THE IMPACT OF STATCOM ON DISTANCE RELAY

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Abstract – In this paper, the analytical and simulation results of the application of distance relay for the protection of transmission line incorporating Static Synchronous Compensator(STATCOM) are presented. A detailed model of STATCOM and its control is proposed and integrated into the transmission system for the purposes of accurately simulating the fault transient. An apparent impedance calculation procedure for transmission line incorporating STATCOM based on the power frequency sequence circuits has been explored. The simulation results show the impact of STATCOM on the distance protection relay during the different fault condition; the influence of location of STATCOM, the setting of STATCOM control parameters and the operation mode of STATCOM are studied as well. The results are presented in relation to a typical 138kV transmission system employing STATCOM.

Keywords: Distance relay, FACTS devices, power system protection, modelling, STATCOM, Distance Relay

1   INTRODUCTION

With the ongoing growth of the electric power demand and deregulation in the electrical power industry, numerous changes have been introduced to modern electricity industry. Transmission systems are now being pushed closer to their stability and thermal limits, and energy needs to be transported from the generation point to the end user along the most desirable path.

Traditional updating of a transmission system by constructing new transmission lines becomes extremely difficult because of economic and environmental pressures. High efficiency in terms of better utilization of existing transmission lines, without compromising on the quality and reliability of electrical power apply has thus to be found via alternative means.

In this respect, due to the recent advances in high power semiconductor technology, Flexible AC transmission System (FACTS) technology has been proposed to solve this problem[1,2]. However, because of the added complexity due to the interaction of FACTS devices with the transmission system, the transients superimposed on the power frequency voltage and current waveforms (particularly under faults) can be significantly different from those systems not employing FACTS devices and it will result in rapid changes in system parameters such as line impedance and power angle. It is thus vitally important to study the impact of the FACTS devices on the traditional protection relay scheme such as the impedance-based distance protection relay [3].

STATCOM is one of the most widely used FACTS devices. It is based on a voltage source convert and can inject an almost sinusoidal current with variable magnitude and in quadrature with the connecting line voltage. It is widely used at the mid-point of a transmission line or heavy load area to maintain the connecting point voltage by supplying or absorbing reactive power into the power system [4].

Because of the presence of STATCOM devices in a fault loop, the voltage and current signals at relay point will be affected in both steady and transient state. This impact will affect the performance of exiting protection methods, such as distance relay.

Some research has been done on the performance of the distance relay for a transmission system with different FACTS devices. The work in [5] presents the analytical results based on steady-steady model of STATCOM, and has studied the impact of STATCOM on distance relay at different load levels.   In [6], the voltage-source model of FACTS devices is used to study the impact of FACTS on the tripping boundaries of distance relay. The work in [7] shows that thyristor controlled series capacitor (TCSC) has a big influence on the mho characteristic, reactance and direction and makes protection region unstable. The study in [8] demonstrates that the presence of FACTS devices on a transmission line will affect the trip boundary of distance relay, and both the parameters of the FACTS device and its location have impact on the trip boundary. All the studies show that when the FACTS devices is in a fault loop, its voltage and current injection will affect both the steady and transient components in voltage and current and hence the apparent impedance seen by a conventional distance relay is different from the that on a system without FACTS.

This paper will analyze and explore the impact of STATCOM employed in a transmission system on the performance of distance relay. First, a detailed model of STATCOM is proposed and secondly, the analytical results based on symmetrical component transformation for single phase to ground fault on a transmission system employing STATCOM are presented, the simulation results clearly show the impact of STATCOM devices on the performance of distance relay.

2 STATCOM MODEL

2.1 Simulation System

SimPowerSystems is a design tool using Simulink environment in MATLAB to model and simulate a power system. It has been used to study a PWM convert-based distributed STATCOM in [9]. In this study, this tool is used to model the 138kV parallel transmission system with 48-pulse STATCOM installed in the mid-point of one transmission line. The system configured with this tool is shown in figure 1. Two 200km parallel transmission lines connect two 138kV, 6500MVA generators and the angle difference between these two generators is 20 degrees. The 160MVA STATCOM is installed in the middle of the second transmission line.

