Analysis of Loss of Excitation Protection Schemes of Synchronous Generators in A Compensated Transmission Line with UPFC

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Abstract: The advantages of using flexible AC transmission system devices increase the penetration of these devices in the existing power systems, but it is necessary to reconsider the protection schemes of a compensated network. This paper investigates four conventional schemes of loss of excitation (LOE) protection, which is used in the commercial relays, in the presence of Unified Power Flow Controller (UPFC) by both analytical and simulation approaches. The first scheme is based on the capability curve of the synchronous generator. The second scheme is the admittance-based method. The third scheme uses two double circled diagrams with a negative offset. The fourth scheme uses doubled circle diagram with a positive offset and directional element. This paper compares and evaluates the performance of these schemes in precise detail. In addition to LOE, the impact of partial loss of excitation, external fault and power swing on the LOE relay in the presence of UPFC is investigated.

Keywords: Synchronous generator, loss of excitation, capability curve of generator, R-X measurement, UPFC

1. Introduction

The excitation system of a synchronous generator helps both the generator and the system to provide stable voltage and controlled reactive power. When the excitation system fails due to the short or open circuit of the circuit breaker, the reactive power of the generator will be negative and will be reduced. The reduction of reactive power converts the synchronous generator to an asynchronous generator, and the negative amount shows that the generator absorbs the reactive power from the system. The absorbing reactive power from the weak system can cause a voltage collapse in the power system. During loss of excitation (LOE), the generator generates the active power the same as before but in a lower value.

Stable power swings (SPSs) and external faults near the generator can be sometimes detected by the LOE relay. Different papers have studied the performance of LOE relays against the LOE, the power swing, and the external fault phenomena. Mal-operation of the LOE relay during power swings and external faults is discussed in [1]. In [2], the application and performance of the offset mho distance relay for the LOE protection are studied. In [3], the LOE is detected based on the flux linkage. In [4], the combination of variation of linkage flux and negative sequence current to discriminate LOE from external fault is proposed. The proposed methods in [5] use the sign of derivation of the terminal voltage of generator, and the output reactive power to discriminate the LOE from any other conditions such as SPS. In [6], the rate of the seen resistance in view of the generator discriminates the LOE from the SPS. In [7], LOE is detected using support vector machines (SVMs). In [8], the SPS and the LOE are discriminated based on the internal voltage of the synchronous generator. In [9], the SPS and the LOE are detected using the derivatives of the machine's external variables and the variation of the Fourier transform coefficient of the active power at the relay location.

From a futuristic power system viewpoint, with the development of FACTS devices, there is a strong motivation to reconsider the performance of the conventional LOE relays. Therefore, the impact of FACTS devices on the LOE relays can be investigated as a new challenge. The FACTS devices can be categorized as a shunt, series, and series-shunt compensation devices.

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They play an important role to improve the performance of an existing transmission line [10]. The first category such as STATCOM and static var compensator (SVC) provides the variable reactive power to improve the stability of the network, but they can affect the LOE relay and in some cases make LOE relay under-reached [11-13]. The second category of FACTS devices such as static synchronous series compensator (SSSC) can control the power transfer by compensating reactance of a transmission network. During the LOE, the SSSC injects the voltage based on a reference voltage, and it can lead to the mal-operation of the LOE relay [14-15]. The third category of FACTS devices has the series-shunt connection to the power system such as unified power flow controller (UPFC). The presence of UPFC in a transmission line and the impact of this compensator on the power swing and the distance relay behavior is shown in [16-17]. Since the presence of FACTS devices in the transmission line compensate the line impedance, they can affect the impedance-based schemes of some numerical relays such as LOE relays and distance relays. In [18], the impact of UPFC on the LOE relay is analyzed. Presence of UPFC in a transmission line could change voltage and current at the LOE relay location and lead to mal-operation. In [19], the STATCOM effect on the LOE relay is removed by using Thevenin model parameters at STATCOM terminals and sending them to the LOE relay via communication channels. In [20], a new modified LOE protection algorithm using the phasor measurement units (PMUs) in the presence of generalized interline power-flow controller (GIPFC) in a transmission line is proposed. Although the existing studies evaluate the performance of the LOE relay in the compensated transmission line, it would be desirable to investigate the effect of a compensation device on the all existing LOE protection schemes used in the commercial LOE relays [21-22]. In [23], all LOE protection schemes are reviewed. The presence of FACTS devices and mal-operation of LOE relay during SPS are not investigated.

The aim of this paper is to investigate and compare the impact of UPFC on the four conventional LOE protection schemes to suggest the most appropriate one with high accuracy and speed. In this regard, the effects of the operational modes of the UPFC on the LOE relay are analyzed in detail using both analytical and software simulation approaches. The possible mal-operation of the LOE relay as the result of the external faults or power swings can cause an unnecessary generator tripping. Therefore, to select the most reliable scheme, the effects of external faults and SPS on the LOE relay in the compensated system are discussed. Moreover, the effect of the UPFC on both the LOE and partial LOE (PLOE) are investigated.

