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Synchrophasors-based transmission line protection in the presence of STATCOM

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Abstract

The distance relay using the transmission line impedance measurement identifies the type and location of the fault. However, any other factors that cause the failure of the measured impedance, makes the relay detect the fault in incorrect location or do not detect the fault at all. One of these factors is the fault resistance which directly increases the measured impedance by the relay. Another factor that indirectly alters the impedance of the transmission line is static synchronous compensator (STATCOM). When a fault happens, current injection by the STATCOM changes the measured signals by the relay and thus makes the calculated impedance incorrect. In this paper, a method is provided based on the combination of distance and differential protection. Firstly, from the current data of buses, faulted transmission line is detected. Then using the presented algorithm, the fault location is calculated on the transmission line. The basis of the algorithm is on the active power calculation of the buses. Fault resistance is calculated from the active powers and its effect will be deducted from calculated impedance by the algorithm. Furthermore, with choosing data of appropriate bus, STATCOM effect is eliminated, and fault location will be obtained.

Keywords: flexible ac transmission system (FACTS) controllers, ground distance relay, phasor measurement units (PMUs), static synchronous compensator (STATCOM), smart grid

Introduction

Distance relays are one of the most useful relays in transmission lines. However, several factors may cause the relay to not function properly in the transmission line. These factors are generally divided into three categories. The first depends on the type of lines such as presence of infeed currents in teed-feeder system. To eliminate this factor various methods have been used in [1]-[7]. The second factor is fault resistance that causes increasing of the measured impedance by the distance relay and relay under-reach. In [8]-[14] different methods have been proposed to reduce the effect of fault resistance. The third category is the presence of compensators on the transmission line including simple compensation such as fixed series capacitor or the FACTS controllers. In [15]-[18] various methods have been studied for eliminating the effect of series capacitors in the relay performance. In [19]-[24] the effect of shunt-FACTS controllers in distance protection is studied. In [19]-[24] it has been shown that the presence of shunt-FACTS causes the relay to not properly recognize the fault. The literature also shows that the impact of FACTS devices in phase to ground faults are more numerous. In recent studies, methods to eliminate the effects of FACTS devices in distance protection are provided. In [19] only the effect of static Var compensator (SVC) in distance protection is studied and has been shown that in phase-to-ground faults, SVC effect on the protection distance is more remarkable. In [20] algorithm is based on the Fuzzy system, the effect of STATCOM on the protection distance is reduced, but the effect of fault resistance is not considered. In [21] adaptive distance protection scheme for shunt-FACTS compensated line connecting wind farm is presented and adaptive tripping characteristics for high resistance line-to-ground fault has been used for this purpose. Impact of fault resistance can be reduced by using tripping characteristics, but measured impedance by the relay is still not corrected. In other words, in this method the shape of relay protection Zone is changing, but in the measured impedance by the relay, the effect of fault resistance remains. Then the fault location is not detected. Because the fault location is obtained by transmission line impedance from relay until fault location, which in this case, the impedance is increased by the fault resistance. This causes the fault location not to be recognized.

Another technique is to use differential protection in transmission line. Using existing algorithms in differential protection, fault location cannot be detected [25]. Also, some methods require complex algorithms or neural networks/ Fuzzy system. Moreover, these days traditional power systems are leading to the smart grid and the use of PMU's are increasing. Especially in power systems that FACTS devices are implemented, communication channels are used for remote control. Through these communication channels, necessary commands are sent to the control systems of FACTS devices. This is useful for various purposes such as improving power system stability, voltage profile, sub-synchronous resonance damping, and so on [26]-[30].

In this paper for the first time a method is provided for removing the effect of STATCOM and fault resistance simultaneously. The presented modified algorithm is a combination of differential and distance protection. The buses data including voltage and current signals will be sent to the relay location or SPC. Then using obtained synchro phasors, the effect of fault resistance and STATCOM is compensated from the measured impedance. In this method, protection Zones are not changed, and backup protection is established similar to distance protection. As in this method, the calculated impedance is improved, then the fault location is accurately identified. In the proposed algorithm, complicated methods have not been used and its capability in various high resistance faults is shown. The modelling has been performed by MATLAB and a detailed model of the STATCOM is used. The paper has the following sections: in Section II, the effects of STATCOM and fault resistance in the calculated impedance by the relay is explained in detail. The modified algorithm is presented in section III. In section IV modeling results are presented in different scenarios and finally we conclude in Section V.

Analytical Analysis

The power system under study (presented in Fig. 1) comprises three transmission lines each 200 km in length. The STATCOM is located in the middle of the line-2 and the distance relays, each with three protection Zones, are located at both ends of the lines. For example, Zone-1 of the relay R_A, comprises 80% of the transmission line-1; Zone-2 comprises whole of line-1 and 50% of the line-2; and the Zone-3 comprises whole of lines-1 and 2 and also 20% of the line-3. The other relays are similar to R_A. Also, applying delay to the operation of Zones-2 and 3 of the distance relays creates backup protection. The positive, zero and negative sequence networks of the power system from the viewpoint of the R_B relay are shown in Fig. 2. In this figure, the STATCOM is considered as a controllable current source because the STATCOM has a shunt impedance making the STATCOM just like a variable or controllable current source while the current following through this impedance. The positive–sequence voltage at the R_{BC} relay location (V_{1B}) can be expressed as:

$$V_{1B} = xZ_{1L2}I_{1B} + (x - .05)Z_{1L2}I_{1SH} + R_f I_{1f} + V_{1f} \quad (1)$$

Negative and zero–sequence voltages (V_{2B} and V_{0B}) are the same as (1), except that the superscripts are changed to 2 and 0, respectively. For a single phase-to-ground fault (A–G) following equations can be used:

$$V_{1f} + V_{2f} + V_{0f} = 0 \quad (2)$$

Using V_{1B}, V_{2B}, V_{0B} and (2) gives:

