measured impedance could result.

Reference [5] has presented the measured impedance at the relaying point in the presence of UPFC on a single circuit line, and [6] has presented the measured impedance in the presence of series connected FACTS devices (TCSC, TCPST and UPFC) on a double circuit line. The importance of the instrument transformers connection points has been mentioned in [7,8] for TCSC and in [9] for UPFC. References [7-9] have discussed the effect of FACTS devices by means of simulation or simple equations and, unlike [5-6], have not presented the detailed equations. The effects of the instrument transformers connection points have been studied for TCSC in [10] and for UPFC in [11] by means of presenting the measured impedance by distance relay for various instrument transformers connection points.

This paper presents the measured impedance at the relaying point in the presence of SSSC at the near end of the line. In addition to the controlling parameters of SSSC, the measured impedance depends on the distance relay instrument transformers connection point. Therefore, the studied connection points for voltage transformers are behind and in front of SSSC installation location. Regarding the measured impedance characteristic, it can be seen how much a distance relay is sensitive to its instrument transformers connection point.

SSSC AND ITS MODELING

As mentioned, the Static Synchronous Series Compensator (SSSC) is placed in the group of series connected FACTS devices. As shown in Figure 1, SSSC consists of a voltage source inverter connected in series through a coupling transformer to the transmission line. A source of energy is required for providing and maintaining the dc voltage across the dc capacitor and SSSC losses compensation [12].

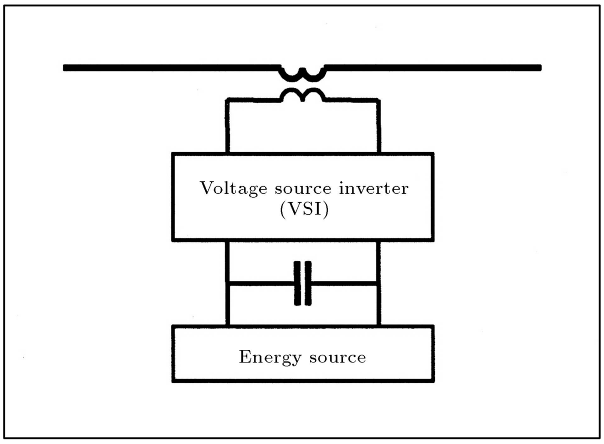

Figure 1. Basic configuration of SSSC.

Figure 2 shows the model of SSSC which consists of a series connected voltage source in series with an impedance. This impedance represents the impedance of a SSSC coupling transformer.

When the energy source only has the ability of maintaining the dc voltage and supplying the losses, SSSC only could compensate the reactive power. In this case, the magnitude of injected voltage can be controlled, due to a compensation strategy, but the phase angle of the injected voltage would be perpendicular to the line current. The injected voltage could either lead or lag the line current by 90°.

MEASURED IMPEDANCE AT RELAYING POINT

Distance relays operate based on the measured impedance at the relaying point. In the absence of SSSC and for zero fault resistance, the measured impedance by a distance relay only depends on the length of the line section located between the fault and the relaying points. In Figure 3, 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 located between the relaying and fault points. In this case, the structural and operational conditions of the power system affect the measured impedance. 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, or, in general, $E_B/E_A = he^{-j\delta}$.

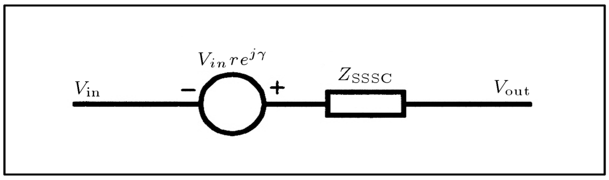

Figure 2. Equivalent circuit of SSSC.

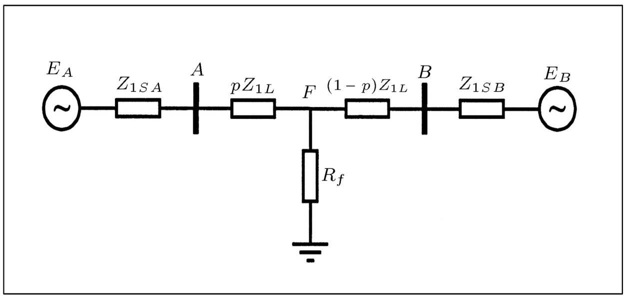

Figure 3. Equivalent circuit for single phase to ground fault.

