FAULT LOCATION ALGORITHM USING IMPEDANCE COMPENSATION METHOD (ICM) FOR FACTS DEVICES COMPENSATED TRANSMISSION LINES

R. ILANGO
Department of EEE, M.A.M. School of Engineering, Tiruchirappalli, Tamil Nadu, India.
Email: ilangorengaraju@gmail.com

Abstract**:** *Accurate fault location is essential in transmission lines to facilitate quick repair and resolution of the faulty line, to improve reliability and availability of the power supply. In this paper, a new distance protection algorithm is developed for locating fault in a transmission line compensated with shunt FACTS devices like STATCOM using an impedance compensation method (ICM). The proposed protection scheme/algorithm considers the impedance deviation angle (α) to correct/compensate the magnitude and phase of the fault loop, apparent impedance and accordingly calculates the actual distance of the fault location. The performance of the proposed method is evaluated and tested with an Indian test transmission system compensated with shunt FACTS devices for various fault types and locations. The results show that the new protection method effectively estimates the exact fault location by mitigating the impact of STATCOM on distance relay performance*.

Key words: *Distance Protection, Flexible AC Transmission Systems (FACTS), Fault location, Reactive Power Compensation, Static Synchronous Compensator (STATCOM).*

1. Introduction

The modern power utility and deregulated market need safe and secured power system operations. The power network performance is frequently affected by transmission line faults. These faults need to be detected, classified, located accurately and cleared as fast as possible to avoid a major block out and damage. Several fault location methods/algorithms were used to locate the fault on transmission lines. Digital distance relays are widely used to protect transmission systems due to its simplicity [1-2].

The use of FACTS devices in the transmission system are popular for over a decade offering better power flow control and enhanced dynamic stability [3]. On the other hand, when the fault occurs, the presence of FACTS devices creates new problems in transmission line distance protection.

Many researches were undertaken on the impact of different FACTS devices on the distance relay [4-16]. Dash, et al. (2000) analyzed the performance of digital protection of power transmission lines in presence of series connected FACTS devices [4]. Khederzadeh (2002) demonstrates the impact of FACTS controllers and their location in the transmission line on the trip boundary of a digital multifunctional protective relay [5]. El-Arroudi et al. (2002) presented the analytical results based on the steady-state model of STATCOM, and outlined the impact of STATCOM on different load levels [6]. Sidhu et al. (2005) analyzed the Performance of distance relays on shunt- FACTS compensated transmission Lines [7]. The authors, Sidhu et al. (2005) and Khederzadeh et al. (2006) presented a comprehensive analysis of the impact of Thyristor Controlled Series Capacitor (TCSC) on the protection of transmission lines [8-9]. They found from the result, that TCSC not only affects the protection of its line, but also that of adjacent line. The work presented by Zhou et al. (2006), derivates apparent impedance calculation seen by a distance relay in the presence of a unified power flow controller (UPFC) based on the power frequency sequence component and explains the effect of UPFC operational mode as well as its control parameters [10]. Albasri et al. (2007) compared the various distance protection schemes for a midpoint compensated transmission line [11]. Khederzadeh (2008) presented a comprehensive analysis of the impact of Unified Power Flow Controller (UPFC) on the protection of transmission lines [12]. The authors, Khederzadeh et al. (2009) presented the impact analysis of Static Synchronous Series

Compensator (SSSC) on the performance of the work reported by the authors, Shojaei, et al. (2010) demonstrates the impact analysis of SSSC on the performance of the distance relay [14]. Ghorbani et al. (2011) investigated the impact of a SSSC and a STATCOM on the impedance calculated by a distance relay using analytical analysis and simulations. Several scenarios were considered in the simulations including the impact of the fault conditions, compensator settings, and power system conditions. The impact of SSSC on the apparent impedance is significant for single phase faults due to the zero sequence component of the injected voltage of a SSSC [15]. Khederzadeh et al. (2012) analyzed and investigated the impact of different multiline VSC-based FACTS controllers on the performance of impedance-based protection relays under normal operation and fault conditions at different load power flows. Different configurations of multiline VSC-based FACTS controllers like, GUPFC, IPFC, and UPFC were analyzed [16].