The STATCOM uses one 48-pulse voltage source inverter which connects with two 4000μF series DC capacitors. The convert connects to the transmission system through a 15kV/138kV Δ/Y shunt transformer, injects or consumes reactive power to the transmission system to regulate the voltage at the connecting point.

The transmission line is based on the distributed parameter line model. The positive and negative sequence line impedances are 0.195+j3.3425Ω/km, the zero sequence transmission line impedance is 2.638+11.27 Ω j.
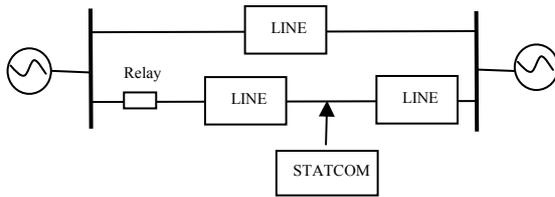

Figure 1: Transmission system with STATCOM

2.2 48-pulse voltage inverter

The voltage source inverter in this research is based on the 48-pulse quasi harmonic neutralized GTO inverter [10]. It consists of four 3-phase, 3-level GTO inverters and four phase-shifting transformers. Each inverter uses a 3-level GTO bridge block to generate a three square-wave voltage; these voltages are fed to the secondary windings of four phase-shifting transformers whose primary windings are connected in series to produce an almost sinusoidal voltage output. A DC capacitor is connected to the four 3-level inverters, the magnitude of square-wave voltage can be +Vdc, 0, -Vdc. The duration of 0 in each quarter cycle is defined as "dead angle" γ, and it can be adjusted from 0-90 degrees. The fundamental component of voltage source inverter has the amplitude of:

$$V_{X,n} = \frac{2}{\pi} v_{DC} \cos(\frac{\pi}{24}) \cos\gamma \tag{1}$$

As seen from above, the magnitude of the output voltage can be adjusted through changing the value of dead angle γ and/or the DC voltage of capacitor. The

phase angle α of the output voltage can be adjusted by using the input signal from pulse generator. In this STATCOM, the dead angle γ=π/48, and this inverter is known as a 48-pulse inverter.

2.3 STATCOM control model

The control of STATCOM is shown in figure 2. It is used to operate the voltage source inverter to inject or absorb reactive power to regulate the connecting point voltage to the setting value V_{ref}. The three phase voltages at the connecting point are sent to the Phase-Lock-Loop to calculate the reference angle which is synchronized to the phase A voltage. The three phase currents of STATCOM are decomposed into its real part I_d and reactive part I_q by abc-dqo transform using the phase-lock-loop angle as reference. The magnitude of the positive sequence component of the connecting point voltage is compared with the desired reference voltage V_{ref}, and the error is passed through a PI controller to produce the desired reactive current I_{qref}; this current reference is compared with the reactive part of the shunt current to produce the error which will be passed through another PI controller to obtain the relative phase angle α, of the inverter voltage with respect to the phase A voltage. The phase angle together with the phase-lock-loop signal are feed to the STATCOM firing pulse generator to generate the desired pulse for the voltage source inverter (the dead angle of STATCOM is kept fixed at γ=π/48).
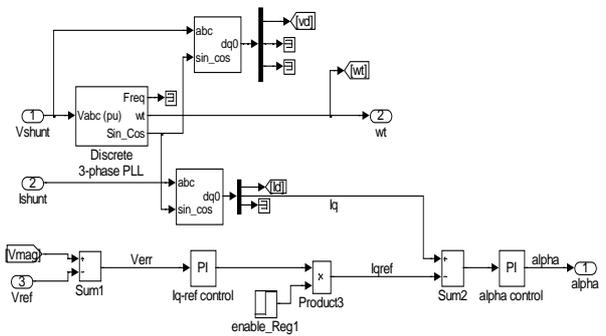

Figure 2: Control model of STATCOM

3 APPARENT IMPEDANCE CALCULATION

For the analysis associated with the operation of a distance relay, the power system shown in Figure 1 is used, the relay is installed on the right side of Bus S. The apparent impedance calculation is based on symmetrical component transformation using power frequency components of voltage and current signals measured at relay point. It is assumed that signal acquisition, preprocessing and sequence component calculations have been performed previously.