The structural conditions are evaluated by the short circuit levels at the line ends, S_{SA} and S_{SB}. In the absence of SSSC and with respect to Figures 3 and 4, the measured impedance at the relaying point can be expressed by the following equations. More detailed calculations can be found in [2]:

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

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

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

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

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

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

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

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

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

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

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

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

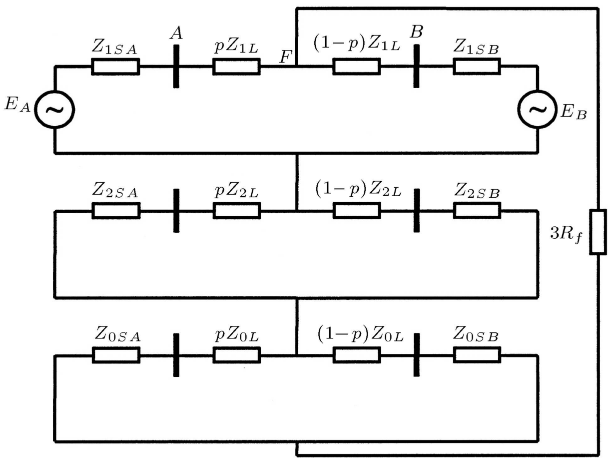

Figure 4. Equivalent circuit of phase A to ground fault.

conditions only affect the measured impedance in the presence of the fault resistance.

Once SSSC is installed at the near end of the line, Equations 1, 3 and 9 should be modified and some new ones are introduced:

$$Z_{1A} = Z_{1SA} + pZ_{1L} + Z_{\text{SSSC}}, \tag{12}$$

$$Z_{0A} = Z_{0SA} + pZ_{0L} + Z_{\text{SSSC}}, \tag{13}$$

$$Z_{1AI} = Z_{1SA}, \tag{14}$$

$$Z_{1IF} = pZ_{1L} + Z_{\text{SSSC}}, \tag{15}$$

$$Z_{1BF} = Z_{1SB} + (1-p)Z_{1L}, \tag{16}$$

$$K_{ld_{\text{SSSC}}} = \frac{1+re^{j\gamma}-he^{-j\delta}}{[Z_{1AF}(1+re^{j\gamma})+Z_{1IF}]he^{-j\delta}+Z_{1BF}(1+re^{j\gamma})}, \tag{17}$$

$$C_{ld_{\text{SSSC}}} = (Z_{\Sigma}+3R_f)K_{ld_{\text{SSSC}}}. \tag{18}$$

The above variations are due to the presence of SSSC at the near end of the line. The variations in the measured impedance not only depend on the SSSC controlling parameters, but also on the distance relay instrument transformers, voltage transformers, connection point. Therefore, the measured impedance is presented for two cases, VT behind and in front of SSSC.

VT Behind SSSC

In this case, the provided voltage signals are affected by the voltage of series converter. Therefore, Equation 11 should be modified and some new equations are introduced:

$$Z_{1BI} = Z_{\text{SSSC}} + Z_{1L} + Z_{1SB}, \tag{19}$$

$$K_{V_{\text{SSSC}}} = \frac{[Z_{1AI}he^{-j\delta}+Z_{1BI}]re^{j\gamma}}{[Z_{1AF}(1+re^{j\gamma})+Z_{1IF}]he^{-j\delta}+Z_{1BF}(1+re^{j\gamma})}, \tag{20}$$

$$C_{V_{\text{SSSC}}} = (Z_{\Sigma}+3R_f)K_{V_{\text{SSSC}}}, \tag{21}$$

$$C_{Z_{\text{SSSC}}} = 3Z_{\text{SSSC}}C_0K_{0L}, \tag{22}$$

$$Z_A = Z_{\text{SSSC}} + pZ_{1L} + \frac{3R_f - C_{Z_{\text{SSSC}}} - C_{V_{\text{SSSC}}}}{C_{ld_{\text{SSSC}}}+2C_1+C_0(1+3K_{0L})}. \tag{23}$$

It can be seen that in the absence of fault resistance, the measured impedance is not equal to the actual impedance up to the fault point, and two new deviating terms are introduced.

