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Setting Considerations of Distance Relay for Transmission Line with STATCOM

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Abstract - Distance relay plays an important role in the protection of transmission lines. The application of flexible AC transmission systems (FACTS) devices, such as the static synchronous compensator (STATCOM), could affect the performance of the distance relay because of compensation effect. This paper analyzes the application of distance relay on the protection of a transmission line containing STATCOM. New setting principles for different protection zones are proposed based on this analysis. A typical 500 kV transmission system employing STATCOM is modeled using Matlab/Simulink. The impact of STATCOM on distance protection scheme is studied for different fault types, fault locations, and system configurations. Based on simulation results, the performance of distance relay is evaluated. The setting principle can be verified for the transmission line with STATCOM.

Keywords: Distance Relay, Power System Protection, Flexible ac transmission system (FACTS), STATCOM, Setting Principle

1. Introduction

The use of FACTS devices in power system transmission to increase the power transfer and optimum utilization of power system capability has been of a worldwide interest in the recent years [1], [2]. FACTS devices are used for voltage regulation at the midpoint in order to segment the transmission line, and at the end of the line to prevent voltage instability. However, other problems emerge in the field of power system protections. Distance protection systems have simple operating principle and are capable to work independently under most circumstances. For these reasons, these systems have been used in several countries to protect their high voltage transmission lines. However, with FACTS device installed in the transmission line, the efficiency of distance relay performance should be studied. The location of the shunt FACTS device depends on the application at which it is installed [3]. Shunt compensation FACTS devices are installed at the endpoints of transmission lines when used to improve system stability while at the midpoint of the lines when used to control the power flow or increase the power transfer capability. STATCOM is widely used at the midpoint of a transmission line or heavy load area in order to maintain the connecting point voltage by supplying or absorbing reactive power into the power system. In this paper, the performance of distance relays with the effect of STATCOM on midpoint compensated line is mainly studied.

Several works have been conducted to test the performance of the distance relay of a transmission system with FACTS devices. Previous works [4], [5] present detailed test results of systems with SVC and STATCOM and have compared the performances between the two devices; however, they failed to give any information on the setting rules. Reference [6] presents the results based on steady-steady model of STATCOM, and studied the impact of STATCOM on distance relay at different load levels. In [7] and [8], the voltage-source model of FACTS devices is used in determining the impact of FACTS on the tripping boundaries of distance relay. Reference [9] examines the influence of STATCOM for distance relay in a parallel line system.

The impact of STATCOM on distance relay performance will be analyzed in this paper. A detailed model of STATCOM and its operation principle are first introduced. Next, the apparent impedance of distance relay for different system configurations with STATCOM at the end of the line and at midpoint are analyzed individually. Setting principles are proposed based on the theoretical analysis. Then, a simulation model for a typical 500 kV system is built in Matlab/Simulink. Simulation results clearly show the impact of STATCOM devices on the performance of distance relay. Settings of the distance relay under influence of STATCOM can be achieved from the simulation results based on the proposed principles

2. Power System with STATCOM

STATCOM is a shunt device of FACTS family using power electronics to control power flow and improve transient stability on power grids [1].

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2.1 STATCOM Configuration

STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. The variation of reactive power is performed by means of a voltage-sourced converter (VSC) connected on the secondary side of a coupling transformer. In Fig. 1, V_1 represents the system voltage to be controlled and V_2 is the voltage generated by the VSC. The VSC uses forced-commutated power electronic devices to synthesize voltage V_2 from a DC voltage source. The principle of operation of the STATCOM is explained below showing the active and reactive power transfer between a source V_1 and a source V_2.

$$P = \frac{V_1 V_2 \sin\delta}{X} \tag{1}$$

$$Q = \frac{V_1(V_1 - V_2\cos\delta)}{X} \tag{2}$$

where

V_1 is the line to line voltage of source;
V_2 is the line to line voltage of STATCOM;
X is the equivalent reactance between transformer and filters;
δ is the angle of $V_1$with respect to V_2.