2. Conventional LOE protection schemes

There are four conventional schemes to detect the LOE and the under-excitation conditions in the protection relay: P-Q measurement, G-B measurement, R-X, and R-X directional schemes [24]. The required settings of these schemes are described in [25]. The LOE affects all three phases of generator, because of that the calculations of the schemes are based on positive sequences. The four protection schemes are described as follows:

A. P-Q measurement scheme

The rated active and reactive powers of a synchronous generator are based on the generator capability curve (GCC). The GCC shows the steady-state and over/under-excitation limit of the generator. Figure.1 shows three factors that limit the active and reactive power generated by the synchronous generators: a) Armature current limit, b) rotor-current limit, and c) stator-end region limit [25-26]. From Figure 1, in the P-Q measurement scheme, the under-excitation or the LOE is detected by the under-excitation limit. The LOE causes the power system to lose the reactive power, and therefore the reactive power of the system from the viewpoint of the generator terminal will be negative. This power reduction can be detected by the measurement of P and Q quantities. During the LOE condition, the reactive power Q decreases, but the active power remains positive until out-of-step occurs. Accordingly, the P-Q trajectory falls in the operation zone of the LOE relay as identified in Figure 1. When the LOE occurs, the generator starts to absorb the reactive power the same as induction generator. Therefore, the generator absorbs negative reactive power, on the other hand the positive active power generated by the generator is the same as before. Before LOE, the P-Q trajectory of normal operation is in the first quadrant, and after LOE, the P-Q trajectory falls into fourth quadrant.

B. G-B measurement scheme

The G-B scheme protects a synchronous generator from the operating in asynchronous mode, and to do so, it uses stability limit factor. G-B measurement has the ability to detect the limiting stability in synchronous generators. The admittance seen by the LOE relay are as follows:

$$\overline{Y} = \frac{\overline{I}}{\overline{V}} = \frac{\overline{I}}{\overline{V}} \times \frac{\overline{V}^*}{\overline{V}^*} = \frac{\overline{S}^*}{\overline{V}^2} = G + jB \quad (1)$$

where I is the positive sequence of current and V is the positive sequence of voltage sampled from the terminal of a synchronous generator. Moreover, G is the conductance and B is the susceptance. The admittance seen by the LOE relay can be calculated based on the active P_G and reactive Q_G powers of the generator, and therefore $G = \frac{P_G}{{E_G}^2}$ and $B = -\frac{Q_G}{{E_G}^2}$ is achieved, where E_G is synchronous generator's voltage. In this scheme, three characteristics that are resulted from the GCC, are used. As shown in Figure. 2, if the G-B trajectory exceeds characteristic 1 and characteristic 2, a delayed time (usually 10 s) is considered, and then the LOE relay will operate. The delayed time makes sure that the automatic voltage regulator (AVR) has enough time to operate and compensate the voltage deviation.

If GCC is transmit to the admittance plane, the characteristic 3 completely match to the stability characteristic of the machine. Therefore, when under-excitation causes an unstable situation for the machine or the LOE occurs, the third characteristic provides the tripping signal without a delayed time [25],[27]. The three characteristics of the protection scheme as shown in Figure 2 are: char.1: $1/X_{d,1} = 1/X_d + (1/X_d - 1/X_q)/2 \quad \alpha 1 \approx 80°$, char.2: $1/X_{d,2} = 1/X_d \;, \; \alpha 2 \approx 90°$, and char.3: $1/X_{d,3} = 2/X_d \;, \; \alpha 3 \approx 110°$.

where Char. 1: Monitor the excitation voltage and if the admittance trajectory reaches to this characteristic, alarming and long term tripping (usually 10 s) will happen, Char.2: Trip with a short time delay (0.5-1.5 s), and Char. 3: Trip with a short time delay (less than 0.3 s). The G-B scheme can detect the LOE condition in the second-quadrant of a diagram. Combination of P-Q measurement and G-B measurement are used in the commercial LOE relay [22].

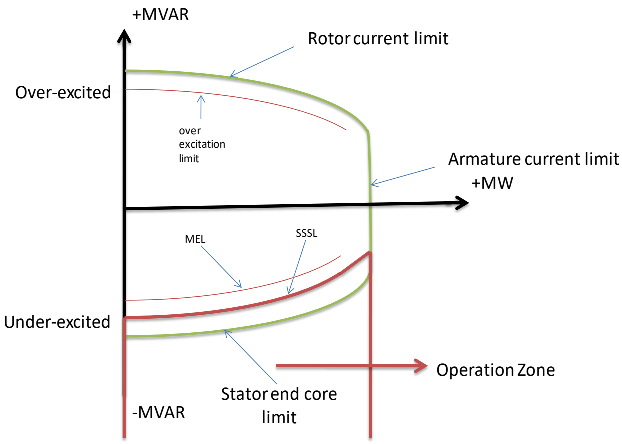


Figure 1. Generators capability curve with SSSL inside GCC

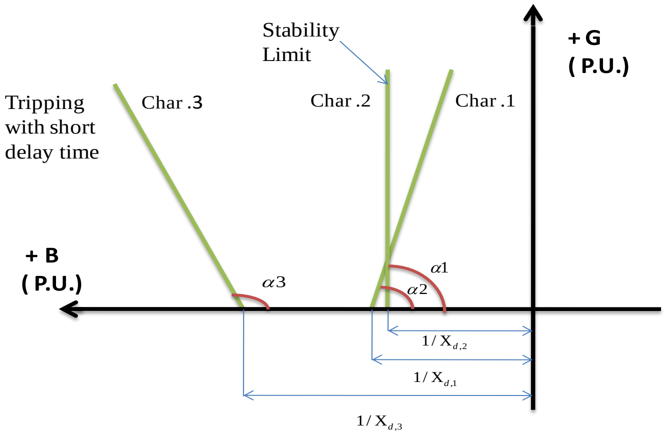


Figure 2. Characteristic of the G-B scheme

C. R-X measurement

R-X scheme consists of two circles with definite offset that usually set with half of direct-axis transient reactance as shown in Figure. 3. Two different diameters create two operation zones for the detection of LOE [2]. According to Figure. 3, zone 1 detects the LOE in the heavy loads condition without delay time. Zone 2 detects the LOE in the light load condition with 0.5-0.7 s delay time. The delay time of zone 2 is required to prevent the mal-operation of the LOE relay during the SPS, and also allow the measured impedance trajectory during the SPS to pass from the LOE scheme. The impedance trajectory seen by the LOE relay are $R = \frac{P_G \times V^2}{P_G{}^2 + Q_G{}^2}$ and $X = \frac{Q_G \times V^2}{P_G{}^2 + Q_G{}^2}$

