Analysis of the Impact of Thyristor Controlled Series Capacitor on the Performance of Distance Relay

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Abstract*- The use of FACTS devices for reactive power compensation offers a lot of benefits. However, these devices affect the distance protection scheme used by the transmission line protection system. This paper examines the impact of the TCSC on the apparent impedance seen by distance relay on the transmission line of Nigeria 330kv transmission network. The system mathematical model was developed and simulated using MATLAB/SIMULINK. Analytical study based on voltages and currents symmetrical components for single phase to ground fault, to show the impact of TCSC on distance relay was investigated. The simulation result showed that the distance relay over-reach or under-reach when power flow was controlled in the system using TCSC.

Index Terms: FACTS, TCSC, Relay, Protection, Compensation.

I. INTRODUCTION

FACTS devices are now being used for more utilisation and control of the existing transmission infrastructure. These devices offer flexible control of the voltage magnitude, phase angle and the line impedance. With their operation power flow in the system can be easily redistributed and therefore transmission capacity is fully utilised.

The presence of these devices like the Thyristor Controlled Series Capacitor (TCSC) in the faulted loop introduces changes to the line parameters seen by the distance relay. The impact of TCSC would affect both the steady state and transient trajectory of the apparent impedance seen by distance relay due to the fast response time of these controllers with respect to that of the protective devices. The impact of the TCSC on distance protection varies depending on the level of compensation, the application for which it is applied and the location of the TCSC in the power system. The apparent impedance calculated are generally carried out using power frequency components of voltage and current measured at relay point.

It is extremely important and necessary to investigate the impact of TCSC on the impedance-based distance protection relay, which is the main protective device at high voltage transmission. This is because the interaction of the TCSC with the transmission system especially during fault condition superimposes transient on power, frequency, voltage and current waveforms thus, yielding to a significant change between the system parameters for a compensated and uncompensated line.

The basic principle of distance protection involves the division of the voltage at the relaying point by the measured current. The apparent impedance so calculated is compared with the reach point impedance. If the measured impedance is less than the reach point impedance, it is assumed that a fault exists on the line between the relay and the reach point. The characteristics can be described using an R-X diagram. They provide primary and backup facilities by their three zones elements. In the presence of FACTS devices, the conventional distance characteristics such as Mho and Quadrilateral are greatly subjected to mal-operate in the form of over-reaching or under-reaching [1].

In [2] the impact of TCSC on MHO distance protection settings in studied while the impact on communication aided distance protection scheme and its mitigation is reported in [3]. In [4] the apparent impedance seen by distance relay for inter phase fault with TCSC on a double transmission line high voltage is

being studied and in [5] the variation of apparent impedance by distance relay for inter phase faults in the presence of TCSC on adjacent transmission line is investigated. Comparing TCSC placement on double circuit line at mid-point and at ends from measured impedance point of view is discussed in [6].

In this paper, the study of the apparent reactance injected by TCSC on the Nigerian transmission line protected by distance relay in the presence of single phase to earth fault with fault resistance has been investigated in order to improve the performance of the relay.

II. MATERIALS AND METHODS

The TCSC is a series FACTS compensator which consist of a capacitance (C) connected in parallel with an inductance (L) controlled by a valve mounted in anti-parallel conventional thyristors T_1 and T_2 and controlled by an extinction angle (α) varied between 90^0 and 180^0.