Since δ is very small, if we set δ=0,

$$P = 0 \tag{3}$$

$$Q = V_1\frac{V_1 - V_2}{X} \tag{4}$$

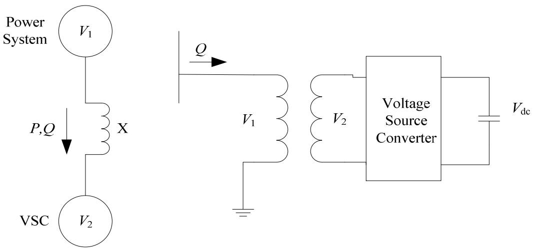

Fig. 1. Operating Principle of the STATCOM.

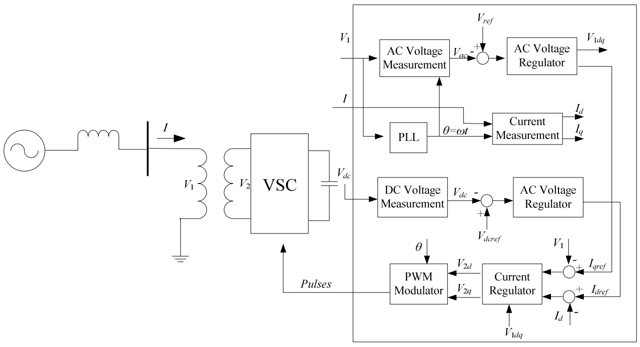

Fig. 2. Single-line Diagram of a STATCOM and its Control System.

If V_1 is higher than V_2, Q is flowing from V_1 to V_2 (i.e., STATCOM is absorbing reactive power). On the reverse, if V_1 is lower than V_2, Q is flowing from V_2 to V_1 (i.e., STATCOM is generating reactive power) [10], [11].

The control system is made up of phase-locked loop (PLL), measurement system, voltage regulators, firing pulses. To explain the regulation principle, it is assumed that the system voltage becomes lower than the reference voltage V_{ref}. The voltage regulator will then ask for a higher reactive current output (positive I_q=capacitive current). The current regulator will increase α phase lag of inverter voltage with respect to system voltage to generate more capacitive reactive power. It results in an active power temporarily flowing from AC system to capacitors, thus, increasing DC voltage, and consequently, generating a higher AC voltage.

A set of voltage-current characteristics for a range of target voltage settings with constant slope is shown in Fig. 3. At reduced voltage, the STATCOM can continue to be operated at rated leading (or lagging) current, with a constant transient overload current margin. These capabilities are available down to very low voltages.

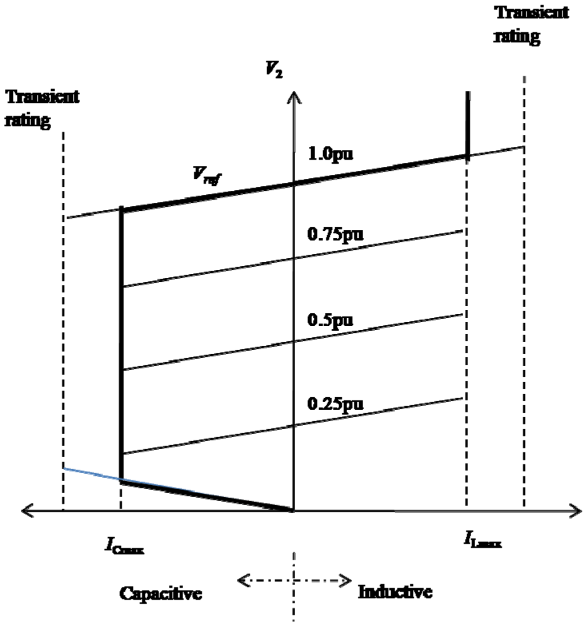

Fig. 3. V/I Characteristic of STATCOM.