There have been a few reports by researchers regarding the mitigation impact of the FACTS devices on distance protection [17-21]. Albasri et al (2007) highlighted the issues encountered on shunt-FACTS devices compensated transmission line using distance protection and presented practical solutions to mitigate the adverse effects of shunt–FACTS compensated lines, on distance protection schemes [17]. Samantaray et al. (2009) presented a new fault location algorithm based on a differential equation-based approach for a transmission line using a Unified Power Flow Controller (UPFC) using Synchronized Phasor Measurements (SPM). The method first, identifies the fault section using a wavelet-fuzzy discriminator and then estimates the fault location using differential equation-based approach[18]. Kazemi et al (2010) addressed a new adaptive distance protection scheme to mitigate the influence of the STATCOM on distance relay digital distance relay [13]. The performance. In this scheme, the tripping characteristic of the adaptive distance relay changes was based on the information received from SCADA about STATCOM controlling parameters and power system conditions [19]. Zhang et al (2010) analyzed the effect of STATCOM on performance of the distance relay of a transmission line and presented new setting principles. But here, the practical difficulty is that when the system parameters change then the setting values have to be adjusted [20]. Seethalekshmi et al (2011) presented an adaptive scheme to predict the trip boundaries of a conventional distance relay in the presence of UPFC through the knowledge of its control parameters. This scheme computes the series voltage and reactive current injection by the UPFC on-line with the help of synchronized phasor measurements and these parameters are utilized in the adaptive trip boundary prediction [21].

It is observed from the above literatures, that most of the methods and models suffered from complexity and dependency on different calculations on a large set of information. To overcome the above difficulties, a new fault location distance relay method has been proposed in this paper to locate the fault exactly by compensating the impedance deviation problems raised by the shunt connected FACTS devices i.e. STATCOM.

In the proposed method, the apparent impedance of the distance relay was corrected using Impedance Compensation Method (ICM). The impedance compensation method of the algorithm uses the measured apparent impedance and the angle of the impedance deviation vector. The angle of impedance deviation was calculated at the relay location by considering the reactive power supplied /observed by the FACTS devices. This method does not use iterative calculations and is independent of the FACTS device models.

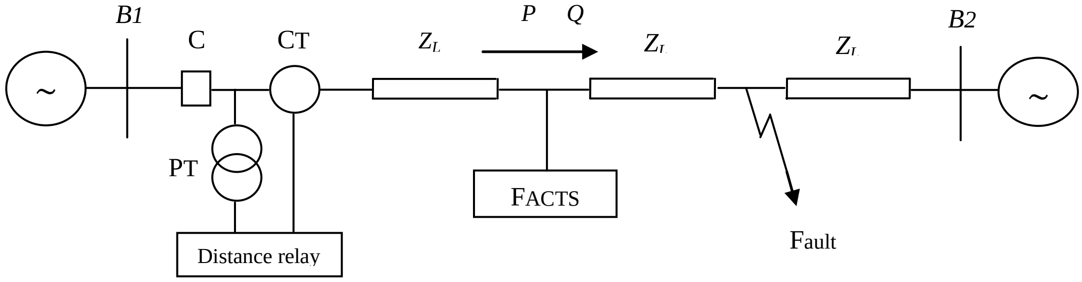

Fig.1. The simplified power system model

The performance of the proposed fault location method was tested with various types of faults at different locations. The test results show that the algorithm has accurate operating characteristics which are not affected by the reactance effect of the FACTS devices operation.

2. Study Test System

2.1 Transmission system Model

A simplified two bus power system model with mid-point compensated FACTS device is shown in Figure1.

The test system consists of a 500 kV 60 Hz, 300 km length transmission line with two equivalent sources connected at the sending and receiving ends respectively. A 100 MVA shunt connected FACTS device such as STATCOM is installed at the midpoint of the transmission line to support the reactive power compensation. The impedance based distance relay which is connected near the sending end bus (B_1) is considered for this analysis. The transmission line is based on the distributed parameter type. Some other relevant system parameters are given in the Appendix A.

2.2 STATCOM control model

The basic principle diagram of STATCOM is shown in Fig.2. The main objective of the STATCOM controller is to regulate the midpoint voltage of the transmission line to the setting value (V_{ref}) by supplying or absorbing the reactive current. The STATCOM consumes or supplies the reactive power to the transmission line system to regulate the connecting point voltage (V_t). The reactive power exchange between STATCOM and the transmission system can be controlled by varying the voltage (V_s) of the three-phase voltage source inverter. If $V_s > V_t$ STATCOM supplies the reactive power to the system, if $V_s < V_t$ it consumes the reactive power from the system. The amplitude of the voltage source inverter can be adjusted by changing the DC capacitor voltage and /or the dead angle (δ).

The control model of STATCOM is shown in Fig.3. The three phase discrete phase lock loop receives three phase voltage from the connecting point and calculates the reference angle which is synchronized with the 'A' phase voltage. The transfer block (*abc-dqo*) receives the three phase current of STATCOM and it gives, real part of three phase current (I_q) considering the phase lock loop angle as a reference.