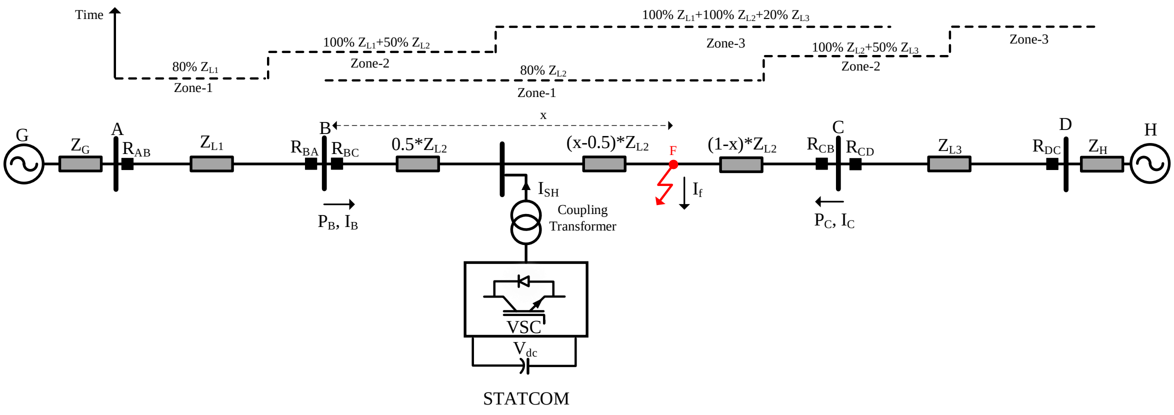


Figure 1: Single-line diagram of multi-line system with the STATCOM

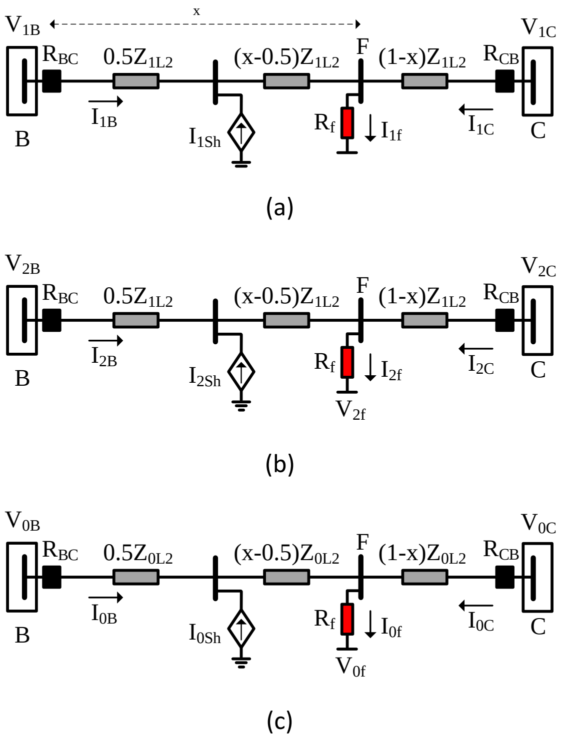


Figure 2: Positive (a), negative (b) and zero-sequence (c) networks of the power system from the viewpoint of the RBC relay for an A-G fault at line–2

$$V_B = V_{1B} + V_{2B} + V_{0B} = xZ_{1L2}I_B + x(Z_{0L2} - Z_{1L2})I_{0B} + R_fI_f + (x-0.5)Z_{1L2}I_{Sh} + (x-0.5)(Z_{0L2} - Z_{1L2})I_{0Sh} \qquad (3)$$

where:

$$I_B = I_{1B} + I_{2B} + I_{0B} \qquad (4)$$

$$I_f = I_{1f} + I_{2f} + I_{0f} \qquad (5)$$

$$I_{Sh} = I_{1Sh} + I_{2Sh} + I_{0Sh} \qquad (6)$$

For a single-phase-to-ground fault (A–G) on the line-2, the apparent impedance seen by R_B relay is as follows:

$$Z_{BC} = \frac{V_B}{I_B + I_{0B}((Z_{0L2} - Z_{1L2})/Z_{1L2})} = \frac{V_B}{I_{BC}} = xZ_{1L2} + \underbrace{R_f\frac{I_f}{I_{BC}}}_{\Delta Z_{Rf}} + \underbrace{(x-0.5)Z_{1L2}\frac{I_{Sh}}{I_{BC}} + (x-0.5)(Z_{0L2} - Z_{1L2})\frac{I_{0Sh}}{I_{BC}}}_{\Delta Z_{Sh}} \qquad (7)$$

It can be seen according to the (7) that the calculated impedance by the single-phase-to-ground element of the relay has three parts:

1) xZ_{1L2}: which represents the impedance of the transmission line from the relay to the fault location. This represents fault location or “x”.

2) ΔZ_{Rf}: This part relates to the fault resistance, and it makes increase to the calculated impedance by the relay.

3) ΔZ_{Sh}: Represent the STATCOM effect, which has a direct impact on the apparent impedance calculated by the relay.

The ΔZ_{Rf} and ΔZ_{Sh} factors cause that the calculated impedance is not equal to the correct or ideal amount, consequently, the fault location is not correctly detected. Then, a method is provided for eliminating these two effects simultaneously.