When a single phase to ground fault occurs at the right side of STATCOM and the distance is $n*L$ from the relay point, the positive, negative and zero sequence networks of the system during the fault can be shown as in fig 3.
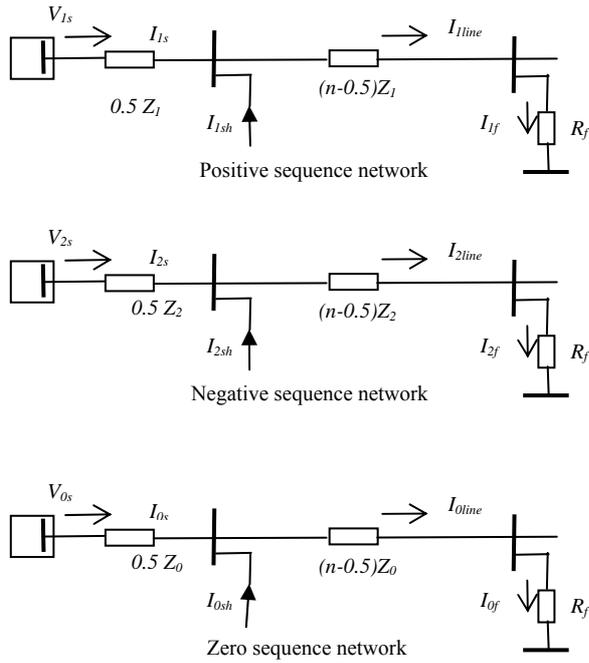
Figure 3: The sequence networks of single-phase fault

The sequence voltages at the relay point can be expressed as follows:

$$V_{1s} = I_{1s} 0.5Z_1 + I_{1line}(n - 0.5)Z_1 + R_f I_{1f} \quad (2)$$

$$V_{2s} = I_{2s} 0.5Z_1 + I_{2line}(n - 0.5)Z_1 + R_f I_{2f} \quad (3)$$

$$V_{0s} = I_{0s} 0.5Z_0 + I_{0line}(n - 0.5)Z_0 + R_f I_{0f} \quad (4)$$

$$I_{1line} = I_{1s} + I_{1sh} \quad (5)$$

$$I_{2line} = I_{2s} + I_{2sh} \quad (6)$$

$$I_{oline} = I_{0s} + I_{0sh} \quad (7)$$

Where

V_{1s}, V_{2s} and V_{0s}	are the sequence phase voltages at the relay location,
I_{1s}, I_{2s} and I_{0s}	are the sequence phase currents at the relay location,
I_{1line}, I_{2line} and I_{0line}	are the sequence phase currents in transmission line,
I_{1f}, I_{2f} and I_{0f}	are the sequence phase currents in the fault,
I_{1sh}, I_{2sh} and I_{0sh}	are the shunt sequence phase currents injected by STATCOM
Z_1 and Z_0	are the sequence impedance of the transmission line
n	is the per unit distance of a fault from the relay location

From above, the voltage at relay point can be derived as:

$$V_s = nI_s Z_1 + nI_{0s}(Z_0 - Z_1) + I_{sh}(n - 0.5)Z_1$$
$$+ (n - 0.5)I_{sh0}(Z_0 - Z_1) + R_f I_f \quad (8)$$

Where

$$V_s = V_{1s} + V_{2s} + V_{0s} \quad (9)$$

$$I_s = I_{1s} + I_{2s} + I_{0s} \quad (10)$$

$$I_{sh} = I_{1sh} + I_{2sh} + I_{0sh} \quad (11)$$

single phase to ground fault, the apparent impedance of distance relay can be calculated using the equation below:

$$Z = \frac{V_R}{I_R + \dfrac{Z_0 - Z_1}{Z_1} I_{R0}} = \frac{V_R}{I_{relay}} \quad (12)$$

Where

V_R, I_R	phase voltage and current at relay point
I_{R0}	zero sequence phase current
I_{relay}	the relaying current,