VT in Front of SSSC

In this case, the provided voltage signals are not affected by the voltage of series converter. So, Equation 11 should be modified as:

$$Z_A = pZ_{1L} + \frac{3R_f}{C_{ld_{\mathrm{SSSC}}} + 2C_1 + C_0(1+3K_{0L})}. \quad (24)$$

It can be seen that in the absence of the fault resistance, the measured impedance is neither affected by the power system conditions, nor by SSSC controlling parameters.

EFFECTS OF SSSC ON DISTANCE RELAY TRIPPING CHARACTERISTIC

The impacts of the presence of SSSC 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 in this study. The structure of this line is shown in [13]. By utilizing the Electro-Magnetic Transient Program (EMTP) [14], various sequence impedances of the line are evaluated according to its physical dimensions. The calculated impedances and the other parameters of the system are as follows:

$R_{1L} = 0.01133\ \Omega/\mathrm{km}$,

$R_{0L} = 0.1535\ \Omega/\mathrm{km}$,

$Z_{1SA} = 8\angle 85^\circ\ \Omega$,

$Z_{0SA} = 12\angle 75^\circ\ \Omega$,

$Z_{1SB} = 16\angle 85^\circ\ \Omega$,

$Z_{0SB} = 24\angle 75^\circ\ \Omega$,

$X_{1L} = 0.3037\ \Omega/\mathrm{km}$,

$X_{0L} = 1.1478\ \Omega/\mathrm{km}$,

$h = 0.96, \qquad \delta = 16^\circ$.

Utilizing the Matlab simulation test bed, in the absence of SSSC, Figure 5 shows the tripping characteristic of the distance relay, which is the measured impedance at the relaying point by distance relay, as the fault resistance varies from 0 to 200 ohms, while the fault location moves from the relaying point up to the far end of the transmission line.

In the following, the measured impedance by distance relay is studied for two cases of distance relay voltage transformer behind or in front of SSSC.

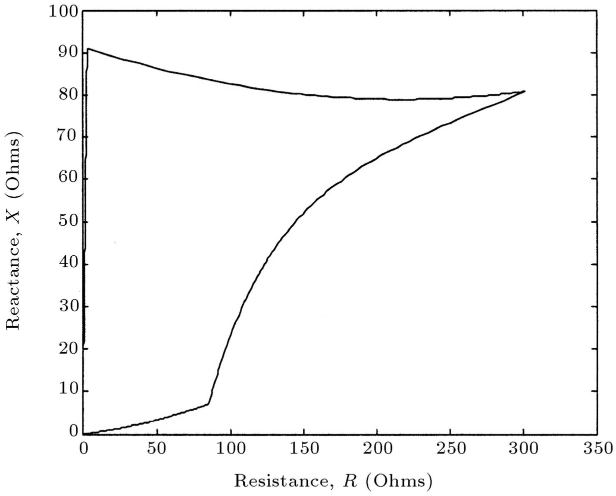

Figure 5. Distance relay tripping characteristic without SSSC.

VT Behind SSSC

As mentioned, in this case the voltage signals are affected by the voltage of series converter. Figure 6 shows the effect of an inactive SSSC presence on the line. Here, the injected voltage of SSSC is zero and it does not inject or absorb the reactive power.

It can be seen that, even in the case of inactive SSSC, i.e. its injected voltage is zero, it would affect the measured impedance at the relaying point. This is due to the presence of the coupling transformer in series with the line. It can be seen that the tripping characteristic shifts upward. The measured resistance increases, as well as the measured reactance.