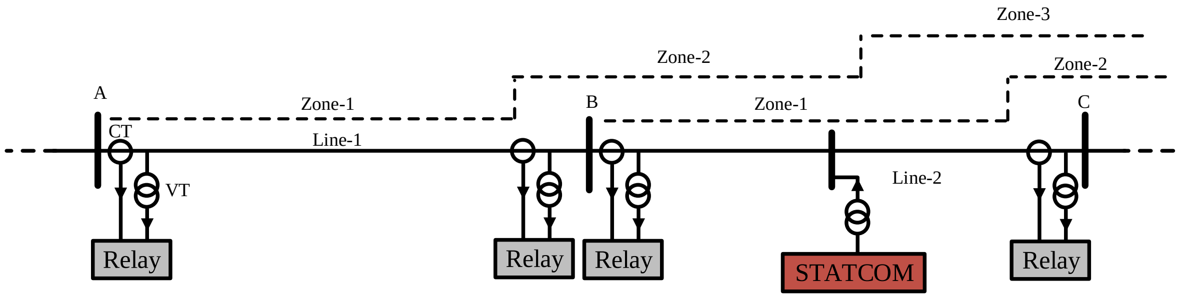
It should be noted that for the *F* fault, STATCOM is not placed in the fault loop of the R_{CB} relay and using the mentioned algorithm, calculated impedance by this relay is:

$$Z_{CB} = \frac{V_C}{I_C + I_{0C}((Z_{0L2} - Z_{1L2})/Z_{1L2})} = \frac{V_C}{I_{CB}} = (1 - x)Z_{1L2} + \underbrace{R_f \frac{I_f}{I_{CB}}}_{\Delta Z_{Rf}} \quad (8)$$

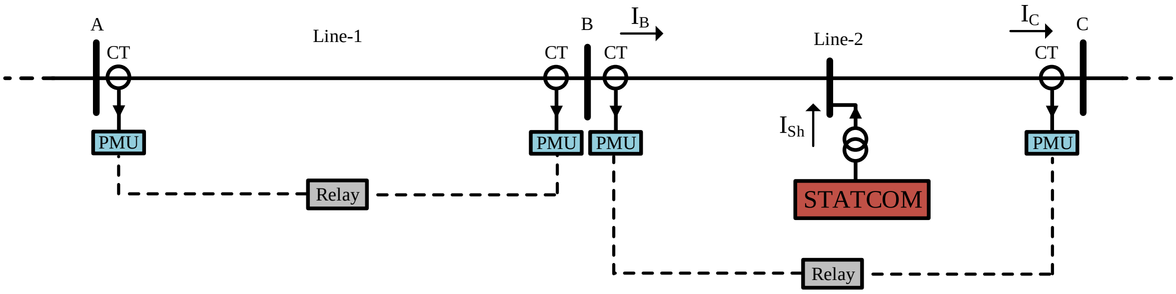
As can be seen, the calculated impedance by this relay is affected only by R_f.

Modified Algorithm

As it can be seen in the analytical analysis, distance relay using measuring of the transmission line impedance can detect the type and location of the fault. One of the advantages of distance relays is having three protective Zones that provide possibility of backup protection. But as can be seen, the presence of fault resistance and compensators altering the calculated impedance by the relay, followed by relay mal operation. Today, using synchrophasors and communication channels, differential protection can be used in the transmission lines that do not have problems with the distance relay. It will not be affected by fault resistance and the effect of the compensator can be eliminated by using two CTs at both ends of the compensator. However, this kind of protection detects only the existence of the fault and not its location. Moreover, backup protection cannot be established as in distance relay. In the following, a method is presented with combination of both methods and having their advantages. For this purpose, two common methods of differential protection and distance protection are shown in Figs. 3. In Fig. 3 (a), distance protection including three protective Zones is shown. In Fig. 3 (b), differential protection of each transmission line is shown in which at both ends of each line CTs are placed and current signals data will be sent to the related relay using communication channels. The presence of the STATCOM in the line-2 causes the currents to be not equal to CTs of line-2. This causes that in normal situation and without fault, relay act incorrectly. To eliminate this problem, in the conventional method, line-2 is divided into two sections as shown in Fig. 3 (c). In this case, STATCOM current (I_{Sh}) is not affecting none of the relays. In this technique the number of relays and CTs are increasing. In a better method it is possible to transmit the data of STATCOM current to the relay. Then its effect will be eliminated from the relay calculation and I_{Sh} will be deducted from the calculated current differences by CTs. This helps to eliminate the STATCOM effect. Despite this, the absence of backup protection and non-recognition of the fault location still remain in this case.



(a)



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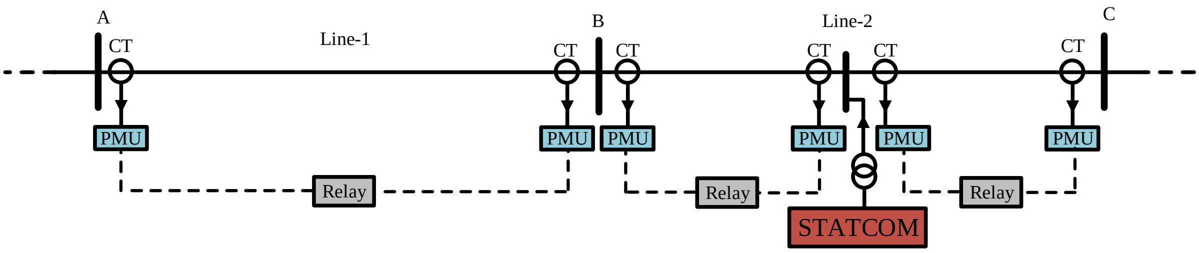
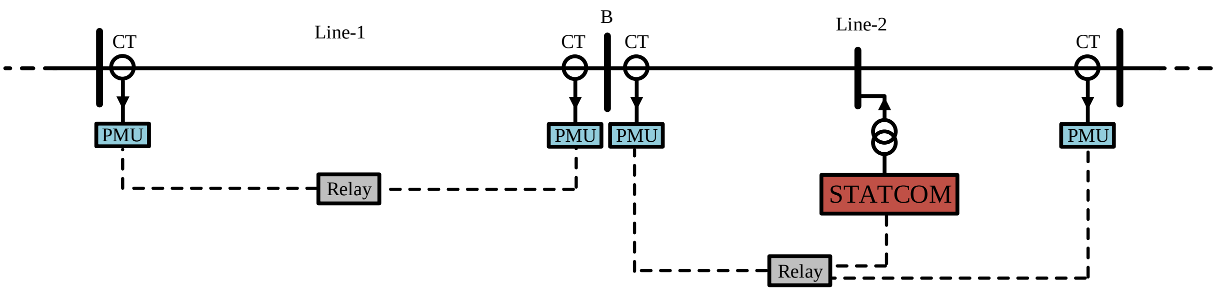