If this traditional distance relay is applied to the transmission system with STATCOM, the apparent impedance seen by this relay can be expressed as:

$$Z = \frac{V_s}{I_s + \dfrac{Z_0 - Z_1}{Z_1} I_{s0}} = \frac{V_s}{I_{relay}} = nZ_1 + \frac{I_{sh}}{I_{relay}}(n - 0.5)Z_1$$

$$+ \frac{I_{0sh}}{I_{relay}}(n - 0.5)(Z_0 - Z_1) + \frac{I_f}{I_{relay}}R_f \quad (13)$$

In practice, one side of the shunt transformer has often a delta connection, so there is no zero sequence current injected by STATCOM, that is to say, $I_{0sh}=0$, and the equation can be rewritten as:

$$Z = nZ_1 + \frac{I_{sh}}{I_{relay}}(n - 0.5)Z_1 + \frac{I_f}{I_{relay}}R_f \quad (14)$$

From above we can see that when the traditional distance relay is applied to the transmission system employing STATCOM during the phase to ground fault, the apparent impedance seen by this relay has three parts: the first is positive sequence impedance from the relay point to fault point, which should be the correct value for the distance relay; second is the impact of STATCOM on the apparent impedance and results from the shunt current I_{sh} injected by the STATCOM; the last part of apparent impedance is caused by fault resistance.

It is clear from equation (14), that if only a solid single phase to ground fault is considered, the equation becomes:

$$Z = nZ_1 + \frac{I_{sh}}{I_{relay}}(n - 0.5)Z_1 \quad (15)$$

The impact of STATCOM on the apparent impedance can be expressed using the ratio: I_{sh}/I_{relay}. In the following parts, the location of fault, the location of STATCOM, the setting of STATCOM will be considered. Mho characteristic with a positive sequence voltage polarization is used as zone one distance relay to cover 80% of the transmission line.

4   SIMULATION RESULTS

In the system shown in the figure 1, an A-phase to ground fault occurs on the right side of STATCOM and the fault distance to relay point is 150km; the setting value in terms of the desired voltage for STATCOM is 1.0pu. The apparent impedance trajectories of the system with and without STATCOM together with the distance relay mho characteristic are shown in figure 4.
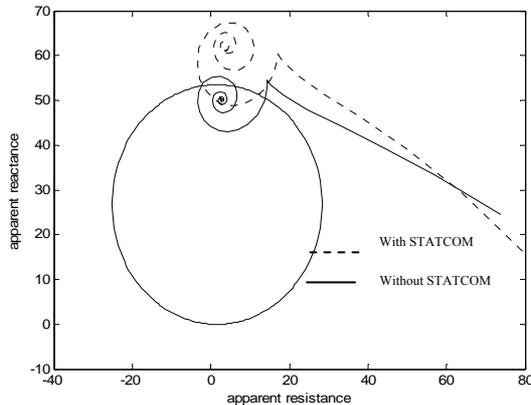

Figure 4: Apparent impedance seen by the A-phase single phase to ground unit, with and without STATCOM

From above, it can be seen that both the resistance and reactance of the apparent impedance of the transmission system with STATCOM are larger than those for the system without STATCOM; the protection zone of the distance relay will thus decrease i.e. it will under-reach.

To study the coverage of the mho characteristic, faults at different positions have been studied, and the apparent resistance and reactance for different fault locations are shown in Fig.5 and Fig.6, respectively.
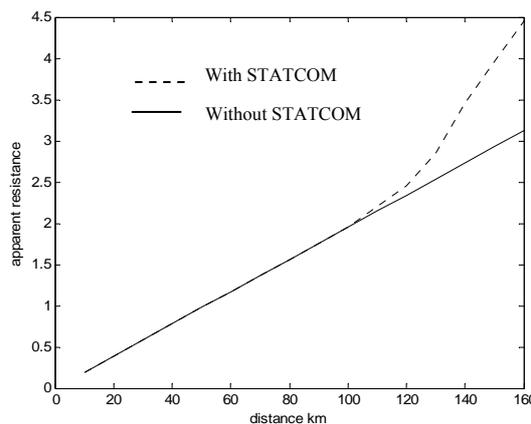