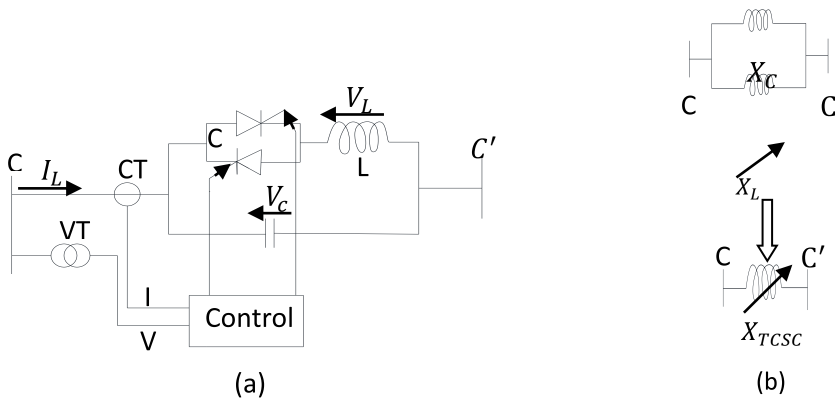

Figure 1: Transmission Line with TCSC System

a) System Configuration (b) Apparent Reactance

This compensator can be modelled as a variable reactance (X_{TCSC}) as shows in Fig. 1(b) and the apparent reactance of the TCSC injected on transmission line is defined by the following equations 1 and 5 [7],[8],[9].

$$X_{TCSC(\alpha)} = X_{L(\alpha)} // X_C = \frac{X_{L(\alpha)} X_C}{X_{L(\alpha)} + X_C} \qquad (1)$$

The reactance of the variable inductance $X_{L(\alpha)}$ controlled by the thyristor is defined by equation

$$X_{L(\alpha)} = X_{Lmax}\left[\frac{\pi}{\pi - 2\alpha - sin(2\alpha)}\right] \qquad (2)$$

Where

$$X_{Lmax} = L\omega \qquad (3)$$

The capacitance is defined by

$$X_c = \frac{-1}{J\omega C} \qquad (4)$$

From equation 2 and 4, the final equation 1 becomes

$$X_{TCSC(\alpha)} = \left[\frac{L\omega.\left[\frac{\pi}{\pi - 2\alpha - \sin 2\alpha}\right].\frac{1}{\omega C}}{L\omega\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right] + \frac{1}{\omega C}}\right] \qquad (5)$$

Or

$$X_{TCSC(\alpha)} = \frac{X_C X_{Lmax}\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right]}{X_c + X_{Lmax}\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right]}$$

The active power (P) and reactive power (Q) on transmission line with TCSC are defined by following equations

$$P(\delta) = \frac{V_A.V_B}{Z_{AB} + X_{TCSC(\alpha)}} \sin\delta \qquad (6)$$

$$Q(\delta) = \frac{V_B^2}{Z_{AB} + X_{TCSR}} - \frac{V_A V_B}{Z_{AB} + X_{TCSC}} \cos\delta \qquad (7)$$

Where, Z_{AB} is impedance of transmission line, δ is line angle, V_A and V_B voltages on extremity of transmission line [11],[12].

A. Fault Calculation In The Presence of TCSC

For a single line to ground fault in the presence of TCSC, the method of symmetrical components are used to analyse the unbalanced fault currents. With the TCSC inserted on the midline and subjected to a single line to ground fault F at phase A which occurs at a fault location represented by n_F in the presence of a fault resistance, R_F . Fault location (n_F) is equal to zero if the fault occurs at bus-bar A and it is 100% if it occurs at bus-bar B. The generator internal impedance denoted by Z_s is ignored due to its small magnitude when compared with the impedance of the line. Basic equations for this type of fault at phase A are given by, [10], [13-14]:

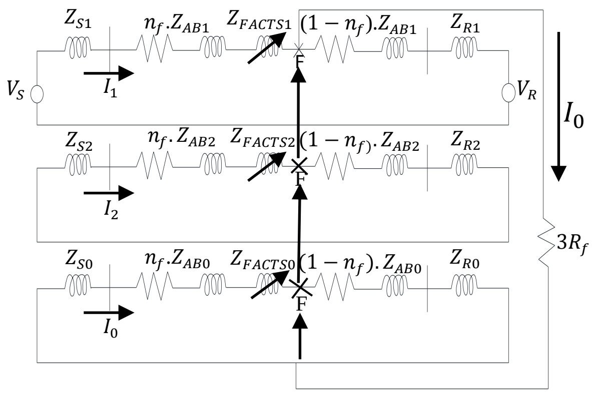

Fig 2: Interconnection of sequence network for a single line to ground fault

The boundary conditions for a single line to ground fault are:

$$I_B = I_C = 0 \tag{8}$$

$$V_A = V_0 + V_1 + V_2 = R_F I_A \tag{9}$$

The symmetrical component of line currents are given by [15-16]