(c)



(d)

Figure 3: Distance protection (a), conventional differential protection (b) generalized differential protection (c) and modified differential protection with the presence of STATCOM in line-2

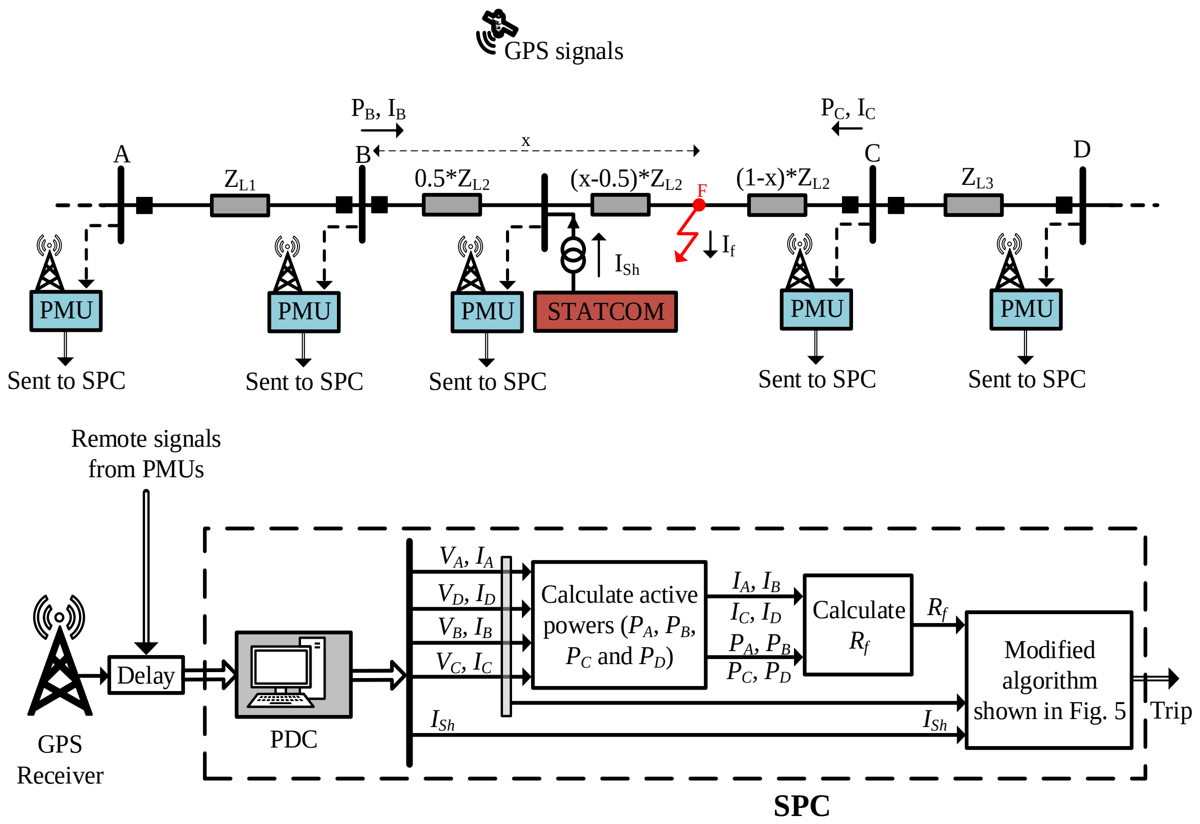


Figure 4: Configuration of modified protection scheme with details of SPC

The new hybrid approach is shown in Fig. 4. In this technique, firstly, the data of buses including current and voltage signals will be sent to SPC. In other words, it is not necessary for each line one (differential protection) or two (distance protection) relays to be considered. Instead, a SPC is considered that using received data, the fault location is identified, and trip command will be sent to the appropriate circuit breakers. More details on how to measure signals are given in Fig. 5 where the measured signals by CT and VT are filtered. Then, they are converted to phasors by full cycle discrete Fourier transform (FCDFT) method and finally using global positioning system (GPS), time information will be added to them. This information will be transmitted to SPC by optical fiber and synchronized by phasor data concentrator (PDC) [31]-[32]. Finally, the measured and synchronized signals are sent to the algorithm of fault calculation. The algorithm is given in Fig. 6. Firstly, using the current data of buses, the faulted transmission line is detected. Hence if a fault occurs in the transmission line, the current will not be the same at both ends of the line. As a result, it can be found that the fault is in which line. It should be noted as in Fig. 3 (b), the existence of the STATCOM in line-2 makes I_B and I_C currents not equal without any fault. For this purpose, the STATCOM current data will be sent to SPC. This current is steadily reduced from the difference between the currents I_B and I_C. This means that in the normal situation a fault is not identified in line 2. After identifying the faulted transmission line, a trip command is sent to the related circuit breakers. Until this point, the algorithm is similar to the differential protection shown in Fig. 3 (d). Except that the SPC is replacing all of relays. Still, this algorithm is not suitable because this algorithm does not indicate the exact location of the fault that is the main disadvantage of differential protection. For this purpose, in the algorithm using voltage and current signals data as was explained in section II, line impedance from relay to fault location is identified and fault location will be calculated. The difference is that conventional methods of distance protection cannot be used in this technique. Because as it was shown in (7), the impedance is altered due to fault resistance and the STATCOM. In this algorithm a method is presented to eliminate these effects simultaneously. At the beginning, using the bus voltage and current signals, active power in the buses of the faulted transmission line will be calculated. In this case, for the fault in line-2, active power in buses B and C will be calculated. The sum of these two active powers is equal to:

$$P_B + P_C = (xR_{L2}) \times {I_B}^2 + (x - 0.5)R_{L2} \times {I_{Sh}}^2 + (1 - x)R_{L2} \times {I_C}^2 + R_f \times {I_f}^2 \quad (9)$$