Figure 7 shows the effect of SSSC voltage magnitude variation on the measured impedance at the relaying point in the lagging mode. Here, r takes the values of 0.0, 0.1, 0.2 and 0.3. The tripping

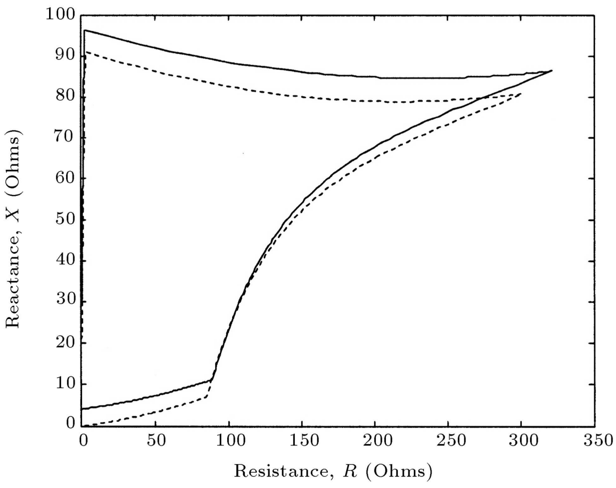

Figure 6. Tripping characteristic: VT behind of inactive SSSC.

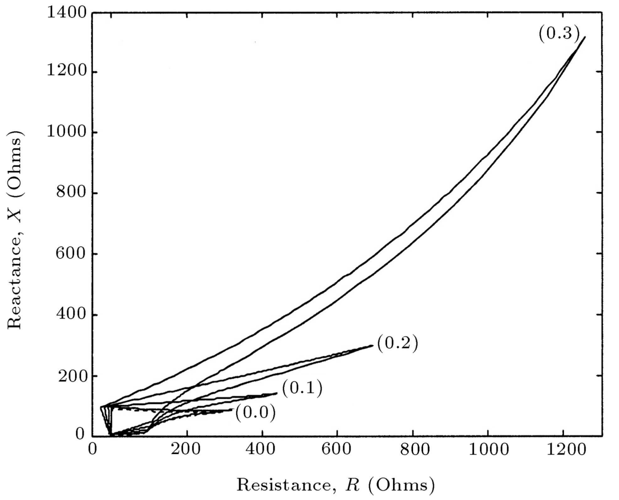

Figure 7. Tripping characteristic: VT behind of SSSC in leading mode.

characteristic without SSSC is also plotted in dotted form for comparison.

It can be seen that, as the injected voltage increases, the measured resistance increases for the high fault resistances, while, in the case of the low fault resistances, the measured resistance decreases; for zero fault resistance and high magnitudes of injected voltage, the measured resistance becomes negative. On the other hand, as the injected voltage increases, the measured reactance also increases. The increase in the measured reactance becomes greater for the higher fault resistances. Generally, it can be said that in the presence of SSSC in the lagging mode at the near end of the transmission line, the tripping characteristic expands and turns in an anticlockwise direction.

Figure 8 is a close-up of Figure 7, which shows the variation of the measured impedance in the case of zero and low fault resistances. The considerable anticlockwise turning of the measured impedance can be observed.

Figure 9 shows the effect of SSSC voltage magnitude variation on the measured impedance in the leading mode. Here, r takes the values of 0.0, 0.1, 0.2 and 0.3. The tripping characteristic without SSSC is also plotted in dotted form.

It can be seen that, as the injected voltage increases, the measured resistance changes complicatedly, it decreases for the high fault resistances, while in the case of low fault resistances, the measured resistance increases. On the other hand, as the injected voltage increases, the measured reactance decreases. Generally, it can be said that, in the presence of SSSC in the leading mode at the near end of the transmission line, the tripping characteristic shrinks and turns in a clockwise direction.

VT in Front of SSSC

As mentioned, in this case, the voltage signals are not affected by the voltage of the series converter. Figure 10 shows the effect of an inactive SSSC presence on the line.

It can be seen that, even in the case of inactive SSSC, the measured impedance is affected due to the presence of the coupling transformer in series with the line. The measured resistance increases, while the measured reactance decreases slightly. In the case of zero fault resistance, the measured impedance is the actual impedance of the line section between the relaying and fault points.

Figure 11 shows the effect of SSSC voltage magnitude variation on the measured impedance at the relaying point in the leading mode. Here, r takes the values of 0.0, 0.1, 0.2 and 0.3.