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{10}$$

From equation (8) and (10) the current symmetrical components take the following form

$$I_0 = I_1 = I_2 = \frac{I_A}{3} \tag{11}$$

Similarly, the voltage symmetrical components are given by, [15-16]

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{12}$$

so, the symmetrical component of impedances are given by [15-16]

$$\begin{bmatrix} Z_0 \\ Z_1 \\ Z_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} Z_A \\ Z_B \\ Z_C \end{bmatrix} \tag{13}$$

Hence, the symmetrical components of the transmission line impedance Z_{AB} and the apparent reactive impedance of the TCSC device Z_{TCSC} are defined according to equation (13) as follows:

$$Z_{AB} = Z_{AB0} + Z_{AB1} + Z_{AB2} \tag{14}$$

$$Z_{TCSC} = Z_{TCSC0} + Z_{TCSC1} + Z_{TCSC2} \tag{15}$$

From figure 2, V_1, V_0 and V_2 have the following form:

$$V_1 = V_s - \left(n_f.Z_{AB1} \pm Z_{TCSC1}\right).I_1 \tag{16}$$

$$V_2 = -\left(n_f.Z_{AB2} \pm Z_{TCSC2}\right).I_2 \tag{17}$$

$$V_0 = -\left(n_f.Z_{AB0} \pm Z_{TCSC0}\right).I_0 \tag{18}$$

Substituting by the above equations (16), (17) and (18) in equation (12) using equation (10) yields:

$$V_s = \frac{I_A}{3}\left(n_f.Z_{AB} \pm Z_{TCSC} + 3.R_f\right) \tag{19}$$

From equation (19), the amount of phase A in the presence of a TCSC device is given by

$$I_A = \frac{3V_s}{(n_f.Z_{AB} \pm Z_{TCSC} + 3R_f)} \qquad (20)$$

From equations (10) and (20), the current symmetrical components in the presence of TCSC take the following form

$$I_0 = I_1 = I_2 = \frac{I_A}{3} = \frac{V_S}{(n_f.Z_{AB} \pm Z_{TCSC} + 3R_f)} \quad (21)$$

Substituting by I_1 from equation (21) into equation (16) using equation (14) and (15), the direct voltage components takes the following form.

$$V_1 = \frac{V_s[n_f(Z_{AB0} + Z_{AB2}) \pm (Z_{TCSC0} + Z_{TCSC2}) + 3R_f}{(n_f Z_{AB} \pm Z_{TCSC} + 3R_f)} \quad (22)$$

Similarly, using equation (17) and (21), the inverse voltage component becomes

$$V_2 = -\frac{V_s.[n_f.Z_{AB2} \pm Z_{TCSC2}]}{(n_f Z_{AB} \pm Z_{TCSC} + 3.R_f)} \qquad (23)$$

Using equations (18) and (21), the zero sequence component of the voltage becomes

$$V_0 = \frac{-V_s.[n_f.Z_{AB0} \pm Z_{TCSC0}]}{(n_f.Z_{AB} \pm Z_{TCSC} + 3R_f)} \qquad (24)$$