Since the fault resistance is much larger compared with the resistance of the transmission line, then it is possible to neglect the loss power in them. Then we will have:

$$P_B + P_C \cong R_f \times {I_f}^2 = R_f \times (I_B + I_C + I_{Sh})^2 \quad (10)$$

In this equation, P_B, P_C, I_B, I_C and I_{Sh} are available and R_f can be obtained from the following equation:

$$R_f \cong \frac{P_B + P_C}{(I_B + I_C + I_{Sh})^2} \quad (11)$$

After obtaining the R_f and determine faulted line, ΔZ_{Rf} is calculated for two relays of that line and will be reduced from the calculated impedance by the relays. In consequence the modified impedance of R_{CB} relay is placed in Zone-1 and the fault is correctly detected by this relay. Because as the (8) shows, for the *F* fault, R_{CB} relay is only affected by the fault resistance. Because of ΔZ_{Sh}, R_{BC} relay does not recognize the fault in Zone-1. Then in the end, the faulted line and fault location will be obtained, and trip command will be sent to related circuit breakers of that line. It should be noted that for the sake of backup protection, if any of the circuit breakers does not operate, trip command will be sent to the neighborhood circuit breakers. Therefore, backup protection will be established. The algorithm flowchart is presented in Fig. 6. It should be noted that for the fault on the left of STATCOM, the method is similar. The only difference is that this time the STATCOM will be located in R_{CB} fault loop. In this case after R_f calculation and eliminating its effect from both relays, fault sill be placed in the Zone-1 of R_{BC} relay and *x* will be obtained from its impedance. For the fault in line 1, as algorithm shows, STATCOM does not impact, and it is enough to calculate R_f and eliminate its effect from calculated impedance and consequently *x* will be obtained. In other words, for other transmission lines in which there is no compensation, one relay is sufficient to calculate *x*. In other words, in the proposed algorithm only in the transmission line containing STATCOM, two relays are required at both ends of the line and in other lines using only one relay is possible to detect fault location. It should be noted that in the above description, the meaning of relays is not their physical existence in transmission lines. Their algorithm is in SPC. This issue is considered as follows using the results of the modelling.