During the LOE, the reactance of the generator will be negative in view of the generator, and therefore the negative impedance falls into the R-X scheme.

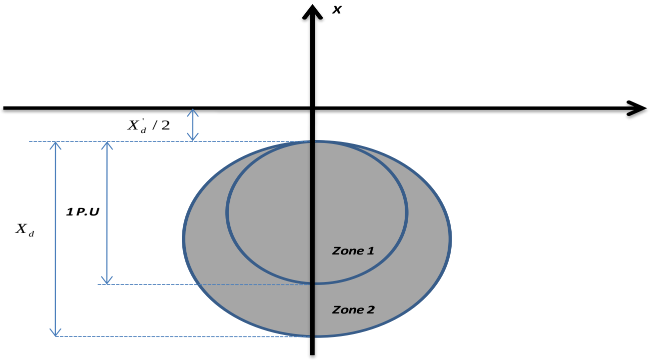


Figure 3. R-X measurement characteristic

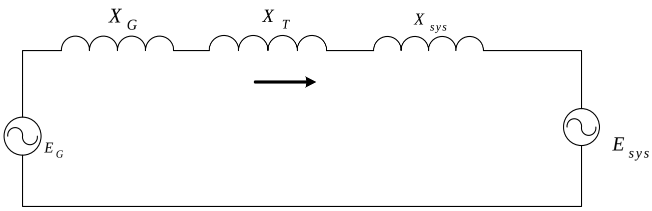


Figure 4. Equivalent circuit of the power system

The generator connected to the step-up transformer and network is considered as shown in Figure. 4 [6]. The LOE relay determines the impedance trajectory by using the voltage and current of generator terminal. According to Figure 4, the generator terminal voltage is $V = E_G\angle\delta - jX_G I$ where E_G, is the internal voltage of the generator and X_G is the generator reactance. The current of the generator I is achieved by $I = \frac{E_G\angle\delta - E_{sys}\angle 0}{j(X_G+X_T+X_{sys})}$ where E_{sys} is the equivalent voltage of power system. The impedance seen by the generator is achieved by

$$Z = \frac{V}{I} = \frac{E_G\angle\delta - jX_G.I}{I} = \frac{E_G\angle\delta}{I} - jX_G \quad (2)$$

The impedance trajectory depends on the load, and the system impedance according to (2). When the LOE occurs, in the case of heavy loads, the impedance trajectory has much faster movement than the light loads. Therefore, the LOE relay has faster detection time in the heavy loads condition.

D. R-X measurement with the directional scheme

The R-X measurement with the directional scheme involves two circles with negative and positive offset, and a directional element normally set to 0.95 leading (under-excited). According to Figure. 5, zone 1 offset and diameter are equal to $-X'_d/2$ and 1.1 X_d, respectively. The zone2 offset is set to X_s with 1 pu diameter. Alarming of this scheme indicates the under voltage situation of the generator terminal [25]. The R-X directional element detects the impedance trajectory more sooner than the R-X scheme because of the positive offset and decreases of reactance trajectory.

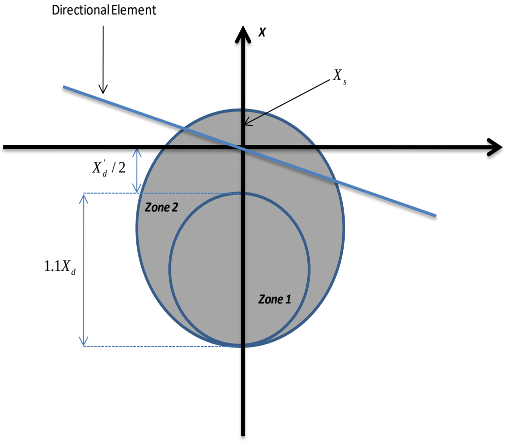


Figure 5. R-X directional scheme characteristic

3. Analysis of UPFC impact on loss of excitation protection

A. Impact of UPFC on P-Q measurement scheme

The P-Q trajectory is measured by the LOE relay in the terminal of synchronous generator. The generator absorbs the reactive power from the network and the voltages of buses are reduced during the LOE condition. In the UPFC-embedded system, the UPFC in the middle of transmission line injects voltage to compensate the reduction of the voltages of buses. The active power and the reactive power seen by the LOE relay in presence of UPFC are $P_R = P_G + P_{UPFC}$ and $Q_R = Q_G + Q_{UPFC}$, respectively, where Q_{UPFC} is reactive and P_{UPFC} is active power of UPFC. The operation of UPFC causes undesirable delay time for the LOE relay, and therefore the P-Q trajectory in the presence of UPFC falls to operation zone later than the absence of UPFC in transmission line.