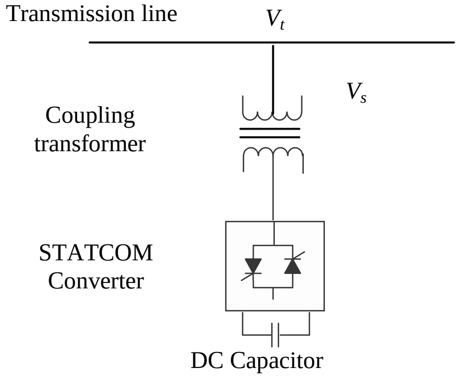

Fig. 2. Basic diagram of the STATCOM

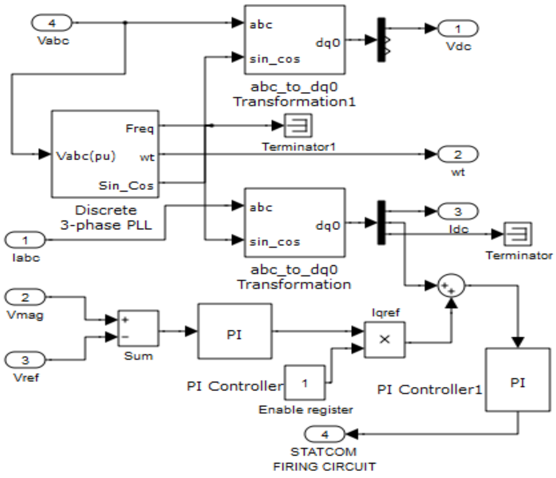

Fig.3. STATCOM control model

The magnitude of the connecting point voltage is compared with the required reference voltage (V_{ref}). The error voltage (V_{err}) is passed through a PI controller to produce the required reactive current (I_{qref}). This current reference (I_{qref}) is compared with the reactive part of the shunt current (I_q) to produce the error and is passed through another PI controller to get the relative phase angle (δ) of the inverter voltage with respect to the 'A' phase voltage. The STATCOM firing pulse generator receives the phase angle together with the phase lock loop signal and generates the required pulse to operate the voltage source inverter [22]

3. FACTS devices impact on distance protection

The introduction of FACTS controllers in the power system opens up new challenges to line protection as they change the voltage and current signals at the relay point in both study and transient conditions, which further changes the apparent impedance calculated by the distance relay. Consequently, distance relays in the associated transmission system have an overreaching or under reaching effect depending on the control modes of the FACTS controllers. During study state (balanced) conditions the FACTS devices are not injecting or absorbing any reactive power to the system so, the values of real power (P) and reactive power (Q) are identical to the output active (P_{B1}) and reactive power (Q_{B1}) of the bus $B1$. But, during transient (unbalanced) conditions the FACTS devices consumes or supplies the reactive power to the transmission line system, which reduces the output powers of the bus $B1$. In other words, some part of the output powers used by the network is injected / absorbed by the FACTS devices.

From the viewpoint of power, the apparent impedance (Z) calculated by the distance relay can be expressed in terms of active and reactive power [1].

i.e. $$Z = \sqrt{R^2 + X^2} \tag{1}$$

In other words, to calculate the impedance measured by the distance relay, the following equations (2) and (3) can be used

$$R = \frac{P(VR)^2}{P^2 + Q^2} \tag{2}$$

$$X = \frac{Q(VR)^2}{P^2 + Q^2} \tag{3}$$

In the above equation, the real power, $P = P_{B1} + P_{FACTS}$ and reactive power, $Q = Q_{B1} + Q_{FACTS}$ where P_{B1} & Q_{B1} are the output active and reactive power of bus $B1$; P_{FACTS} & Q_{FACTS} are the active and reactive powers injected /observed by the FACTS devices. From the equations (2) and (3) it is clear that the value of resistance (R) and reactance (X) is impacted due to reactive power injected / observed by the FACTS devices. So, the apparent impedance (Z) measured by the distance relay is also impacted which can be outside the trip boundary (under-reach) or inside the trip boundary (over-reach). So, distance relay mal-operates and in turn affects the protection sensitivity.

4. Compensation of facts devices reactance impact on distance protection

4.1. Impedance Compensation Method

The concept of the apparent impedance correction method is to minimize the impedance estimation error caused by the FACTS devices reactance effect is shown in Fig.4. In Figure 4, the impedance deviation angle (α) changes with the fault location, fault type and value of the fault resistance.