2.2 Apparent Impedance of Distance Relay

When a fault occurs on a transmission line, distance relay protection would trip according to its measured impedance. In the absence of fault resistance, measured impedance for the system without STATCOM equals the actual impedance from relaying location and the fault. However, with the existence of STATCOM, the apparent impedance seen by the distance relay needs to be observed to clarify the performance of distance relay. The different installation locations of STATCOM would have varying effects on apparent impedance.

A. STATCOM Installed at the Beginning

Fig. 4 shows a single-line diagram of the system with STATCOM connected at the beginning of the line. Since the STATCOM is at the left of the relay, the apparent impedances in fault condition are the same as the system without STATCOM according to circuit analysis allowing the distance relay to function correctly. Simulation results will be shown later to prove this analysis.

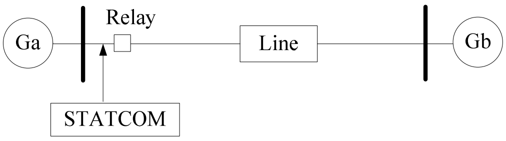

Fig. 4. Power System with STATCOM Installed at the Beginning.

B. STATCOM Installed at the Midpoint

In the single-line diagram shown in Fig. 5, STATCOM is connected at the midpoint. The STATCOM compensates for the reactive power. Its value varies with the power transfer between the sending and receiving ends to maintain constant voltage at the midpoint. All types of faults can be simulated on the line section and the fault location can be changed as desired.

The apparent impedance measured by the relay is not affected by the presence of STATCOM when faults are located before the compensation point. Therefore, faults beyond the compensation point are given focus. If the system shown in Fig. 5 is subjected to a three-phase fault, its equivalent circuit of Fig. 6 is drawn with reference to the faulted system.

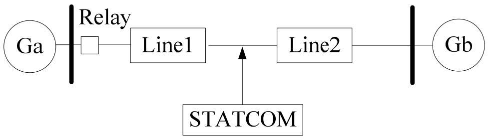

Fig. 5 Power system with STATCOM Installed at the Midpoint

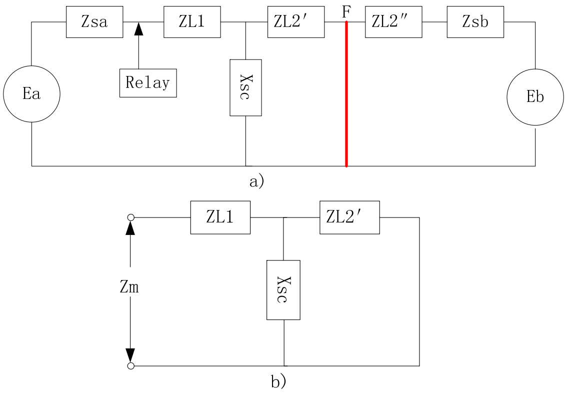

Fig. 6. a) Equivalent Circuit for a Three-phase Fault; b) Reduced Equivalent Circuit.

The measured impedance of distance relay in Fig.6 can be calculated as the following:

$$Z_{Act} = ZL1 + ZL2' = k \times ZL \tag{5}$$

$$k = \frac{ZL1 + ZL2'}{ZL} = \frac{ZL1 + ZL2'}{2ZL1} \tag{6}$$

$$Z_{App} = ZL1 + \frac{ZL2' \times Xsc}{ZL2' + Xsc} \tag{7}$$

$$N = \frac{Z_{App}}{Z_{Act}} = \frac{1}{2k}\left(1 + \frac{(2k-1)\times 2\lambda}{(2k-1)+2\lambda}\right) \tag{8}$$

$$\lambda = \frac{Xsc}{ZL} \approx \frac{Xsc}{XL} \tag{9}$$

where

Z_{App} Impedance measured by the relay

$ZL1$ Positive sequence impedance of line section up to the FACTS device location

$ZL2'$ Positive sequence impedance of line section after the FACTS device location up to the fault point

ZL Total line impedance

Xsc Positive sequence reactance of the FACTS device

k Fault location on the line in per unit of line length

Known from the operating principle of STATCOM, if the system voltage is larger than the reference voltage, STATCOM will perform as inductance; otherwise, it will work as capacitance. Therefore, the apparent impedance measured by distance relay is determined by the “midpoint voltage.”