B. Impact of UPFC on G-B measurement scheme

The UPFC compensates the reduction of voltage in the transmission line during the LOE condition, and therefore the active and reactive powers seen by the generator can be changed. In this scheme, the conductance and susecptance seen by the LOE relay in presence of UPFC are $G_R = \frac{P_G+P_{UPFC}}{{E_G}^2}$ and $B_R = -\frac{(Q_G+Q_{UPFC})}{{E_G}^2}$, respectively. The active and reactive powers of the UPFC affect the admittance measured by the LOE relay and cause a delay time to detect the LOE condition.

C. Impact of UPFC on R-X measurement scheme

Although the presence of FACTS devices in power networks have some advantages like controlling voltage and power in the long transmission line, they have some negative effects on the LOE and other relays in transmission lines as well. These devices cause mal-operation of LOE relay and make it under-reached in some cases. The LOE relay under-reaching depends on the partial and complete loss of excitation, and it also depends on the selected protection scheme of the relay [18].

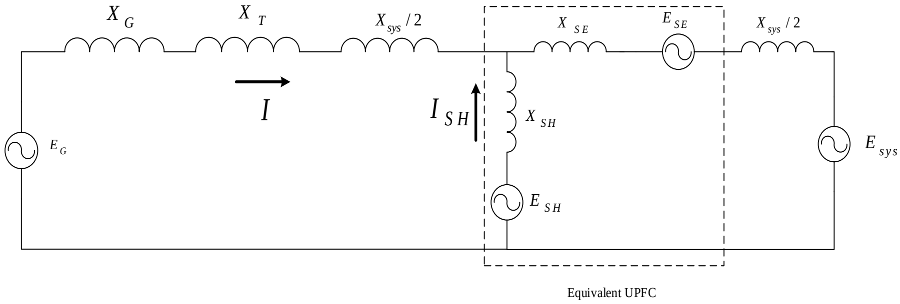


Figure 6. Equivalent circuit of power system with UPFC

The equivalent model of the power system with UPFC model is shown in Figure. 6 [28]. The following equation is written based on Figure 6

$$-\mathrm{E_G} + \mathrm{E_{sys}} + \mathrm{E_{SE}} + j(X_G + X_T + \frac{X_{sys}}{2} + \frac{X_{sys}}{2} + X_{SE})\mathrm{I} + j(\frac{X_{sys}}{2} + X_{SE})\mathrm{I_{SH}} = 0 \quad (3)$$

where E_G is the generator voltage, E_{sys} is the voltage of the system which is connected to the generator through transmission line, X_{sys} is the equivalent reactance of the transmission line, X_{SE} is the series reactance of the UPFC model, E_{SE} is the series injected voltage by the series part of the UPFC, and I_{SH} is the injected current of the shunt part of the UPFC. By assuming, $X_G + X_T + \frac{X_{sys}}{2} + \frac{X_{sys}}{2} = X_{Tot}$, the current of system is

$$\mathrm{I} = \frac{\mathrm{E_G} - \mathrm{E_{Se}} - \mathrm{E_{sys}} - j(\frac{X_{sys}}{2} + X_{SE})\mathrm{I_{SH}}}{j(X_{Tot} + X_{SE})} \quad (4)$$

Therefore, the impedance seen by the generator according to (2) is

$$Z_{seen} = \frac{E_G\angle\delta}{\mathrm{I}} - jX_G \quad (5)$$

By assuming $\frac{X_{sys}}{2} + X_{SE} = K$, the seen impedance in the presence of UPFC is achieved by

$$\mathrm{Z_{seen}} = j\left[\frac{\mathrm{E_G}}{\mathrm{E_G} - \mathrm{E_{sys}} - (\mathrm{K})\mathrm{I_{SH}} - \mathrm{E_{Se}}}(X_{Tot} + X_{SE})\right] - jX_G. \quad (6)$$

The presence of UPFC causes the LOE relay to see the impedance with some delays. The impedance seen has two additional parameters $(K)I_{SH}$ and E_{Se} based on (6). By comparing Z_{seen} in the presence of UPFC (6) with the Z_{seen} in the absence of UPFC (5), it can be concluded that: 1) $(K)I_{SH}$ is a part of Z_{seen} that shows the impact of injected current by the shunt converter of UPFC. In normal condition, the shunt converter has a reactive mode. When a LOE happens, injected shunt current can affect Z_{seen} significantly, and 2) as shown in (6), the series injected voltage E_{Se} subtracts from E_G and the impedance seen by the generator increases. These parameters make the impedance seen by the relay bigger than the impedance in the case of without UPFC, and therefore, it will lead to more delays.

D. Impact of UPFC on R-X directional scheme

The impedance trajectory in the presence of UPFC is shown in (6). Presence of UPFC causes to detect the LOE with some delays, but R-X directional scheme detects the LOE much sooner than R-X scheme.

4. Sample system

The single machine infinite bus (SMIB) with UPFC device in the middle of the transmission line is shown in Figure. 7. Moreover, four schemes of LOE relay to calculate the impedance, admittance, and P-Q trajectory is simulated. The LOE relay locates at the generator terminal in this simulation.