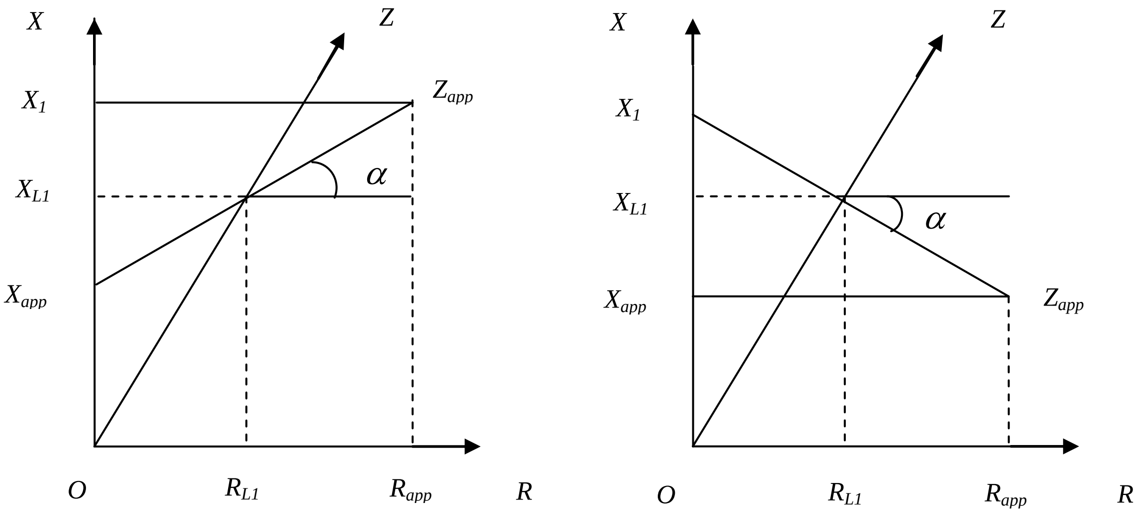

Fig.4. Apparent impedance correction method

Hence, this value may vary between maximum and minimum values. A point (X_1) is determined from the apparent impedance (Z_{app}) and the impedance deviation angle (α).

$$\text{i.e.} \quad X_1 = X_{app} \pm \left(R_{app}.\tan\alpha\right) \qquad (4)$$

The actual line impedance to a fault is the intersection of the two straight lines, Z_{app}- X_1 and *O*-*Z* and is obtained as follows.

$$R_{LI} = \frac{X_1}{\left(\frac{L}{R}\right) - \frac{(X_{app}-X_1)}{R_{app}}} \qquad (5)$$

$$X_{LI} = \left(\frac{L}{R}\right)\frac{X_1}{\left(\frac{L}{R}\right) - \frac{(X_{app}-X_1)}{R_{app}}} \qquad (6)$$

Where,

R is the transmission line resistance (Ω/km)
L is the transmission line inductance (mH/ km)
X is the transmission line reactance (Ω/km)
R_{LI} is the actual positive sequence resistance to a fault (Ω)
X_{LI} is the actual positive sequence reactance to a fault (Ω)
R_{app} is the apparent resistance (Ω)
X_{app} is the apparent reactance (Ω)

$$Z_{act} = \sqrt{{R_{L1}}^2 + {X_{L1}}^2} \qquad (7)$$

The actual line impedance (Z_{act}) is determined by the apparent impedance (Z_{app}) and impedance deviation angle (α).The apparent impedance (Z_{app}) is estimated by dividing the phase voltage (V_R) with phase current (I_R) at the relay location.

4.2. Distance Relaying Algorithm

The new fault location algorithm using one terminal data with Impedance Compensation Method (ICM) was designed and modeled using MATLAB/ SIMULINK software [23]. The ICM is implemented to compensate the magnitude and phase error of the apparent impedance due to the impact of FACTS controllers. This algorithm uses the angle of impedance deviation vector (α) and this is calculated from the reactive power measured at the relay location, before and after the occurrence of a fault.

4.3. Flow Chart of the Distance Relaying Algorithm

The flow chart of the proposed distance relaying algorithm is shown in Fig.5.