The plot of the measured impedance given by (8) for different fault locations and compensation factor *N*, as well as the assumption of lossless line, is shown in Fig. 7. According to the changes of fault location, the reach of the distance relay judged by the compensation factor *N* can be categorized into three types: no-effect cases, under-reach cases, and over-reach cases.

Curves with $0<k<0.5$ denotes that the measured impedance is not affected by the compensation since fault happens before the STATCOM is installed in place. Curves with $0.5<k\leq 1$ show compensation rate for faults on the rest of the line, while the curves with $k>1$ represent faults beyond the protected line. If the rate λ between STATCOM reactance and line reactance is larger than 0, STATCOM works in an inductive compensation mode and the curves are all overreach cases. On the other hand, if STATCOM works in a capacitive compensation mode, its effect on the distance relay would rely on the fault location k and the rate λ. The highest impact of the shunt compensation occurs around the point at which the shunt compensator reactance value is equal to the reactance of the line between the FACTS device and fault location. This condition results in a resonance. If λ is larger than the resonance value caused by parallel of STATCOM and line reactance, the compensation factor would appear as “under-reach,” otherwise it would be “over-reach.” However, these cases are

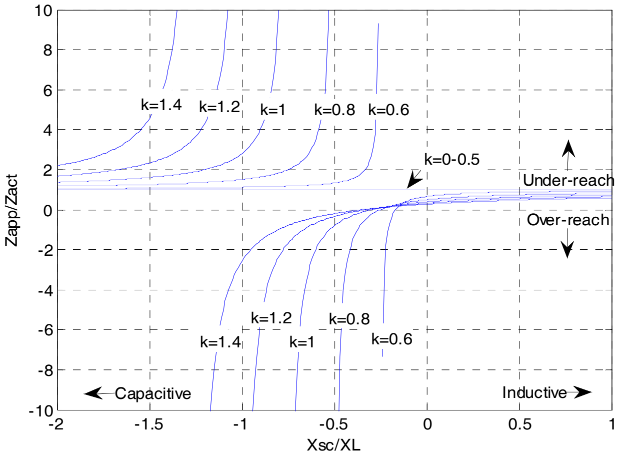

Fig. 7. Apparent Impedance of Distance Relay in the Presence of STATCOM.

just results from theoretical analysis. In practical conditions, the equivalent reactance of STATCOM and the transmission line impedance would be carefully selected to avoid the resonance when the equivalent shunt capacitance equals the line reactance. Therefore, the over-reach cases caused by capacitive compensation do not exist in practical conditions.

3. Setting Principle

Typically, STATCOM is installed at the low voltage side in the substation that connects two power systems. We can build an equivalent system (Fig. 8) to consider the setting principles. Theoretical analysis shows that the apparent impedance measured by distance relay Ra1 and Rb1 are not affected by the STATCOM compensation. The apparent impedances of faults in its own line are not affected in distance relay Ra and Rb. However, for faults in the next line, the apparent impedance will be different because of the STATCOM compensation. This mechanism indicates that Zone1 performs correctly, but the Zone2 and Zone3 settings need to be revised by considering the effect of STATCOM. Here, Ra relay is taken as an example to explain the new setting principle.