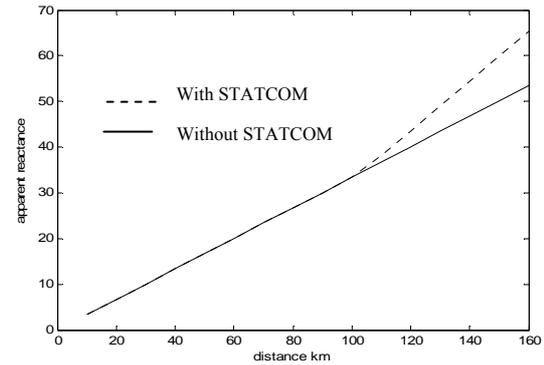**Figure 5:** Apparent resistance versus the fault location with and without STATCOM

Figure 6: Apparent reactance versus the fault location with and without STATCOM

It is clearly evident that when the fault is on the left side of STATCOM, the apparent impedance seen by the distance relay is almost identical to that for the system without STATCOM. However when the fault is on the right side of STATCOM, both the apparent resistance and reactance of the system with STATCOM are larger than that for the system without STATCOM, this can be explained by the I_{sh}/I_{relay} ratio in table1:

Fault location	110	120	130	140	150	160
Apparent impedance	2.15+j37.8	2.4+j43	2.8+j48.5	3.5+j54	4+j60.5	4.5+j65
Influence ratio	0.48	0.52-j0.01	0.55-j0.02	0.6-j0.03	0.6-j0.03	0.62-j0.03

Table 1: The apparent impedance and influence ratio

As seen from table 1, because of the reactive power injection by STATCOM, the voltage at the STATCOM connecting point is higher compared to the system without STATCOM; in other words, seen by the distance relay the fault is further than its real distance, duo to an increase in the apparent impedance, this would lead to the under-reaching of distance relay. The influence ratio increases with an increase in the location of the fault; this can be explained by the fact that when the fault is further away from the relay point, the relay current and STATCOM injecting current will decrease, but the variation in relay current is bigger than that of the injected current.

When the STATCOM is installed in the middle of the transmission line, and the original distance relay's reach is set of 80% then, the reach point N_{new} for the system with STATCOM can be derived from following:

$$50\%.Z_1 + (N_{new} - 50\%)(1 + I_{sh}/I_{relay})Z_1 = 80\%.Z_1 \quad (16)$$

$$N_{new} = 50\% + \frac{30\%}{1 + I_{sh}/I_{relay}} \quad (17)$$

According to different system conditions, STATCOM may have different setting values for desired voltage, and this setting will also affect the performance of the distance relay. The next study shows the apparent impedance and reactive power injected by

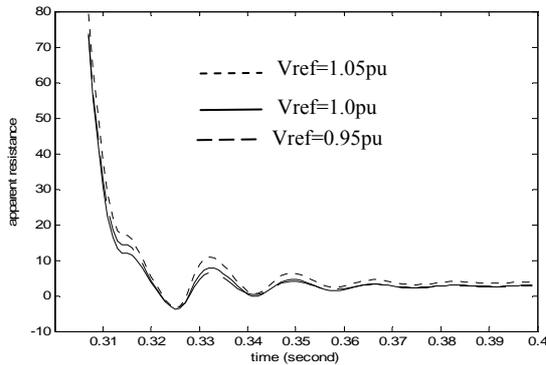STATCOM during a single phase to ground when the STATCOM settings are 0.95, 1.0 and 1.05 respectively.