B. Apparent Impedance Analysis

Distance relays are widely used in the protection of transmission lines. Such a relay is designed to operate only for faults occurring between the relay location and the selected reach point thus discrimination of faults that may occur in different line zones. Since the impedance of a transmission line is proportional to its length, distance relays have the capability of measuring the impedance of a line up to a predetermined point (the reach point). The basic principle of distance protection involves the division of the voltage at the relaying point by the measured current. The apparent impedance so calculated is compared with the reach point impedance. If the measured impedance is less than the reach point impedance, it is assumed that a fault exists on the line between the relay and the reach point. The protection of a transmission line is zoned with each zone protected by a relay having different reach and operating time. The setting zones for protected electrical transmission line without TCSC is

$$Z_1 = R_1 + jX_1 = 80\% Z_{AB} = 0.8(R_{AB} + jX_{AB}) \qquad (25)$$

$$Z_2 = R_2 + jX_2 = R_{AB} + jX_{AB} + 0.2(R_{BC} + jX_{BC}) \qquad (26)$$

$$Z_3 = R_3 + jX_3 = R_{AB} + jX_{AB} + 0.4(R_{BC} + jX_{BC}) \qquad (27)$$

The total impedance of electrical transmission line AB measured b distance relay without fault is [17]:

$$Z_{seen} = K_Z.Z_{AB} = \left({}^{K_{VT}}/_{K_{CT}}\right).Z_{AB} \qquad (28)$$

Where

$$K_{VT} = {}^{V_{prim}}/_{V_{sec}} \qquad (29)$$

And

$$K_{CT} = {}^{I_{prim}}/_{I_{sec}} \qquad (30)$$

The impedance Z_{AB} is real total impedance of protected transmission line AB, and K_{VT} and K_{CT} are a ratio of voltage to current transformer respectively. The presence of the TCSC with its reactor (X_{TCSC}) has a direct influence on the total impedance Z_{AB} of the line protected by the distance relay but no influence on the resistance. The new setting zones for a protected line with TCSC connected at midline are [18]:

$$Z_1 = 0.8[R_{AB} + jX_{AB} + jX_{TCSC}] \qquad (31)$$

$$Z_2 = R_{AB} + jX_{AB} + jX_{TCSC}(\alpha) + 0.2(R_{BC} + jX_{BC}) \qquad (32)$$

$$Z_3 = R_{AB} + jX_{AB} + jX_{TCSC}(\alpha) + 0.4(R_{BC} + jX_{BC}) \qquad (33)$$

III. CASE STUDY AND ANALYSIS OF SIMULATION RESULTS

The case study of this research work is for a 330 kV, 50 Hz, transmission line connecting Onitsha and Alaoji substations in the Nigerian power system which is shown in Figure 3. The series FACTS devices is installed between bus-bar A at Onitsha substation and bus-bar B at Alaoji substation. Figure 3 shows the Nigeria 41-bus power system.