Besides the effect of STATCOM, the effective reach of the setting is also affected by measurement errors resulting from relay imperfections, CT and VT inaccuracy, and line constants from imperfect modeling. In [12], all these measurement errors are modeled by uniform probability distribution and the combination of these uniform distributions yields an approximate Gaussian function. Assuming all the parameters as 1, and by setting 5% CT error, 5% VT error, 3% impedance error, and 5% calculation error, the distribution curve would have a standard deviation of σ 5%. Notably, [-4σ, +4σ] could cover 100% of the distribution curve. This means that for a protected line, a setting of 80% of its line length could avoid the mis-tripping fault probability for the next line, and a setting of 120% of its line length could fully protect this line.

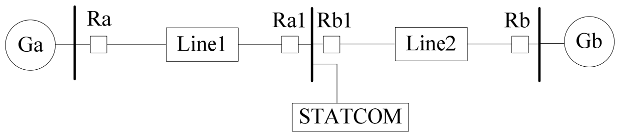

Fig. 8. Typical STATCOM Compensation System.

3.1 Setting Principle for Under-reach Cases

A. Zone1 Setting

Zone1 of distance relay is aimed to protect its own line and not overreach the faults beyond the ending bus [13].

For the distance relay Ra in Fig. 8, its Zone1 is not affected by the STATCOM compensation, so it could be set as 80% considering the measurement errors.

B. Zone2 Setting

Zone2 is set to protect the remainder of the line left unprotected by Zone1 and provide an adequate margin. It also needs to be checked to ensure that it does not reach beyond the Zone1 setting of the neighboring lines.

The fault at the end of Line 1 is not affected by the STATCOM. Considering the measurement errors only, Zone2 could be set as 120% to fully protect Line 1. However, to provide more back up protection for Line 2, the under-reach effect for faults in Line 2 caused by STATCOM compensation must be taken into account. The effective reach of Zone2 must not reach beyond the Zone1 of Rb1, while Zone1 of Rb1 can be set as 80% of Line 2. To avoid superposition, Ra can be checked so that its apparent impedance will not exceed Line 1 plus 80% of Line 2. This means that Zone2 could be set maximally at the point where the apparent impedance of Ra relay is equal to Line 1 plus 80% of Line 2. As shown in (8) and Fig. 7, the Zone2 setting would change with the system parameter changes.

C. Zone3 Setting

Traditionally, Zone3 is applied as backup for Zone2 and may be applied as remote backup for relay or station failures at the remote terminal.

Zone3 setting should protect its own line and the longest neighboring line. Without compensation, the setting should be at least Line 1 plus 120% of Line 2 to achieve this protection aim considering the measurement errors. The apparent impedance of relay Ra when fault happens at the end of Line 2, which corresponds to the minimum setting of Zone3, should be checked because of the under-reach effect caused by capacitive compensation.

3.2 Setting Principle for Over-reach Cases

Theoretical analysis reveals the presence of over-reach cases when STATCOM performs as inductance. This case might happen if system capacity is high and the reference voltage of STATCOM is low, so STATCOM connecting point voltage may be higher than the reference voltage, which would lead to over-reach of the distance relay.

Fig. 8 shows that faults in Line 1 are not affected by the STATCOM resulting in Zone1 being set as 80% by considering measurement errors. Setting Zone2 as 120% can provide full protection for Line 1 but it has the probability to mis-trip for the faults beyond Zone1 of Line 2 because of the over-reach, which can be seen from (8) and Fig. 7. Zone3 setting is even harder because of the severe over-reach effect. Based on the above analysis, Zone1 is the only reliable setting. Therefore, communication channel-aided scheme should be equipped to the relays at both side of the line as a supplement to the lost of backup protection [14]. Under fault occasions, especially metallic fault, the system voltage would decrease greatly resulting in under-reach.

If the STATCOM is installed at other locations in the sample system in Fig. 8, similar process considering the compensation effect of STATCOM could be applied to achieve the distance relay settings. The proposed setting principles based on the theoretical analysis can be verified by the simulations in the following section.