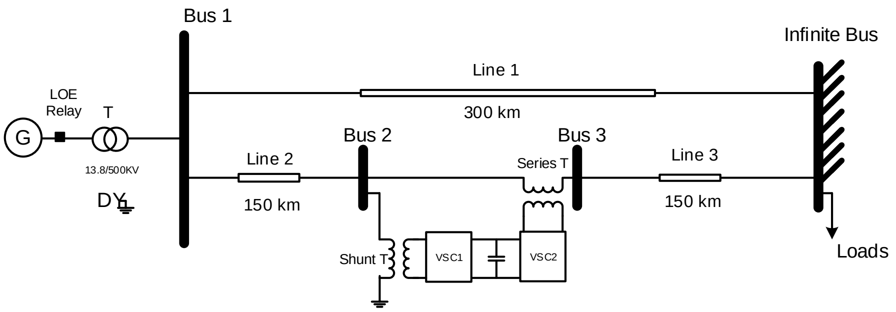


Figure 7. Sample power system with UPFC

In SMIB, one 1400 MVA generator includes power system stabilizer (PSS) and excitation system that connected to delta-star step-up transformer. The LOE and the PLOE occur at t=1.5 s. The excitation voltage in case of the PLOE is set on 0.5 p.u, and the impacts of all operation modes of UPFC on the four schemes are investigated by using the simulation software. As shown in Figure. 7, the UPFC includes the parallel and series branches. The parallel part operates as STATCOM, and it acts as a reactive current source. The capacity of the UPFC is ±80 MVA, and it operates in three modes of SSSC, STATCOM, and UPFC. When the UPFC operates in the SSSC or STATCOM modes, the compensation device uses ±40 MVA.

5. Simulation Results

In this section, different operation modes of UPFC with the same setting are simulated. The performances of four protection schemes during LOE, PLOE, SPS, and external three-phase fault are investigated in the cases with and without UPFC. The impedance, admittance, and P-Q loci of external faults and power swing sometimes enter to operation zones of LOE schemes, and therefore this issue is discussed in simulation results.

A. Impact of UPFC on LOE for four schemes

P-Q measurement: The trajectory of active and reactive power measured from the generator's terminal are depicted in Figure. 8(a). The pickup time of operation zone of capability curve are 3.40 s, 5.04 s, 4.98 s, and 4.91 s in the cases of without FACTS, with UPFC, SSSC, and STATCOM, respectively. According to Table 1, the UPFC causes 5.04-3.40= 1.64s delay time. The pickup times show that the most delay time to detect the LOE condition in the operation zone of the capability curve belongs to the UPFC mode.

G-B measurement: The performance of G-B scheme is shown in Figure. 8(b). The admittance trajectory is changed in the presence of UPFC in the power network compared with one in the case of no FACTS condition. To calculate the admittance, the active power, the reactive power, and also the generator terminal voltage are measured, and therefore the presence of FACTS device affects the measured quantities. The pickup time for Char. 3 (tripping zone) is shown in Table 1. The pickup time of the G-B scheme are 3.19 s, 4.73 s, 4.614 s, and 4.54 s in the cases of without FACTS, with UPFC, SSSC, and STATCOM, respectively. Similar to P-Q scheme, the longest delay time in this scheme is related to the UPFC mode.

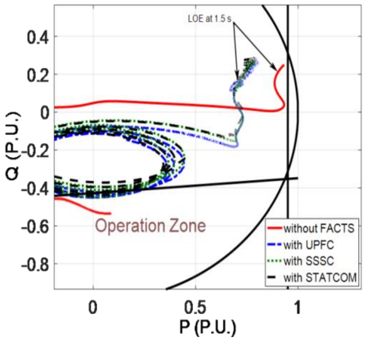
R-X measurement: As shown in Fig. 8(c) and (d), the compensation device affects the impedance trajectory seen by the LOE relay. In the presence of UPFC, SSSC, and STATCOM, the pickup time of the entrance of the impedance trajectory into the zone 1 is different from one in the case of no compensation device. According to (6), the impedance seen by the generator in the presence of UPFC is larger than the impedance in the case of the absence of UPFC due to compensation parameters I_{SH} and E_{Se} . Based on Fig. 8(c), the pickup time of the R-X scheme are 3.42 s, 4.71 s, 4.41 s, and 4.33s in the cases of without UPFC, with UPFC, SSSC, and STATCOM, respectively. A comparison among these delay times shows that the most severe effect on the detection time of a LOE condition belongs to UPFC operation mode.

R-X directional measurement: In Fig. 8(d), the pickup time for the R-X directional scheme is 2.57 s, 3.14 s, 3.125 s, and 3.02 s in the cases of without FACTS, with UPFC, SSSC, and STATCOM, respectively. This scheme has the most delay time for the UPFC operation mode. A comparison between the delay time in R-X scheme and R-X directional scheme at UPFC mode shows that R-X scheme has more delay to detect the LOE than R-X directional.

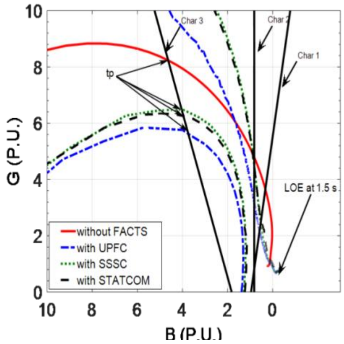
Table 1. Pickup and Trip time of each mode of UPFC for LOE

Protection Scheme	FACTS device	pickup time tp (s)	Tripping time (s)
R-X	Without FACTS	3.421	4.121
	UPFC	4.517	4.717
	SSSC	4.412	4.612
	STATCOM	4.331	4.531
R-X directional	Without UPFC	2.574	3.274
	UPFC	3.144	3.844
	SSSC	3.126	3.825
	STATCOM	3.025	3.826
G-B	Without UPFC	3.190	3.890
	UPFC	4.733	5.433
	SSSC	4.614	5.314
	STATCOM	4.549	5.249
P-Q	Without UPFC	3.401	4.101
	UPFC	5.045	5.745
	SSSC	4.980	5.680
	STATCOM	4.915	5.615

A comparison among pick up times of the operation zone for four schemes in the presence of UPFC shows that the P-Q measurement needs the longest time to detect LOE. Moreover, the R-X directional scheme is the fastest protection scheme because of using the positive offset.