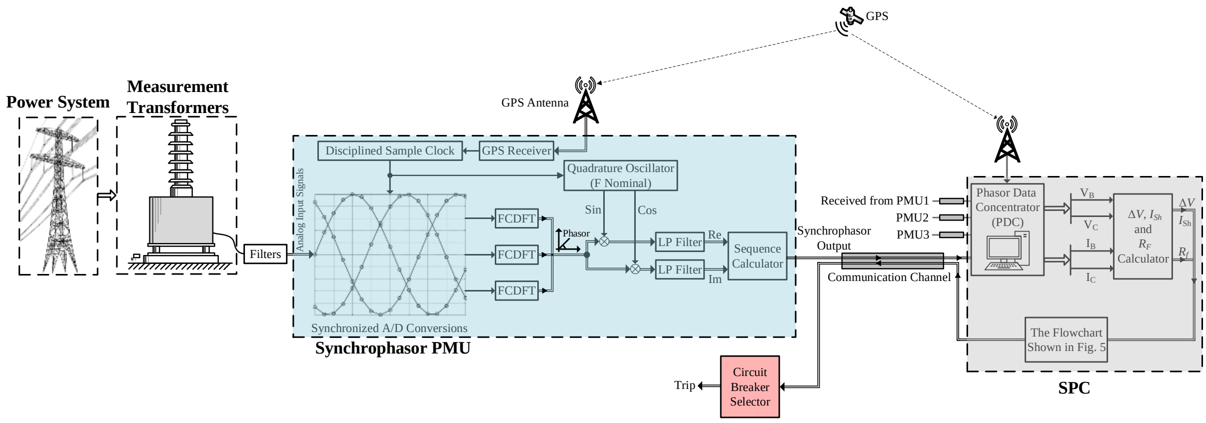


Figure 5: The main parts of the modified algorithm

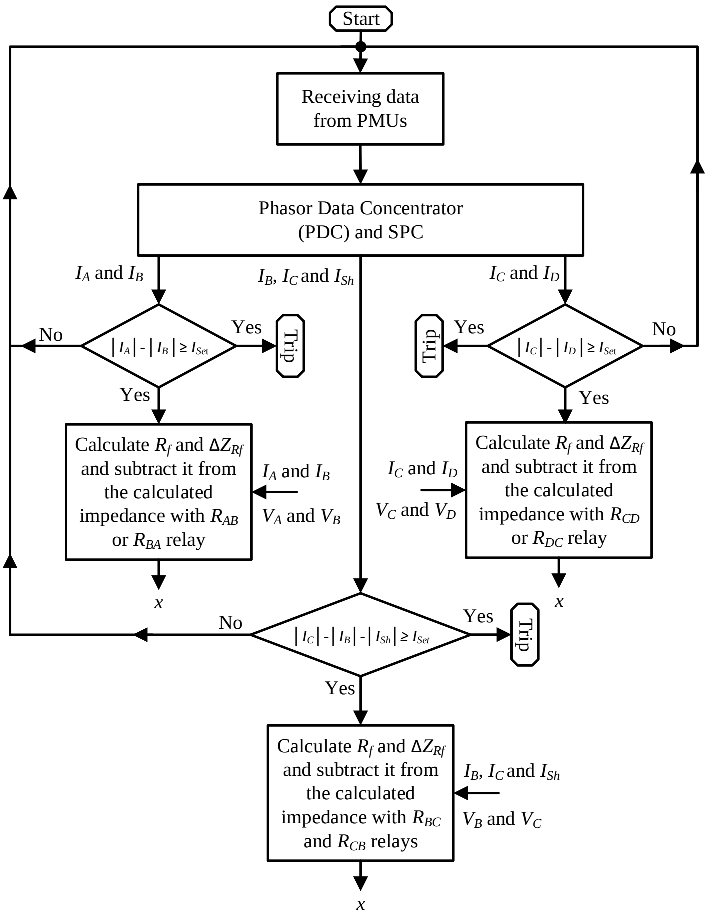


Figure 6: The flowchart of the modified algorithm

Modeling Results

In this section, the results are presented for different scenarios. The power system studied is shown in Fig. 1. Results are mostly about modified algorithm and this paper investigates the method for eliminating STATCOM effect on distance protection. Furthermore, the impact of STATCOM control and power system working conditions in calculated impedance is brought in [23]. In this investigation, 48–pulsed voltage source converters are used for modeling STATCOM. It consists of four 3–phase, 3–level inverters and four phase–shifting transformers. The four voltages generated by the inverters are applied to secondary windings of four zig–zag phase–shifting transformers connected in Wye (Y) or Delta (D). The four transformer primary windings are connected in series to the transmission line. The results of modeling for A-G fault in 150 km of R_{BC} relay with R_f = 0 Ω are shown in Fig. 7. In this figure, the calculated impedance by both R_{BC} and R_{CB} relays and for the conventional algorithm is presented. According to the figure, it can be seen that as the STATCOM is located in the fault loop of R_{BC} relay, the relay is under-reach and detects incorrectly the fault in its Zone-2. While this fault is in 150 km of R_{BC} relay and its first Zone covers 160 km. It also can be seen that R_{CB} relay is correctly detecting the fault in its Zone-1 and in 50 km. It should be noted that line impedance is 0.0201+j0.2868 Ω/km and the fault in 50 km of the relay represents impedance of 1.0+j14.34 Ω. Comparing this impedance by calculated impedance by the R_{CB} relay shows that relay is correctly detecting the fault in 50 km. It should be noted that in this case R_f = 0 Ω and therefore according to the (8), putting R_f equal to zero, calculated impedance by the relay does not change by any factors. While in the R_{BC} relay and according to (7), relay is affected by I_{Sh} and under-reach. This causes interruption in coordination of the relays and as R_{BC} relay detect the fault in its Zone-2, send the command trip by delay and right circuit breaker of line-2 will be opened by delay. Results for the same fault but this time assuming R_f = 50 Ω, are shown in Fig. 8. As can be seen both relays, due to R_f did not detect fault in any of their protective Zones.

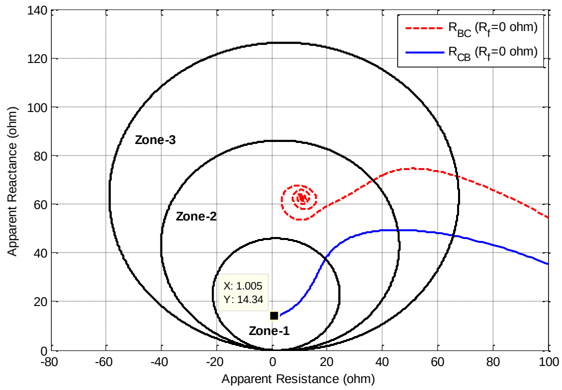


Figure 7: Apparent impedance seen by conventional relays with the presence of STATCOM and for an A–G fault in line-2 and 150 km away from the RBC (Rf = 0 Ω)

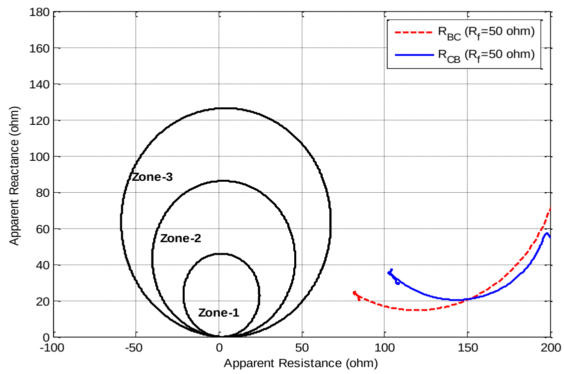


Figure 8: Apparent impedance seen by conventional relays with the presence of STATCOM and for an A–G fault in line-2 and 150 km away from the RBC (Rf = 50 Ω)

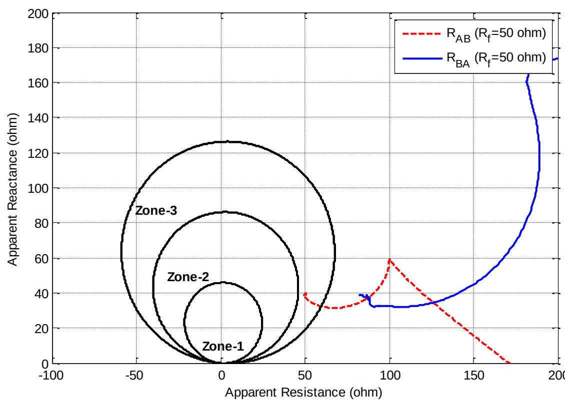


Figure 9: Apparent impedance seen by conventional relays with the presence of STATCOM and for an A–G fault in line-1 and 150 km away from the RAB (Rf = 50 Ω)