4. Simulation Results

According to the above analysis, an equivalent system shown as Fig. 9 can be built to explore the impact of STATCOM on distance relay. The STATCOM model uses a square-wave, 48-pulse VSC and interconnection transformers for harmonic neutralization. The STATCOM is made up of a three-level 48-pulse inverter and two series-connected 3000 μF capacitors acting as a variable DC voltage source. The variable amplitude 60 Hz voltage produced by the inverter is synthesized from the variable DC voltage that varies around 19.3 kV. In Fig. 9, simulation shows that under normal operation, the reactive power output of the STATCOM is -14.7 Mvar, which means it is working at an inductive compensation mode and its equivalent reactance X_{SC} is j1712.8 Ω. The system parameters are given in Table 1 as follows:

Table 1. System Parameters

Power System Element	Parameters
Equivalent Source	500 kV
Transmission Line 1	100 km
Transmission Line 2	100 km
$R_1+j\omega L_1(\Omega/km)$	0.0255 + 0.3520i
STATCOM Rating	± 100 MVA
Droop	0.03
Vref	1.0 p.u

A three-phase fault at 60% of Line 2 is assumed to determine the effect of STATCOM installed at different positions vis-à-vis relay measured impedance.

The measured impedances in system with STATCOM installed at the beginning of Line 1 and without STATCOM equal 4.15+j57.15 Ω and 4.07+ j56.32 Ω, respectively, which means that the STATCOM hardly brings any effect on distance relay. R-X diagrams shown in Fig. 10 is coincident with theoretical analysis.

For the system with STATCOM installed at midpoint, measured impedances equals 7.16+j65.13 Ω. Comparing to

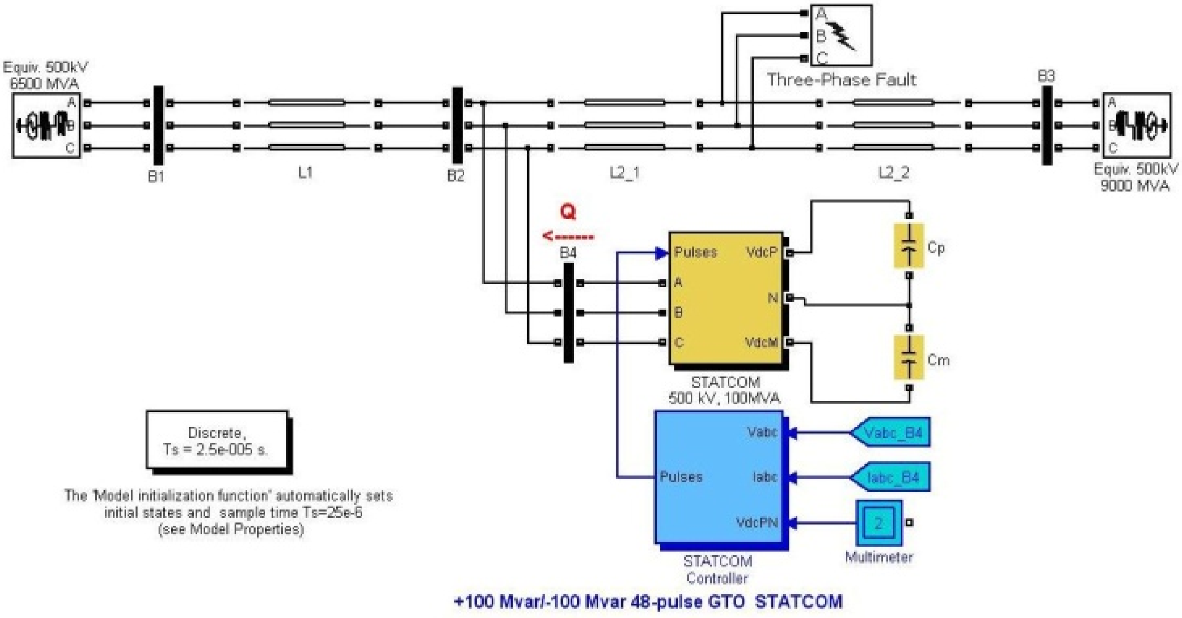

Fig. 9. Simulation Power System in Matlab/Simulink.