(a)



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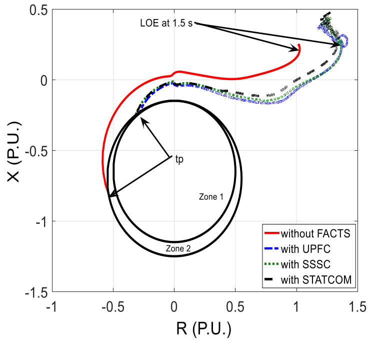
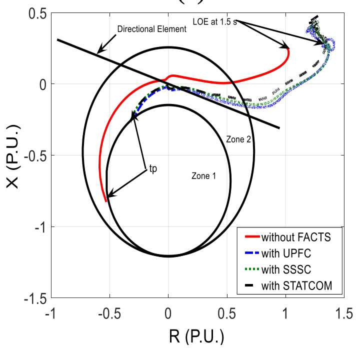


(c)



(d)

Figure 8. The performance of four schemes during the LOE (a) seen P-Q trajectory in GCC (b) seen admittance trajectory in G-B diagram (c) seen impedance in negative mho offset (d) seen impedance in mho directional

Table 1 shows the pickup and tripping times obtained through the four schemes. It can be observed that the most delays time belongs to the UPFC operation mode.

B. Impact of UPFC on PLOE for four schemes

The PLOE occurs when the excitation's breaker failed. LOE is typically partial phenomenon, though the complete loss of field can occur in rare instances. In some cases, the PLOE can cause the relay to be under-reached. In this case, the amount of reactive power absorbed by the generator from the power system is less than the LOE condition. Therefore, decreasing of the X and Q will be smoother and the LOE detection schemes detect it with some delays.

P-Q measurement: Presence of UPFC in the transmission line changes the active and reactive power seen by the LOE relay. The pickup times to detect the PLOE by the GCC-based scheme according to Figure. 9(a) are 3.938 s, 6.835 s, 6.445 s, and 6.982 s in the cases of without FACTS, UPFC, SSSC, and STATCOM, respectively.

G-B measurement: Because of changing the active and reactive power seen by the LOE relay, the admittance trajectory is also affected. In the case of PLOE condition, the pickup times of admittance trajectory according to Figure. 9(b) are 3.910 s, 5.973 s, 5.917 s, and 5.836 s in the cases without FACTS, UPFC, SSSC, and STATCOM, respectively.

R-X measurement: In Figure. 9(c), the pickup times to detect the PLOE are 4.202 s, 5.761 s, 5.712 s, and 5.621 s in the cases of without FACTS device, with UPFC, SSSC, and STATCOM, respectively. The most severe delay time is for the UPFC operation mode, and the difference between the delay times of cases with UPFC and without FACTS is 1.55 s. Based on the obtained delay time in the UPFC operation mode, the PLOE can cause more severe damage to the generator compared with the LOE.

R-X directional measurement: According to Figure. 9(d), the pickup time of this scheme is less than the one in the R-X scheme. The pickup time of this scheme in the cases of without FACTS, UPFC, SSSC, and STATCOM are 3.860 s, 5.582 s, 5.533 s, and 5.436 s, respectively. A comparison between this scheme and the R-X scheme shows that the detection of this scheme because of using the positive offset is sooner than R-X scheme.

Again, the P-Q measurement scheme has the most delay time to detect the PLOE. Moreover, the R-X directional scheme is preferred to detect the PLOE and it causes less damage to the generator.

Table 2 shows the pickup and trip times of four schemes corresponding to three operation modes of UPFC for the PLOE condition. According to Table 2, the PLOE is detected with more delay time compared to Table 1. The R-X and P-Q schemes take more time to detect PLOE. Moreover, in the UPFC operation mode, with so-called schemes the detection will need more time compared to other operation modes mentioned in Table 2.

From Tables 1 and 2, the difference between the delay time during the LOE and PLOE conditions is noticeable. All schemes detect the LOE situation with a large delay time, and subsequently in the PLOE situation, in the presence of UPFC, the detection of the LOE relay has more delay which can damage the generator severely. The presence of UPFC in the transmission line causes more delay time to detect the LOE as shown in Table 2 corresponding to all protection schemes. Therefore, choosing the most reliable and the fastest protection scheme can shorten the delay time, and detect the LOE and PLOE situation sooner than the other ones. A Comparison among all modes of UPFC shows that the longest reduction of the generator terminal voltage is related to UPFC, SSSC, and STATCOM, respectively, and this longer reduction causes more delay time to detect the PLOE.