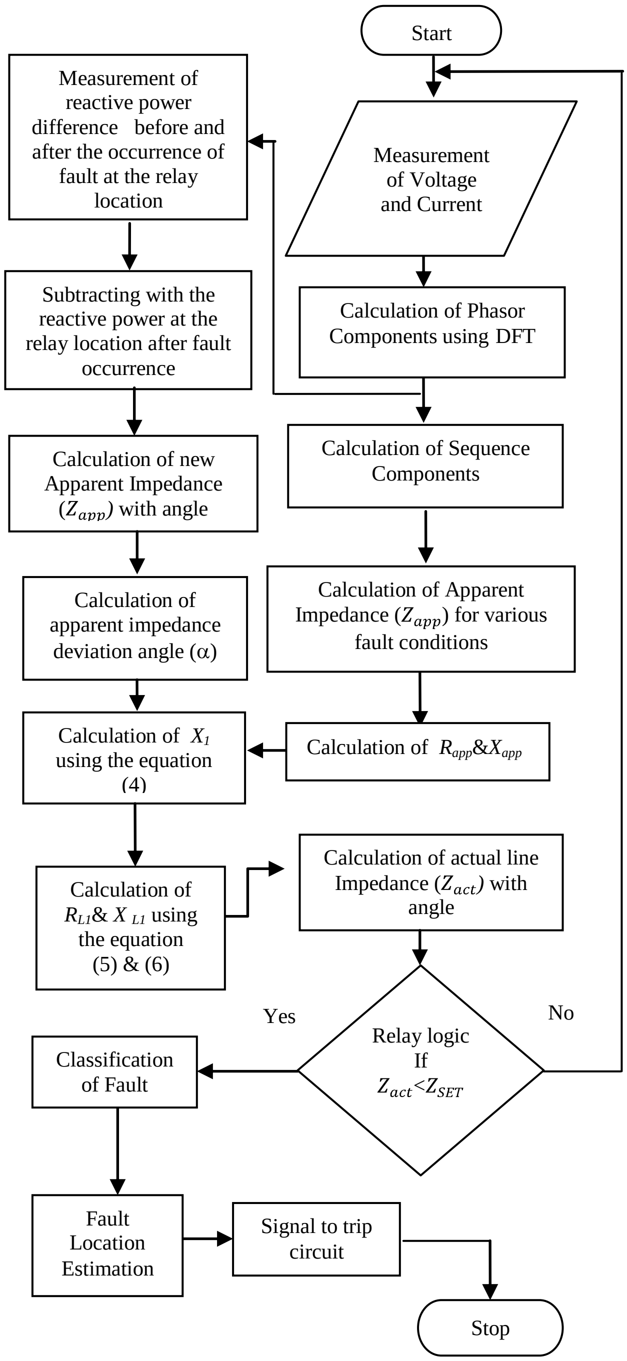

Fig.5. Flow chart of the distance relaying algorithm

The instrument transformers (CT and PT) are used to measure the voltage and current signals at the relay point. An analog anti aliasing filter filters the fault transients before sampling to avoid aliasing in the input waveforms. A data acquisition system calculates the signals as a string of samples. The Discrete Fourier Transform (DFT) block transfers the sampled current and voltage signals to in phasor quantities.

The symmetrical component block extracts the residual current from the phase current. The DFT block also calculates the difference of reactive power before and after the fault occurrence. By subtracting the reactive power from sending end bus reactive power, the reactive power supplied by the STATCOM is calculated. From this, the angle of impedance deviation vector (α) is calculated. The new values of reactance (X_{L1}) and resistance (R_{L1}) are calculated. Then the actual apparent impedance (Z_{act}) is calculated and compared with the set value. The relay logic issue decides whether to trip or not when the calculated apparent impedance is equal or less than the set value. So the exact location of the fault is identified by mitigating the impact caused by the STATCOM device.

5. Results and Discussion

5.1 Impact of STATCOM on conventional method

The apparent impedance seen by the conventional distance relay with and without STATCOM for a single phase fault (with zero fault resistance) created at a distance of 240 km is shown in Figure 6; from this, it is evident that the apparent impedance of the transmission system is higher than that of the system without STATCOM, so the protection zone of the distance relay will be under reach.

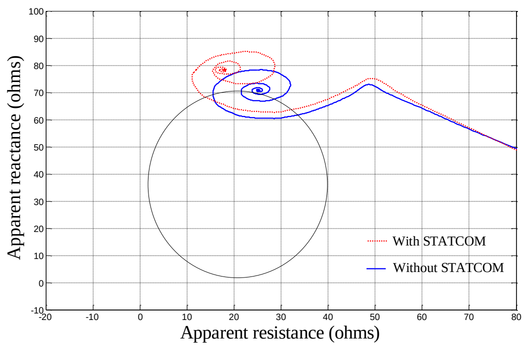

Fig. 6.The apparent impedance seen by the relay for a single phase fault

The impedance trajectory of the distance relay for a three phase fault (with zero fault resistance) at a distance of 240 km with and without STATCOM is shown in Fig.7.; it clearly shows that the apparent impedance of the transmission system is greater than that of the system without STATCOM, so the protection zone of the distance relay is under reach.

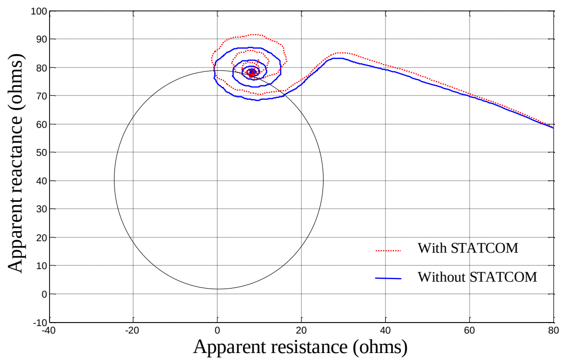

Fig.7.The apparent impedance seen by the relay for a three phase fault

5.2 The performance of the proposed method

The performance of the proposed method was successfully evaluated for various types of faults applied to the transmission system at various locations. The results i.e. three phase voltages and currents obtained at the relay point were exported as the input to the distance relay model. The mho relay characteristics at a sampling rate of 120 samples per second were used to detect the faults. The relay is set to protect 80% (240 km) of the transmission line.