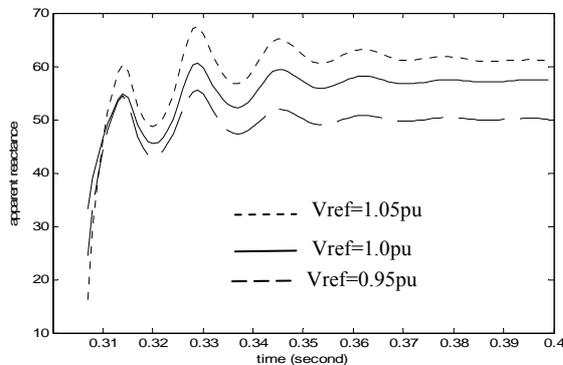**Figure 7:** Apparent resistance versus the setting voltage of STATCOM

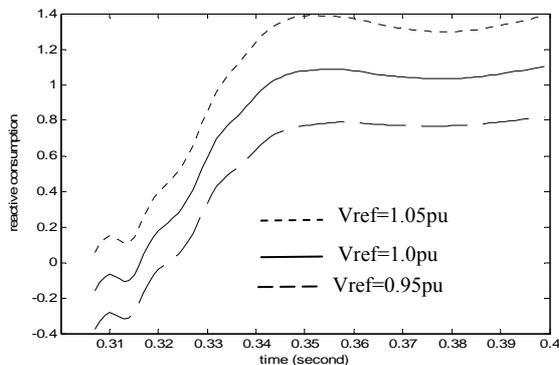**Figure 8:** Apparent reactance versus the setting voltage of STATCOM

Figure 9: Reactive power injection versus the setting voltage of STATCOM

As seen from the figures 7 and 8, both the apparent resistance and reactance seen by the distance relay for a single phase to ground fault will increase with the increase of STATCOM setting reference voltage. This can be explained by the different reactive power injection.

When the setting voltage is high, as seen from figure 9 during the fault, to keep the higher desired voltage, the STATCOM will inject more reactive power; in other words, the reactive current injection of STATCOM I_{sh} is high; this will increase the influence ratio, according to equation (15) and the apparent impedance seen by the

distance relay will increase.

It is worth mentioning that for certain conditions, when the system capacity is high and the STATCOM voltage setting value is low, if a single phase-ground fault occurs outside zone 1, the STATCOM connecting point voltage may be higher than the setting value, in this case the STATCOM will absorb reactive power in the system, the current I_{sh} will become inductive, the influence ratio I_{sh}/I_{relay} will become negative rather than positive and the apparent impedance seen by the distance relay will decrease compared to the system without STATCOM. This may lead to over-reaching of distance relay, and this is clearly undesirable.

The above case can be demonstrated when the system capacity is 14000MVA and the STATCOM setting value is 0.9pu. It is found, that when a fault occurs 165km from the relay point(i.e. outside the relay setting), the apparent impedance enters the mho boundary right towards the end, that is to say the distance relay over-reaches and this is as a direct consequence of the fact that during the fault the STATCOM absorbs rather than injects reactive power from the transmission system.

For a phase to phase fault, the relay voltage input is line-to-line voltage and the current is delta line current. Figures 10 and 11 show the apparent impedance seen by distance relay during a B-C phase fault. The relay voltage is V_{BC} and relay current is I_{BC}. The fault is 150km from relay point and the STATCOM setting value is 1.0pu.

As can be seen from figure 10, during a phase to phase fault, because of the STATCOM, the apparent reactance increases, but unlike the single phase to ground fault, the apparent resistance decreases and hence the distance relay can not operate properly.
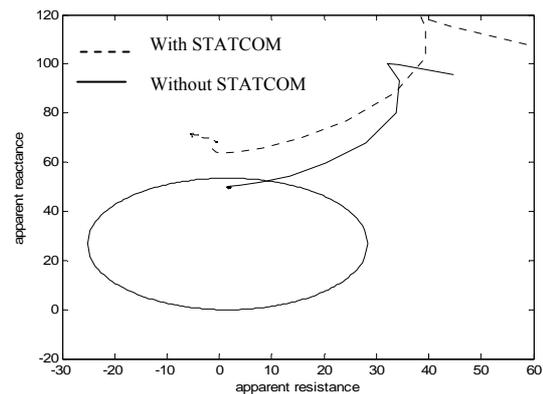

Figure 10: Apparent impedance seen by distance relay during B-C fault, with and without STATCOM