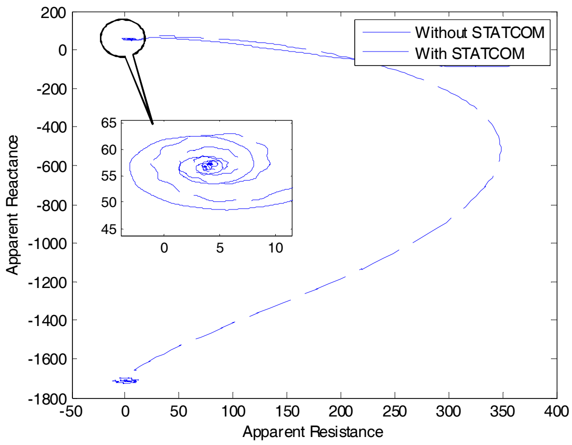

Fig. 10. Apparent Impedance with STATCOM at the Beginning.

measured impedance 4.07+ j56.32 Ω in system without STATCOM, STATCOM compensation leads to under-reach of the distance relay. The reactive power output of STATCOM is 29 Mvar (capacitive) and its equivalent reactance is -j80.55 Ω, which also show the under-reach effect. The solid line in Fig. 11 represents the locus of measured impedance of system without STATCOM compensation and the dotted line shows the system with STATCOM installed at the midpoint of the transmission line.

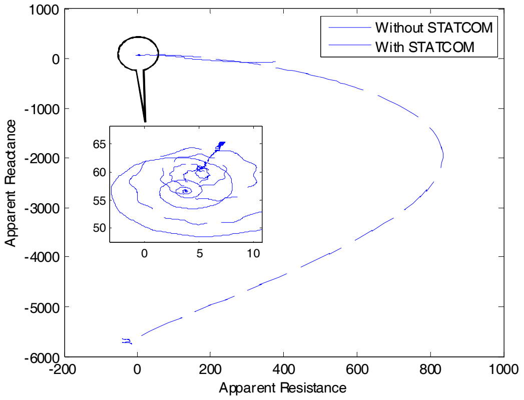

Fig. 11. Apparent Impedance with STATCOM at Midpoint.

The measured fault impedances at various locations of the transmission line under three-phase ground fault and single-phase-to-ground fault are shown in Figs. 12 and 13, and Table 2.

Figs. 12 and 13 show the absence of compensation before midpoint, the apparent impedances equal actual impedances. However, after the STATCOM installation point, both apparent resistance and reactance are larger than actual values, implying the under-reach effect resulting from capacitive compensation.

From the simulation results in Table 2, Fig. 8 shows that the apparent impedance of Ra amounts to 91% of Line 2 when fault happens at 80% of Line 2. This result means

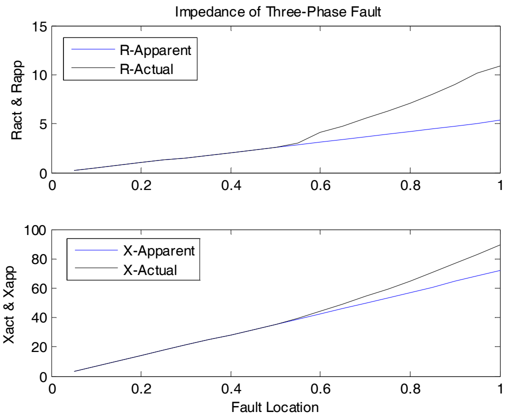

Fig. 12. Impedance for Different Fault Locations under a Three-phase Fault.