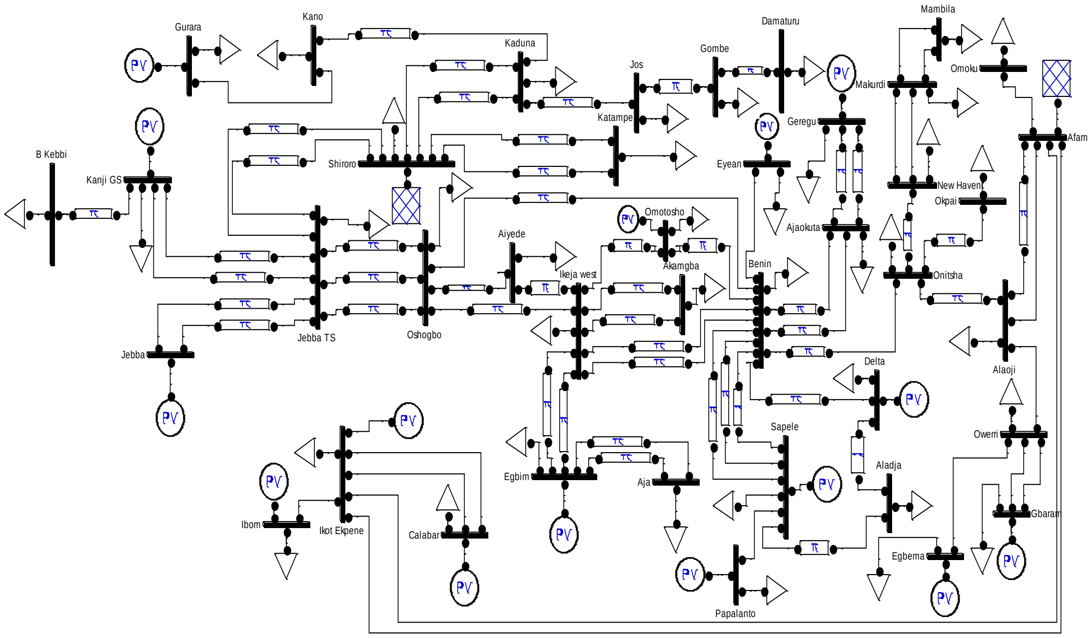

Figure 3: Nigeria 41 bus Power System

The series compensator TCSC is installed in midline of the line between Onitsha and Alaoji. The single line diagram of the transmission line was simulated without TCSC and in the presence of TCSC using MATLAB/Simulink and the results discussed.

A. System Simulations

With the aid of MATLAB/Simulink software, the SimPower tool was used to develop the models of the distance relay. Each subsystem was established separately and then connected together to compose the larger power transmission system.

The subsystems used were based on the main function of a typical digital distance relay. These include: Fault detection and classification subsystem, apparent impedance measurement, zone detection and tripping signal subsystem.

The Mho characteristics of the distance relay was obtained using M-file MATLAB. This enhances the understanding of the distance relay behaviour. To obtain the shape of mho characteristics, calculations of the setting impedance for each zone has to be performed first, and then attaching the corresponding results in a specific code in M-file MATLAB , which draws the shape of each zone of Mho relay characteristic, as presented in figure 4.