5.2.1 Estimation of Apparent Impedance

Even though several cases were involved in the analysis, only two cases of impedance variations i.e. ‘A’ phase-to-ground fault and ‘A’ phase-to-‘B’ phase-to-‘C’ phase-to- ground fault with zero fault resistance are discussed below. In addition, the effect of the fault occurring before the STATCOM location and after the STATCOM location is also discussed.

The accuracy of the presented method is evaluated considering the percentage error. The error of the apparent impedance variations is expressed in terms of percentage of the total transmission line length as follows

$$\%\ error = \frac{calculated\ apparent\ impedance - actual\ apparent\ impedance}{transmission\ line\ length} \times 100 \qquad (8)$$

5.2.2. Impedance Variations of Single Phase Fault

The test results of the apparent impedance variations of the conventional distance relay and the proposed distance relay for 'A' phase-to-ground fault occurring at various fault distances is shown in Table1.

Table 1. Variations of the apparent impedance for single phase fault.

Actual fault location		Conventional distance relay		Proposed distance relay	
Distancein km	Apparent impedance in ohms	Apparent impedance in ohms	Error, %	Apparent impedance in ohms	Error, %
20	6.58	6.62	0.0133	6.61	0.0100
40	13.16	13.17	0.0033	13.15	-0.0033
60	19.74	19.70	-0.0133	19.69	-0.0166
80	26.32	26.29	-0.0100	26.26	-0.0600
100	32.90	32.84	-0.0600	32.82	-0.0800
120	39.48	39.46	-0.0066	39.45	-0.0100
140	46.06	45.99	-0.0233	45.98	-0.0266
160	52.64	52.92	0.0933	52.55	-0.0300
180	59.22	59.75	0.1766	59.11	-0.0366
200	65.80	66.75	0.3166	65.62	-0.0600
220	72.38	73.25	0.2900	72.25	-0.0433
240	78.96	79.95	0.3300	78.75	-0.0700
260	85.54	87.95	0.8033	85.45	-0.0300
280	92.12	96.81	1.5633	92.00	-0.0400

5.2.2.1. Effect of Fault Occurring Before the STATCOM Location

It is clearly seen that when the fault occurs between the relay point and the STATCOM location (between 10 and 150 kilometers in this case), there is not much change in the apparent impedance measured by the conventional distance relay and the proposed distance relay measurements i.e. the measured apparent impedance by both conventional and proposed method is almost the same.

For example, when the fault occurs at a distance of 120 km, (actual apparent impedance is 39.48) the apparent impedance measured by the conventional distance relay is 39.46 ohms and the proposed distance relay is 39.45ohms. This is due to the fact that when the STATCOM is not present in the fault loop, then the measured impedance is equal to the actual line impedance of the line section between the relay point and the fault point. Since the STATCOM device is not injecting or observing any reactive power in to the transmission line during such conditions.

5.2.2.2. Effect of Fault Occurring After the STATCOM Location

When the fault ('A' phase-to-ground fault) occurs beyond the STATCOM location i.e. between 150 and 300 kilometers, the apparent impedance measured by the conventional method is greater than that of the proposed method as the STATCOM involves the fault loop.

It is observed that (refer Table 1) when the fault occurs at a distance of 260 km, the proposed distance relay measures 85.45ohms, whereas the conventional distance relay measures the apparent impedance as 87.95ohms, which is greater than that of the proposed distance relay measurement. The conventional method of measurement gives is high percentage of error compared with the proposed method.

The proposed method compensate the reactance effect of the STATCOM so, the apparent impedance measured is same as that of the actual apparent impedance of the fault line, which gives, less percentage of error.

5.2.3. Impedance Variations of Three Phase Fault

The variations of the apparent impedance for 'A' phase-to-'B' phase-to-'C' phase-to- ground fault with different fault locations in the conventional distance relay and the proposed distance relay is shown in Table 2.