It can be seen that, as the injected voltage

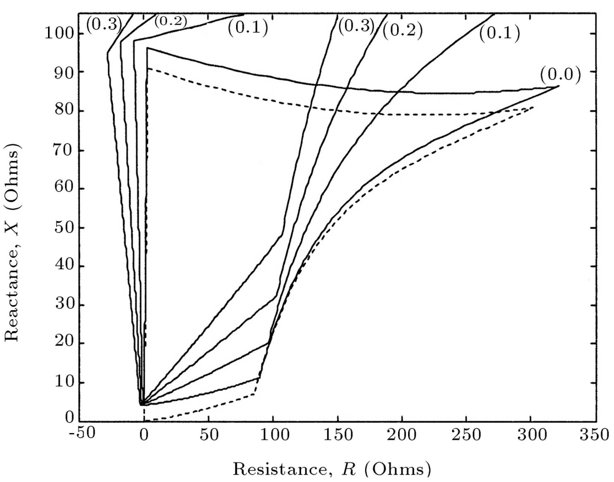

Figure 8. Tripping characteristic: VT behind of SSSC in leading mode, close look.

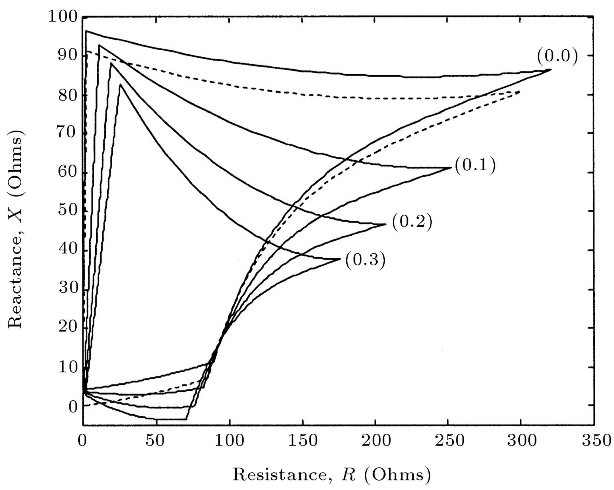

Figure 9. Tripping characteristic: VT behind of SSSC in lagging mode.

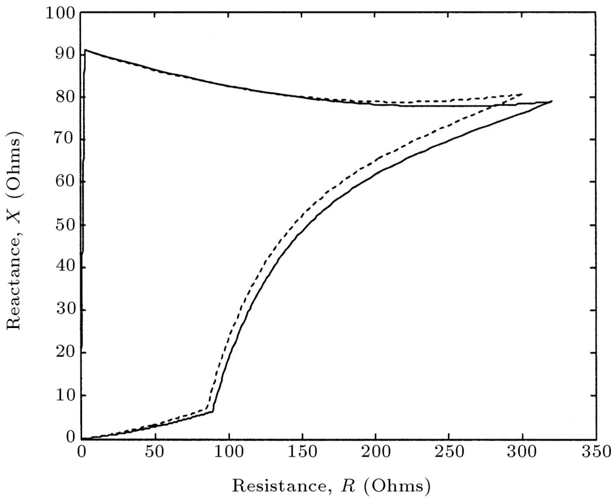

Figure 10. Tripping characteristic: VT in front of inactive SSSC.

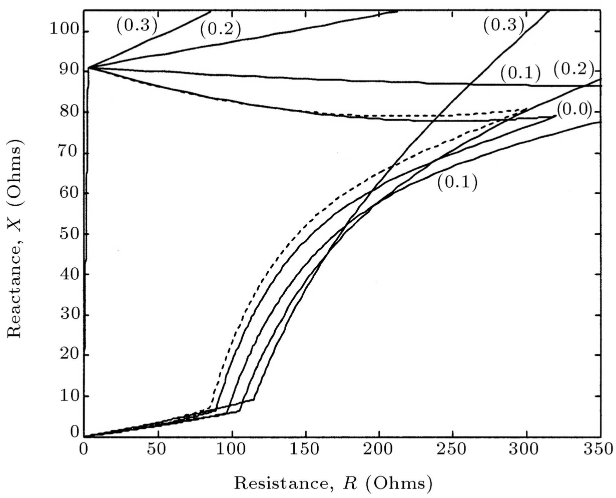

Figure 12. Tripping characteristic: VT in front of SSSC in leading mode, close look.