If a quadrilateral characteristic rather than mho characteristic is used as the relay boundary, in this case both the A-B phase fault element, B-C phase element will treat the fault as internal fault which is unacceptable for the distance relay, as shown in Fig 11.
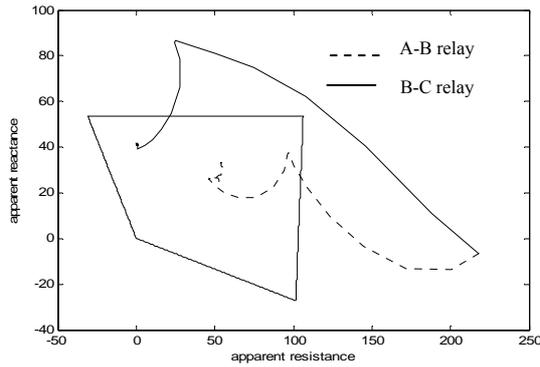
Figure 11: Apparent impedance seen by A-B and B-C relay unit during a B-C fault, with STATCOM

In the above studies, the relay is located on the left side of STATCOM. The next case will study the performance of distance relay when it is put on the right side of STATCOM. In practice, it means that the relay can only protect faults in the transmission line and another protection is needed to protect fault occurring in STATCOM. In this case, the set up is shown in Fig 12 and the line length is 200km. Other system parameters are the same. A-phase to ground fault is at 150km . As can be seen from the figure 13, the apparent impedance difference between system with and without STATCOM is very small, i.e. the distance relay functions correctly.
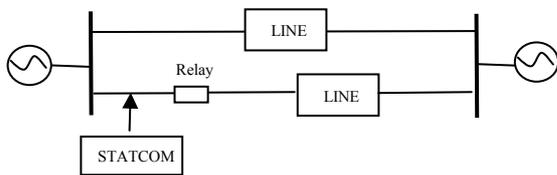

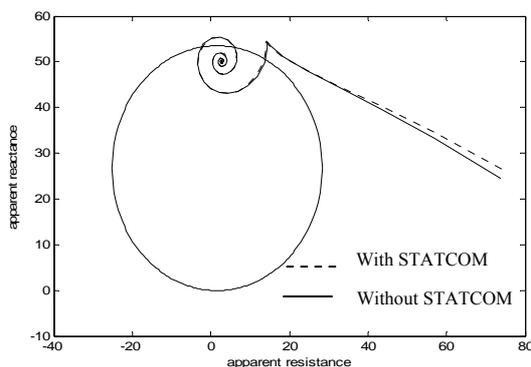**Figure 12:** System model to study the effect of relay position

Figure 13: Apparent impedance seen by distance relay during A-ground fault, with and without STATCOM

From above simulation results, the following conclusions can be drawn:

1. During a fault, the apparent impedance will increase if the STATCOM supplies reactive power to the system, the apparent impedance will decrease if the STATCOM consumes reactive power from the system.
2. The influence ratio will increase with an increase in location of the fault.
3. The distance relay will under-reach when the STATCOM supplies the reactive power, and will over-reach when the STATCOM consumes the reactive power.
4. The setting of STATCOM has a big impact on the apparent impedance. The higher the voltage setting is, the larger the apparent impedance will be.
5. During a phase to phase fault, the apparent reactance increases but the apparent resistance may decrease
6. During a phase to phase fault, if the quadrilateral characteristic is used as the relay boundary, the healthy phase relay may not function correctly.
7. The position of distance relay has a big impact on the relay performance.

5   CONCLUSIONS

This paper firstly presents a detailed model of a transmission system employing STATCOM. Secondly, a calculation procedure of the apparent impedance of system with STATCOM during single phase to ground fault is outlined. The simulation results show clearly the impact of STATCOM on distance relay performance. The apparent impedance is influenced by the lever of reactive power injected by the STATCOM resulting in either under reaching or over reaching of the distance relay. For a phase to phase fault, the phase-to-phase fault elements in the healthy phase may not function correctly. Work is underway in extending the study for other types of system and fault conditions such as the effect of the location of STATCOM on distance relay, STATCOM control strategy as power factor control. These will be reported in due course.

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BIOGRAPHIES

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