Table 2. Variations of the apparent impedance for three phase fault

Actual fault location		Conventional distance relay		Proposed distance relay	
Distance in km	Apparent impedance in ohms	Apparent impedance in ohms	Error, %	Apparent impedance in ohms	Error, %
20	6.58	6.88	0.1000	6.60	0.0066
40	13.16	13.37	0.0333	13.20	-0.0530
60	19.74	19.69	-0.0166	19.70	-0.0133
80	26.32	26.31	-0.0033	26.30	-0.0066
100	32.90	32.96	0.0200	32.89	-0.0033
120	39.48	39.51	0.0100	39.46	-0.0066
140	46.06	45.96	-0.0333	45.98	-0.0266
160	52.64	53.13	0.1633	52.56	-0.0266
180	59.22	59.89	0.2233	59.12	-0.0333
200	65.80	66.50	0.2333	65.68	-0.0400
220	72.38	75.11	0.9100	72.26	-0.0400
240	78.96	83.47	1.5033	78.80	-0.0533
260	85.54	90.47	1.6433	85.58	0.0133
280	92.12	96.89	1.5900	92.13	0.0033

For a system with STATCOM, it is observed that when the fault occurs before the STATCOM location, the proposed distance relay and the conventional distance relay measure almost the same values. (For example, when the fault occurs at 120 km, the apparent impedance measured by the conventional distance relay is 39.49 ohms and the proposed distance relay is 39.46 ohms.). But, if the fault occurs after SATACOM location i.e. for 260 km, the proposed distance relay measures 85.58 ohms and conventional distance relay measures 90.47ohms.

It clearly shows that when the fault occurs between the relay location and after the STATCOM location, the conventional distance relay measurement is greater than that of the proposed distance relay measurement and the apparent impedance measured by the proposed distance relay is almost same as actual apparent impedance of the fault.

The test results given in Tables 1 and 2 clearly show that the percentage error of the apparent impedance measured by the proposed method is less compared with the conventional method.

The proposed method compensate the reactance effect of the STATCOM, hence the apparent impedance measured is less percentage of error. So it is evident that the new proposed distance protection method effectively mitigates the impact of STATCOM on the apparent impedance measurement of the distance relay and functions well without error.

5.3. Estimation of Fault Location

The test results under several fault scenarios with different fault resistances and fault locations are shown in Table 3 and Table 4 for both conventional and proposed measurements respectively. The Table consists of fault type, actual fault location, estimated fault location percentage error, using conventional measurements and the proposed distance relay measurements. The error of the fault location is expressed in terms of percentage of the total transmission line length as follows.

$$\%\,error = \frac{calculated\ distance - actual\ distance}{transmission\ line\ length} \times 100 \qquad (9)$$

Table 3. Estimation of Fault Location Based on Conventional Measurements

Fault Type	Actual fault location (km)	R=0Ω		R=1Ω		R=10Ω		R=100Ω	
		Estimated fault location (km)	Error,%	Estimated fault location (km)	Error,%	Estimated fault location (km)	Error,%	Estimated fault location (km)	Error,%
Single Phase to ground	20	20.12	0.040	21.30	0.433	27.20	2.400	360.3	113.4
	60	60.06	0.020	62.00	0.660	65.12	1.706	408.4	116.1
	100	100.12	0.040	102.14	0.713	106.21	2.070	462.9	120.9
	140	140.21	0.070	142.45	0.816	157.02	5.673	518.6	126.2
	160	161.34	0.446	164.20	1.400	168.20	2.733	548.7	129.5
	180	182.16	0.720	183.90	1.300	188.02	2.673	575.2	131.7
	200	203.50	1.166	209.20	3.066	213.30	4.433	604.9	134.9
	220	223.32	1.106	225.20	1.733	229.20	3.066	637.1	139.0
	240	243.80	1.266	256.30	5.433	262.20	7.400	673.7	144.5
	280	295.20	5.066	309.20	9.733	314.30	11.430	773.7	164.5
Three Phase to ground	20	20.97	0.323	22.30	0.766	26.90	2.300	238.7	72.9
	60	60.03	0.010	62.20	0.733	66.20	2.066	269.1	69.7
	100	100.48	0.160	103.10	1.033	106.20	2.066	307.9	69.3
	140	140.12	0.040	142.49	0.830	147.00	2.333	356.5	72.1
	160	161.90	0.633	161.20	0.400	166.20	2.066	385.4	75.1
	180	182.59	0.863	184.20	1.400	190.00	3.333	418.3	79.4
	200	203.74	1.246	209.10	3.033	214.50	4.833	456	85.3
	220	229.00	3.000	233.00	4.333	241.60	7.200	500.3	93.4
	240	254.50	4.833	261.20	7.066	264.80	8.266	553.4	104.4
	280	295.40	5.133	313.30	11.100	316.00	12.000	701.5	140.3