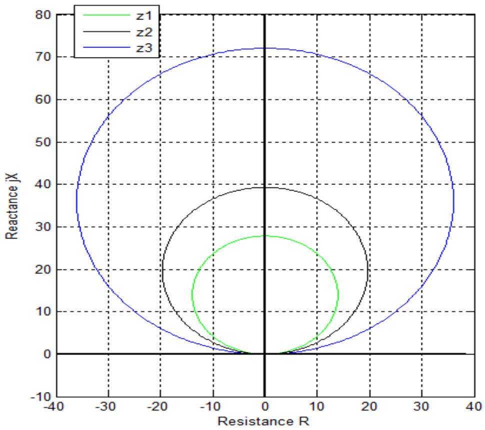

Figure 4: Mho Characteristics of distance relay

B. System Simulation of Distance Relay

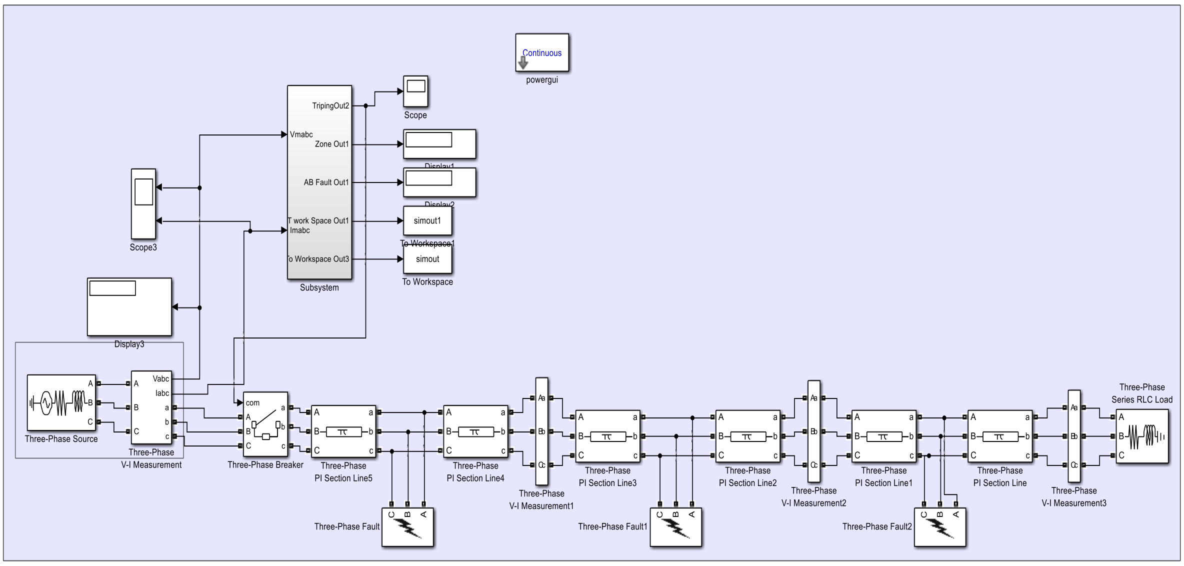

Figure 5: MATLAB/Simulink Model of Distance relay

The system was firstly simulated for a single line to ground (SLG) fault without the FACTS device and it showed that the relays acted accurately for faults occurring at their preset zones of operation. Figure 6(a) shows trace of apparent impedance as seen by the Mho distance relay due to SLG for fault occurring at 70 km, the impedance trajectory fall in the first zone of R-jX plain which is correct function of the relay. While figure 6(b) and figure 6(c) demonstrate the impedance measured by the Mho distance relay under SLG fault at the distance of 115 km and 210 km from the relay location respectively, the results shows that the relay has indicated impedance in the second and third zone respectively (correct function).