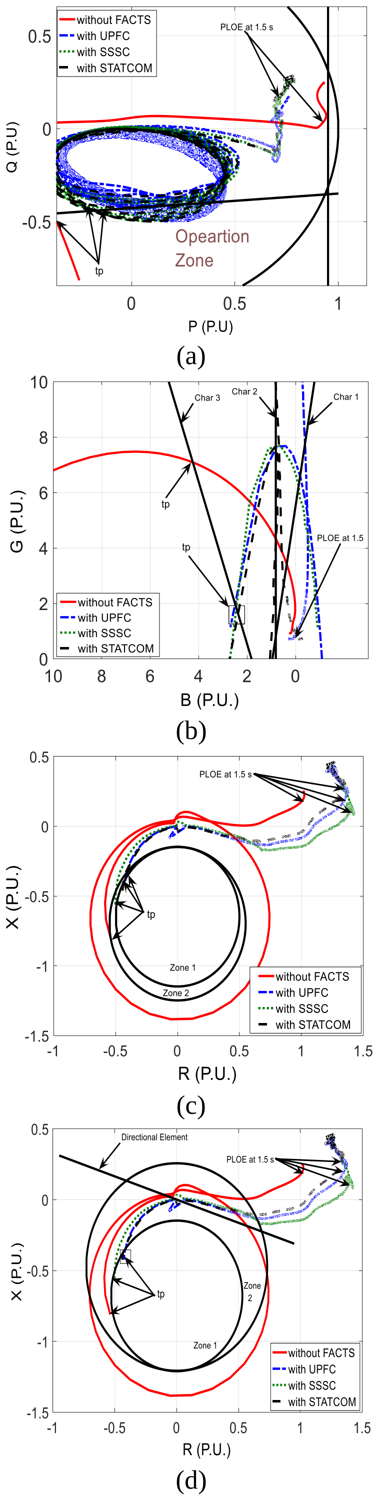


Figure 9. The performance of four schemes during the PLOE (a) seen P-Q trajectory in GCC (b) seen admittance trajectory in G-B diagram (c) seen impedance in negative mho offset (d) seen impedance in mho directional

Table 1. Pickup and Trip time of each mode of UPFC for PLOE

Protection Scheme	FACTS device	Pick up time	Tripping time
R-X	Without FACTS	4.202	4.902
	UPFC	5.761	6.461
	SSSC	5.712	6.412
	STATCOM	5.621	6.321
R-X directional	Without UPFC	3.860	4.560
	UPFC	5.582	6.282
	SSSC	5.533	6.233
	STATCOM	5.436	6.136
G-B	Without UPFC	3.910	4.610
	UPFC	5.973	6.673
	SSSC	5.917	6.617
	STATCOM	5.836	6.536
P-Q	Without UPFC	3.938	4.638
	UPFC	6.835	7.535
	SSSC	6.445	7.145
	STATCOM	6.282	6.982

C. Effect of power swing on LOE Relays in the presence of UPFC

SPS sometimes is detected by the LOE schemes unintentionally. In this case, two load conditions will be discussed. For simulating SPS, a three-phase fault time setting's is arranged between 0.02 to 0.08 s. Figure. 10 shows the SPS situation with inductive loads. In Figures. 10(a), (b), the power swing trajectories do not fall into P-Q and G-B schemes. Figure. 10(c) shows that the negative offset of R-X scheme could prevent the LOE relay from the mal-operation. The positive offset of R-X directional scheme that shown in Figure. 10(d) has some benefits to detect the LOE and the PLOE sooner than other schemes, but sometimes R-X directional scheme could detect the SPS by mistake.

The SPS may fall into the LOE scheme and stay in there for a short time. If the duration time of the power swing in the LOE schemes is longer than the delay time of the scheme, the generator will be tripped due to mal-operation of the LOE relay. In heavy loads of generator, the SPS can be detected by the LOE relay, and therefore the detection depends on the load condition in the power system. Figure 11 shows the SPS situation with capacitive load. In Figure 11(a), P-Q scheme uses P and Q trajectories seen by the LOE relay, and this scheme does not have an adequate parameter for the detection, and also prevention of mal-operation. As SPS happens, the impact of UPFC in the transmission line can prevent mal-operation of R-X, R-X directional and G-B schemes, but it does not happen in Figure 11(a). Other schemes like R-X, R-X directional and G-B schemes use terminal voltage of generator as well as active and reactive power to diagnose in a much better way than P-Q scheme. Figure. 12 shows the reactive power seen by the LOE relay. According to Figure. 11 (b), again delay time of Char. 2 in the G-B scheme is longer than the SPS duration time, so the LOE relay based on G-B scheme does not detect this situation. The main reason for this operation is that the presence of UPFC compensates the reactive power Q, and hence the compensation effect prevents the R-X, R-X directional, and G-B schemes from the mal-operation. The effect of UPFC in transmission line could prevent the LOE relay from the mal-operation. In Figures. 11(c), (d) SPS duration is 0.3 s and the delay time of R-X and R-X directional zones is 0.7 s. Therefore, the delay time of LOE detection is longer than the duration time of SPS, and the LOE relay in the presence of UPFC does not detect the SPS.