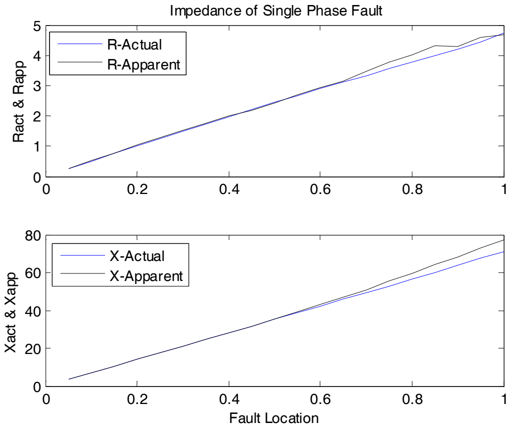

Fig. 13. Impedance for Different Fault Locations under a Single-phase Fault.

Table 2. Three-phase and A-phase ground faults at various fault locations

Fault length (km)	3p-g Impedance (Ohms)	1p-g Impedance (Ohms)
10	0.2575 + j3.5200	0.2563 + j3.5200
20	0.5150 + j7.0425	0.5135 + j7.0350
30	0.7660 +j10.6650	0.7635 +j10.5525
40	1.0233 +j14.0925	1.0277 +j14.0675
50	1.2775 +j17.6250	1.2933 +j17.5775
60	1.5357 +j21.1625	1.5325 +j21.0950
70	1.7943 +j24.7075	1.7525 +j24.6225
80	2.0510 +j28.2500	1.9905 +j28.1500
90	2.3142 +j31.8250	2.1957 +j31.6750
100	2.5750 +j35.4000	2.4192 +j35.2000
110	3.0575 +j39.3250	2.7050 +j39.0500
120	4.0775 +j44.1500	2.9325 +j43.0000
130	4.7600 +j49.3250	3.1625 +j47.0250
140	5.5350 +j54.5250	3.4750 +j51.0750
150	6.2825 +j59.6250	3.7950 +j55.4250
160	7.1225 +j65.0000	4.0275 +j59.6250
170	8.0000 +j70.7500	4.3350 +j64.1000
180	8.9950 +j76.8000	4.2800 +j68.4000
190	10.1400 +j82.9500	4.5950 +j72.9000
200	10.9325 +j89.6250	4.6700 +j77.1500

that if Zone2 of Ra were set smaller than Line 1 plus 91% of Line 2, there would be no probability of superposition. Considering the measurement errors, the maximum setting of Zone2 must be smaller than Line 1 plus 71% of Line 2 to guarantee full protection for Line 1 and no mis-coordination with next Zone1.

This maximum setting value should be checked when the system parameters change in the engineering, and the setting could be adjusted between the minimum value and maximum value to meet different practical requirements.

Similarly, the apparent impedance for the fault at the end of Line 2 is 124.4 % of the actual impedance, which means setting of Zone3 should be set to 124.4% of Line 2, at least to fully protect the two lines. Taking measurement errors into consideration, minimum setting of Zone3 should be 100% of Line 1 and 145% of Line 2. This setting would also change with the system parameters in practical situation.

In simulations, overreach case does not exist because of the rapid voltage decrease under fault occasions.

5. Conclusion

This paper first introduced the model and operating principle of STATCOM in a transmission system. Second, the apparent impedance calculation for systems with STATCOM installed at different locations during the three-phase fault is outlined. Theoretical analysis shows that the apparent impedance is not affected if STATCOM is installed at the beginning of the line, whereas it will be influenced when fault occurs beyond the midpoint if STATCOM is installed at the middle of the line.

Both under-reach and over-reach cases could emerge when the system voltage changes. New setting principles for the system with STATCOM are proposed to correctly trip the faults. Simulation results show clearly the impact of STATCOM on distance relay performance under different fault types and various fault locations. For specified systems, settings for different protection zones can be achieved based on the proposed setting principles. This paper would provide a good reference for the distance relay setting in the engineering application.

Acknowledgements

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