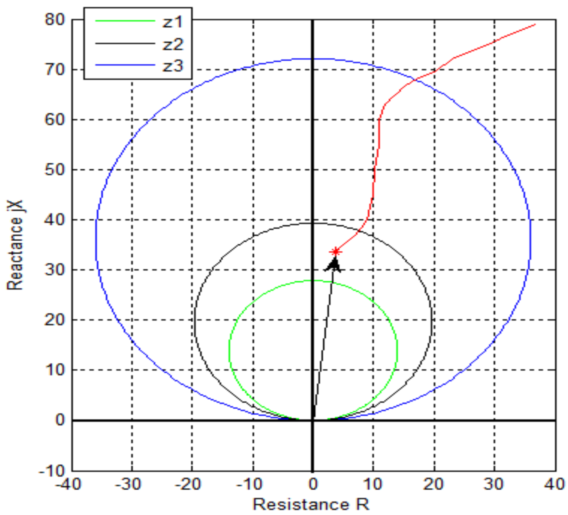

Figure 6(b). R-jX plot Impedance for a fault at 115 km distance

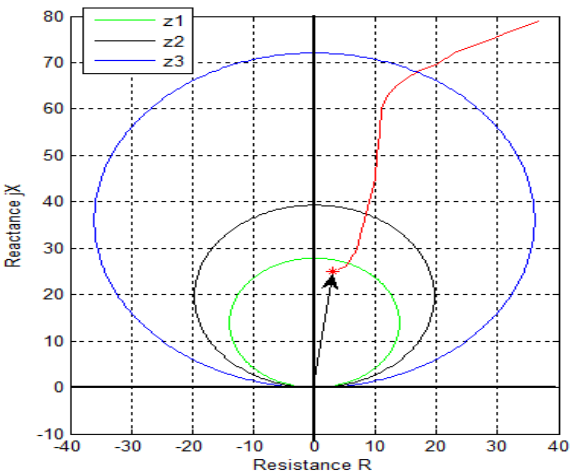

Figure6(a). R-jX plot Impedance for a fault at 70 km distance

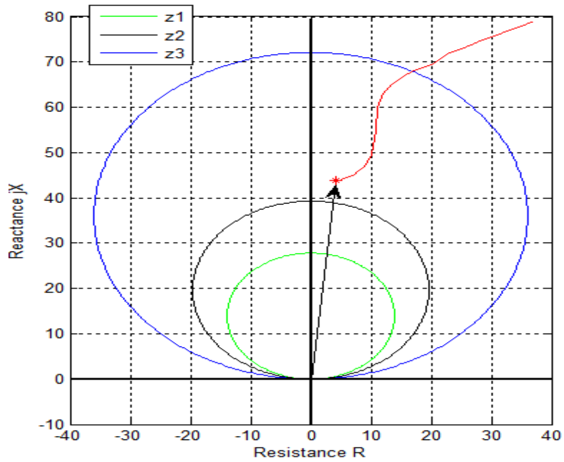

Figure 6(c). R-jX plot Impedance for a fault at 210 km distance

C. *System Simulation with FACTS Devices*

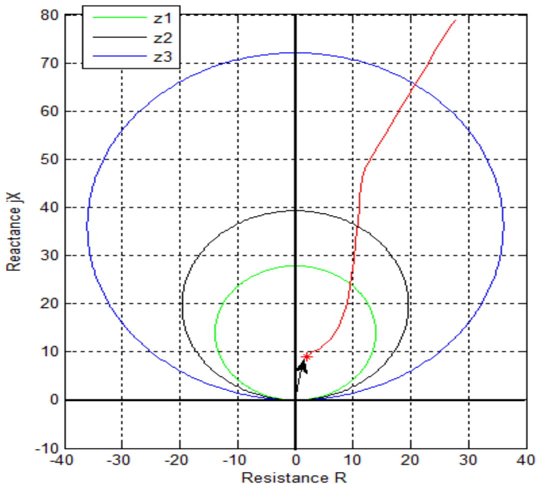

Figure 7: TCSC placed before the fault loop

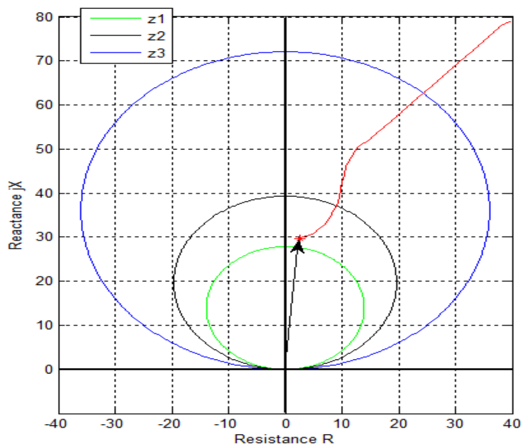

Figure 8: TCSC placed after the fault loop

Figure 7 and Figure 8 represent the Mho characteristics of the distance relay when TCSC was placed at different positions with respect to the fault loop on the transmission line between Onitsha and Alaoji. The length of the transmission is 128km with operation frequency of 50Hz, and fault on resistance to be 0.1Ω. A single line to ground fault was initiated at about 50km of the line. This implies that the zone 1 distance of the relay is 100km (80% ofthe protected line). The setting value in terms of the desired voltage for TCSC is 1.0pu. The TCSC was placed at 30km of the transmission line which is exactly 20km before the fault and also placed at 70km of the transmission line which is 20km after the fault.

IV. RESULT AND DISCUSSION

For the fault initiated with TCSC placed before the fault position, the relay tripped in zone 1 which is a correct operation of the relay. The relay tripped without having any interference from the TCSC, as the TCSC is not within the fault loop. When the TCSC was placed at 70km of the transmission line which is 20km after the fault, the relay tripped in zone 2, which is a malfunction of the relay (under reach) because at that distance, the relay is supposed to see the fault in zone 1. This is as a result of the change in apparent impedance seen by the relay as the fault transient passes through the TCSC.

V. CONCLUSION

The simulation of the Nigeria 330kv power system has shown that the position of the TCSC with respect to the fault loop on the transmission line protected by distance relay greatly affect the trip boundaries of the distance relay by setting it to either an over reaching or an under reaching state. This is undesirable as it disorients the relay setting which may cause multiple relays to trip on a fault thereby putting more customers out of power. It is recommended that an Adaptive relay setting be adopted to mitigate these challenges that the TCSC poses.

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