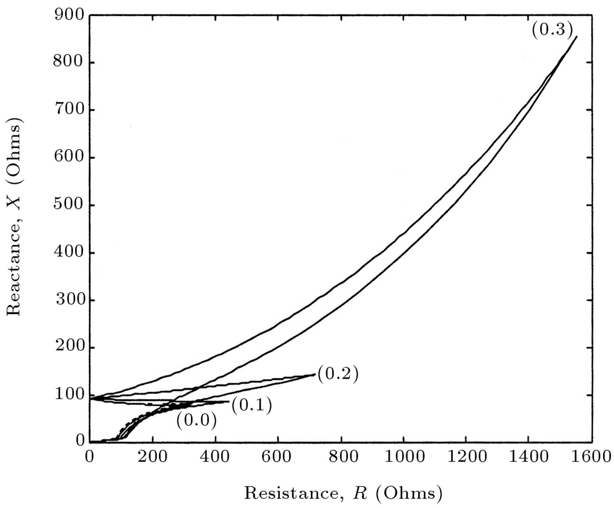

Figure 11. Tripping characteristic: VT in front of SSSC in leading mode.

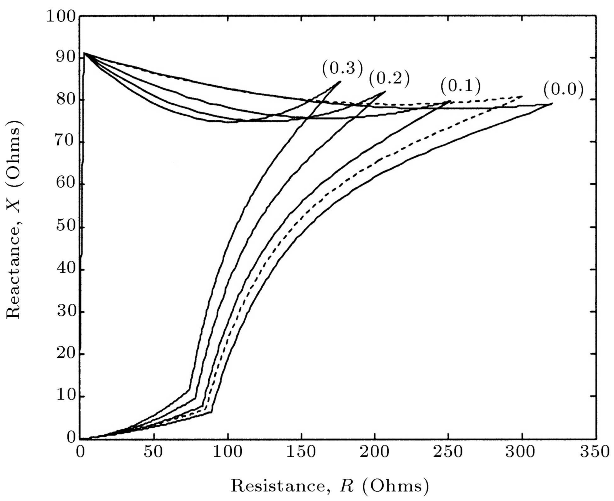

Figure 13. Tripping characteristic: VT in front of SSSC in lagging mode.

increases, the measured resistance increases. On the other hand, as the injected voltage increases, the measured reactance also increases. The increase in the measured reactance becomes greater for the higher fault resistances. In the case of zero fault resistance, the measured impedance is the actual impedance of the line section between the relaying and fault points. Generally, it can be said that the tripping characteristic expands and no turning can be observed.

Figure 12 is a close-up of Figure 11, which shows the measured impedance in the case of zero and low fault resistances. The fixed measured impedance for zero fault resistance can be observed.

Figure 13 shows the effect of SSSC voltage magnitude variation on the measured impedance in the leading mode. Here, r takes the values of 0.0, 0.1, 0.2 and 0.3.

It can be seen that, as the injected voltage increases, the measured resistance decreases. On the other hand, as the injected voltage increases, the measured reactance changes complicatedly, it increases for the faults near the relaying point, but at the far end it increases for the high fault resistances, while in the case of the low fault resistances, it decreases. Generally, it can be said that in the presence of SSSC in the lagging mode, the tripping characteristic shrinks and no turning could be observed.

COMPARISON

As mentioned, in the case of VT behind SSSC, Equation 23 indicates the measured impedance at the relaying point, whereas, in the case of VT in front of SSSC, Equation 24 presents this value. In the case of VT behind SSSC, apart from the minor changing of (Equation 11) elements, the measured impedance at the relaying point deviates from its value without SSSC in three terms. The first term is Z_{SSSC}, which is added to pZ_{1L} and transfers the tripping characteristic upward. The second term is $C_{Z\mathrm{sssc}}$, which is due to the presence of the coupling transformer in series with the transmission line. The third term is $C_{V\mathrm{sssc}}$, which is due to the presence of the series voltage source in series with the transmission line. In the case of inactive SSSC, $C_{V\mathrm{sssc}}$ is zero, but $C_{Z\mathrm{sssc}}$ is not zero; therefore, the measured impedance deviates from its actual value. For zero fault resistance, both $C_{V\mathrm{sssc}}$ and $C_{Z\mathrm{sssc}}$ are not zero, so lead to the measured impedance deviation.