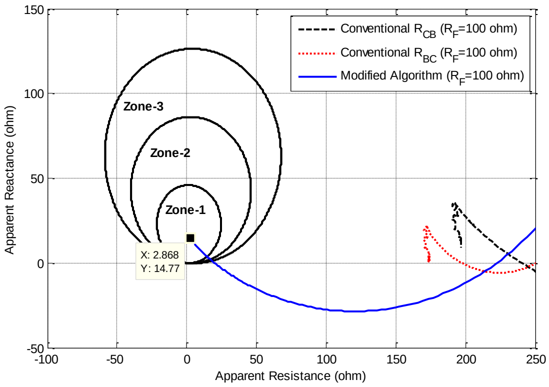


Figure 10: Measured apparent impedance with the presence of STATCOM and for an A–G fault in line-2 and 150 km away from the RBC (Rf = 100 Ω)

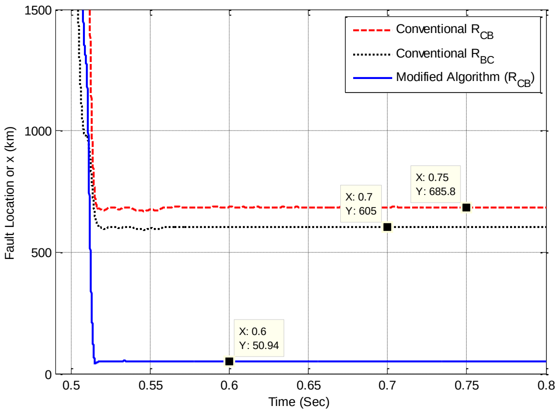
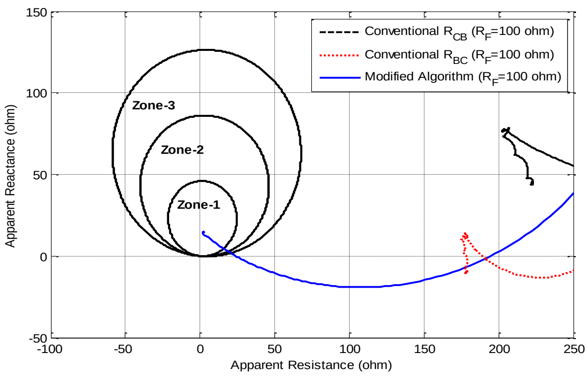
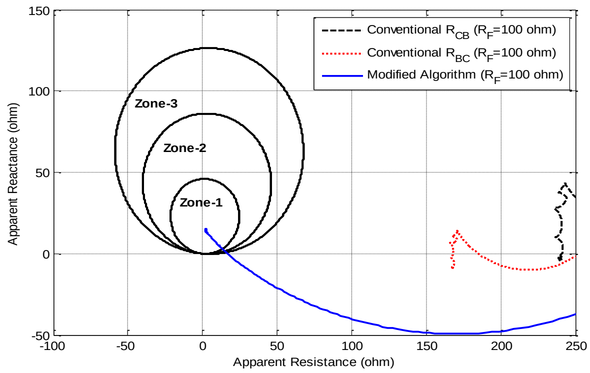


Figure 11: Fault location (x) calculated by modified algorithm with the presence of STATCOM and for an A–G fault in line-2 and 50 km away from the RCB (Rf = 100 Ω)



(a)



(b)

Figure 12: Calculated apparent impedance with the presence of STATCOM and for an A-B-G (a) and A-B-C-G (b) faults in line-2 and 150 km away from the RBC (Rf = 100 Ω)

Calculated impedance by the R_{AB} relay and for A-G fault in 150 km of R_{AB} and with R_f = 50 Ω is shown in Fig. 9. According to the figure it can be seen that the presence of fault resistance causes that R_{AB} relay identifies incorrectly the fault in its Zone-3 and R_{BA} relay also does not recognize the fault. Comparing the results of the R_{BC} and R_{AB} relays in Figs. 8 and 9 respectively show that although the fault happened in 150 km of both relays and in both R_f = 50 Ω but R_{BC} relay is more under-reach and did not identify the fault at all. The reason is the presence of STATCOM in the fault loop of R_{BC} relay which has caused more change in calculated impedance. The results of other cases are similar in that relays become under-reach or do not recognize the fault at all. The presented results in Figs. 7, 8 and 9 are for the conventional method. The following shows the results of the presented algorithm. The calculated impedance by the modified algorithm for A-G fault at 150 km of R_{BC} relay and R_f = 100 Ω is brought in Fig. 10. The results of conventional relays are also brought for the comparison. As can be seen from the results, both conventional relays are extremely under-reach and did not identify the faults in their protective Zones. It can be seen that in the presented algorithm the consumed active power in the line resistance is neglected compared to the high fault resistance. As can be seen, it does not have significant impact on the result and the fault is correctly identified in Zone-1 and is more appropriate compared with the non-operation of any of the relays. For this purpose, the value of x

(fault location) is calculated by the two modified methods and conventional relays brought in Fig. 11. Results show that fault location using conventional relays is incorrectly identified in 685.5 and 605 km. But, in the presented method the fault location is detected with high precision in 50.94 km away from the R_{CB} relay. The results of other ground faults (two-phase-to-ground and three-phase-to-ground fault) occurred in150 km of R_{BC} relay and R_f = 100 Ω is given in Figs. 12. The calculated x is presented in Figs. 13 for mentioned faults. Results in these figures show that similar to the A-G fault, in the A-B-G and A-B-C-G faults, the proposed algorithm detected the fault with high precision in Zone-1 of R_{CB} relay. The fault location is calculated as 50.95 and 50.19 km for A-B-G and A-B-C-G faults respectively.