Table 4. Estimation of Fault Location Based on Proposed Measurements

Fault Type	Actual fault location (km)	R=0Ω		R=1Ω		R=10Ω		R=100Ω	
		Estimated fault location (km)	Error, %	Estimated fault location (km)	Error, %	Estimated fault location (km)	Error, %	Estimated fault location (km)	Error, %
Single Phase to ground	20	20.09	0.030	20.09	0.030	20.03	0.010	20.04	0.067
	60	60.03	0.010	60.03	0.010	60.09	0.030	60.10	0.033
	100	100.06	0.020	100.07	0.023	100.09	0.030	100.13	0.043
	140	140.18	0.060	140.19	0.063	140.21	0.070	140.23	0.076
	160	160.21	0.070	160.23	0.076	160.35	0.116	160.37	0.123
	180	180.21	0.070	180.22	0.073	180.28	0.093	180.29	0.096
	200	200.06	0.020	200.08	0.026	200.16	0.053	200.19	0.063
	220	220.27	0.090	220.29	0.096	220.37	0.123	220.38	0.126
	240	240.09	0.030	240.09	0.030	240.90	0.300	240.80	0.266
	280	280.79	0.263	280.79	0.263	280.91	0.303	280.81	0.270
Three phase to ground	20	20.12	0.040	20.13	0.043	20.22	0.073	20.26	0.086
	60	60.06	0.02	60.08	0.026	60.16	0.053	60.17	0.566
	100	100.27	0.090	100.28	0.093	100.39	0.130	100.41	0.136
	140	140.18	0.060	140.19	0.063	140.28	0.093	140.29	0.096
	160	160.24	0.080	160.29	0.096	160.34	0.113	160.39	0.130
	180	180.24	0.080	180.27	0.090	180.34	0.113	180.36	0.120
	200	200.24	0.080	200.26	0.086	200.29	0.960	200.30	0.100
	220	220.30	0.100	220.32	0.106	220.39	0.130	220.41	0.136
	240	240.24	0.080	240.25	0.083	240.28	0.093	240.39	0.130
	280	280.80	0.266	280.87	0.290	280.92	0.306	280.14	0.046

A single-phase fault (‘A’ phase-to-ground fault) condition (with R= 0 Ω) is an example, when the fault is at 240 km, the estimated fault location based on conventional measurement is 243.8 km, but estimated fault location based on the proposed distance relay measurement is 240.09 km. Similarly for a three phase fault (‘A’ phase-to-‘B’ phase-to-‘C’ phase-to-ground fault) condition, the estimated fault location based on conventional distance relay measurement is 254.50 km, but estimated fault location based on the proposed distance relay measurement is 240.24 km.

The test results given in Tables 3 and 4 clearly show that the percentage error of the fault location distance calculated by the proposed method is less compared with the conventional method, even in high fault resistance conditions. The proposed method compensate the impedance variations caused due to the reactive power injected /observed by the FACTS controllers to the transmission line and high fault resistance, during transient (fault) conditions, hence the fault location distance is having less percentage of error. So it is evident that the new proposed distance protection method effectively mitigates the impact of FACTS controllers such as STATCOM on the apparent impedance measurement of the distance relay and functions well without error.

The results show that the proposed distance protection method estimates the fault location correctly and effectively mitigates the impact of STATCOM on the distance relay performance for various fault conditions.

6. Conclusion

A new fault location algorithm for FACTS devices connected transmission line distance protection is developed and tested successfully to overcome the problems arising from the conventional methods. The proposed distance location algorithm utilized the Impedance Compensation Method (ICM) to estimate the impedance to the fault point independent of the effect of FACTS devices and accordingly, the actual distance to the fault is calculated. This impedance compensation method uses impedance deviation angle (α) to compensate the magnitude and phase of the apparent impedance at the relay location. The angle of impedance deviation was calculated at the relay location considering the reactive power supplied /observed by the FACTS devices. This method does not use any iterative calculations and is independent of the FACTS device models. The proposed algorithm is not sensitive to fault resistance and does not require any knowledge of the FACTS' devices operating mode. The results of computer simulations for different fault conditions prove the accuracy and reliability of the algorithm.

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Appendix A
Parameters of the test system

Short circuit level at base voltage source 1	9000 MVA
X/R ratio	8
δ	20°
Frequency	60 Hz
Transmission line	
Positive sequence resistance R_1	0.02546 Ω/km
Zero sequence resistance R_0	0.3864 Ω/km
Positive sequence inductance L_1	0.9337mH/km
Zero sequence inductance L_0	1.264 mH/km
Positive sequence capacitance C_1	12.74 nF/km
Zero sequence capacitance C_0	7.751 nF/km
Length of the line	300 km
STATCOM	
Rated capacity	±100 MVA
Rated voltage	500 kV
Number of pulses	48
Capacitance	3000 µF
Reference voltage	1 p.u.
Droop	0.03