Figure 14 shows a close-up of the tripping characteristic, in case of VT behind and r of 0.0, 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 in both leading and lagging modes. The tripping characteristic without SSSC is also plotted in the dotted form.

It can be seen how much the measured impedance, in the case of zero fault resistance, deviates from the actual impedance of the line section between the relaying and fault points in both forms of magnitude and phase angle deviations.

In the case of VT in front of SSSC, only the minor variations could be seen in elements of Equation 11. There is no additional deviating term in Equation 24. Therefore, in the case of zero fault resistances, the measured impedance is the actual impedance of the line section between the relaying and fault points.

Figure 15 shows a close-up of tripping characteristic in case of VT in front and r of 0.0, 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 in both leading and lagging modes. The tripping characteristic without SSSC is also plotted in the dotted form.

It can be seen that, in the case of zero fault resistance, there is no deviation from the actual impedance of the line section between the relaying and fault points.

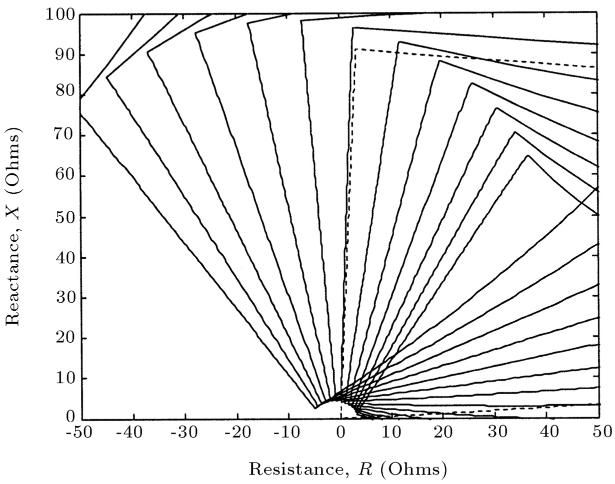

Figure 14. Tripping characteristic: VT behind.

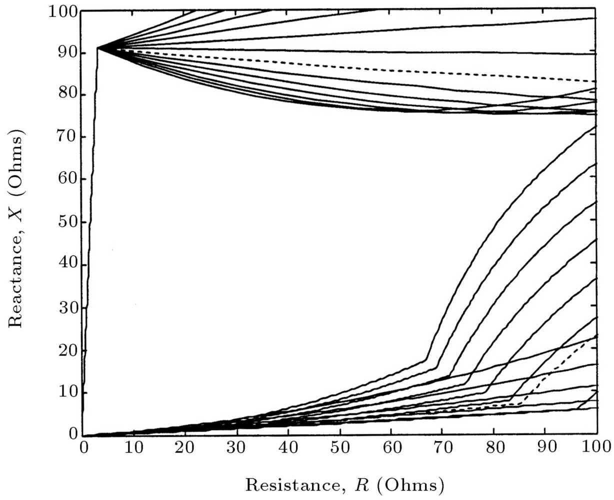

Figure 15. Tripping characteristic: VT in front.

CONCLUSION

The variation of the system conditions affects the tripping characteristic. The combination of the changes in the system conditions, SSSC controlling parameters and the distance relay instrument transformers connection points have a complicated influence on the measured impedance at the relaying point and, therefore, on the tripping characteristic.

Comparing the cases of VT behind and in front of SSSC, it can be concluded that VT in front of SSSC is the preferred case. In the case of VT in front of SSSC, the measured impedance and, therefore, tripping characteristic, deviates only in the presence of the fault resistance, because in Equation 24 there is no deviating term other than $3R_f$. On the other hand, in the case of VT behind SSSC, there are two additional deviating terms, i.e. $C_{Z\mathrm{sssc}}$ and $C_{V\mathrm{sssc}}$, which lead to incorrect impedance measurement in the absence of fault resistance.

Therefore, providing voltage signals from the voltage transformers, which are connected in front of SSSC, leads to a much more realistic operation of the protective relays for the faults in the first zone.

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