More results are brought in Table 1 and for a variety of ground faults and for different values of R_f. In the results presented in this table, fault is placed in the in-transmission line 2. Both STATCOM and fault resistance effects exist in this line simultaneously and in other words, the results are presented for worst-case scenarios. Two faults are considered in this line. A fault on the left side of the STATCOM or 50 km away from R_{BC} and another fault on the right side of the STATCOM and 150 km of R_{BC} or 50 km away from R_{CB} relay. The values given in Table I are the calculated x by the relays and obtained from the calculated impedance by the relays. In the presented flowchart, there is only one x output and is brought in the Table I for the related relay. In other words, as shown in Fig. 6 in the flowchart, firstly the faulted transmission line is identified and then appropriate relay of the line is recognized and from its impedance, x is obtained. For the fault occurred in the 50 km of R_{BC} relay and R_f = 0 Ω, as can be seen in the result, R_{BC} relay in all three types of faults correctly diagnosed the fault location in 50 km. But R_{CB} relay due to the presence of STATCOM in its fault loop become under- reach and detected the fault location for A-G, A-B-G and A-B-C-G faults in 222, 190 and 151 km respectively. As it can be seen from the results, fault location is correctly detected with high precision in all cases by the algorithm. As for all the faults that occurred in the left side of the STATCOM, R_{BC} relay detected the fault and for the faults in the right side of the STATCOM, R_{CB} relay correctly identified the fault location.

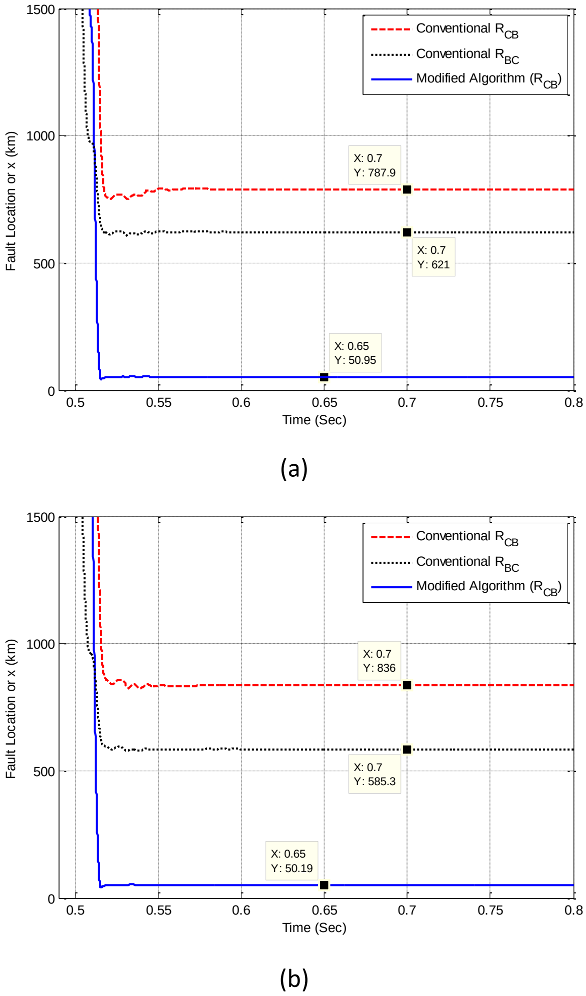


Figure 13: Calculated fault location with the presence of STATCOM and for an A-B-G (a) and A-B-C-G (b) faults in line-2 and 150 km away from the RBC (Rf = 100 Ω)

Conclusion

As it can be seen from the analytical and modeling results, fault resistance and STATCOM existence cause increasing of the calculated impedance by the distance relay. It makes that relay incorrectly detect the fault location and in the most cases the fault does not place in none of the protective Zone and in other words fault cannot be detected.

Table 1: Calculated fault location (x) with conventional and modified R_{BC} and R_{CB} relays with the presence of STATCOM

Fault Type	Fault Resistance, R_f [Ω]	Fault Location, [km]	Method			
			Conventional		Modified	
			R_{BC}	R_{CB}	R_{BC}	R_{CB}
A - G	0	50	50	222	50	-
		150	220	50	-	50
	100	50	405	1454	49.6	-
		150	605	685	-	50.94
	200	50	671	6360	49.75	-
		150	909	1987	-	50.36
A – B – G	0	50	50	190	50	-
		150	170	50	-	50
	100	50	450	1437	50.09	-
		150	621	787	-	50.95
	200	50	728	4739	50.27	-
		150	921	2479	-	50.10
A – B – C – G	0	50	50	151	50	-
		150	151	50	-	50
	100	50	465	1289	49.45	-
		150	585	836	-	50.19
	200	50	753	4240	49.27	-
		150	895	2474	-	49.79

Digital relays, the use of PMUs and communication channels in the network makes differential protection suitable in the transmission lines. They do not have defect of fault resistance and shunt compensation effect in them can be eliminated by adding current data of the compensator to the relay. But in this type of protection, fault location cannot be detected and there is no backup protection as in distance protection. For this purpose, in the paper a method was presented in which the buses voltage and current data were sent to the SPC and from the currents at the end of lines, faulted transmission line was detected (such as differential relay). Then with active power calculation in buses, the fault resistance was detected and its effect was deducted from calculated impedance in the algorithm. Then with the appropriate selection of the relay, fault location was calculated. Finally, the effects of fault resistance and STATCOM were eliminated. The results showed that the proposed method has high accuracy and good performance in a variety of faults with different values. This method is useful for transmission lines connected to the wind power or the multi-terminal transmission lines that will be considered in our future work.

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