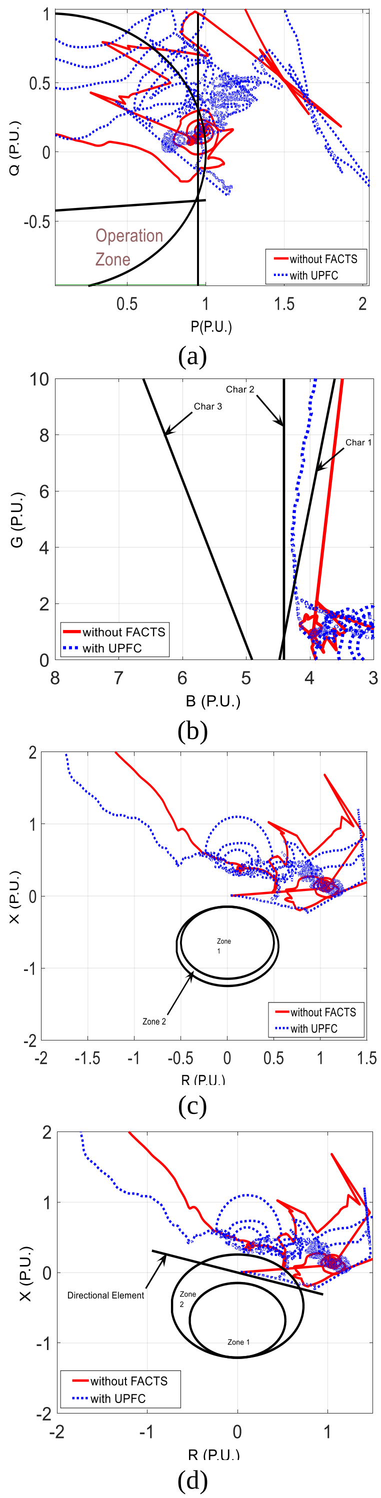


Figure 10. The performance of four schemes during the SPS in inductive load (a) seen impedance in negative mho offset (b) seen impedance in mho directional (c) seen P-Q trajectory in GCC (d) seen admittance trajectory in G-B diagram.

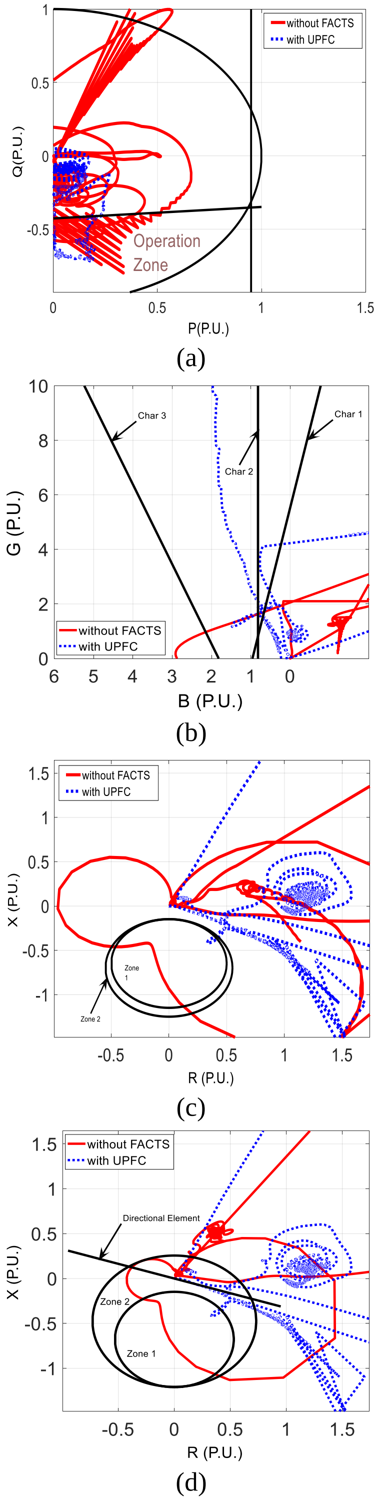


Figure 11. The performance of four schemes during the SPS in capacitive load (a) seen P-Q trajectory in GCC (b) seen admittance trajectory in G-B diagram (c) seen impedance in negative mho offset (d) seen impedance in mho directional

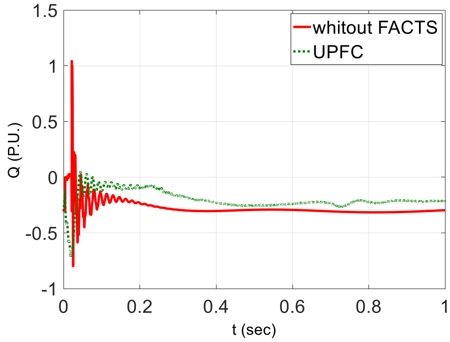


Figure 12. Reactive power of generator during SPS with capacitive load

D. Effect of three-phase fault on LOE Relays in the presence of UPFC

The LOE relay may detect external three-phase faults unintentionally if the duration time of the fault is much longer than the time setting of the relay. In this section, the effect of the three-phase fault on the generator bus or on any part of the power system that generator is connected on the LOE schemes is analyzed.

As shown in Figure. 13(a), the P-Q trajectory is not in the operation zone during the three-phase fault. In Figure. 13(b), the G-B trajectory remains on the right side of the operation zone. With or without UPFC, all these trajectories have the same behavior. Figure. 13(c), the R-X scheme have not seen the impedance trajectory in the operation zone during the three-phase fault with inductive load. In point of fact, the offset prevents the R-X scheme from any possible mal-operation. In Figure. 13(d), the impedance trajectory is near to the R-X directional characteristic but it is not detected by the LOE relay. As mentioned above, the load condition can affect the external fault in the power system.

Figure 14 indicates the three-phase fault situation with capacitive load. In Figure. 14(a), P-Q trajectory falls into four quadrants. According to Figure. 14(b), in G-B scheme, the G-B trajectory passes through Char. 3. In SPS situation, the UPFC could avoid the mal-operation of LOE relay, but the impedance seen by the relay falls into all relay characteristics during the external three-phase faults. When the fault occurs near the generator, as shown in Figures. 14(c), (d), the impedance trajectory seen by the generator in R-X and R-X directional are in the fourth quadrant. In R-X scheme without UPFC, the negative offset and zone 1 diameter prevent to detect the three-phase fault. The results obtained during other modes of UPFC because of similarity are not mentioned.

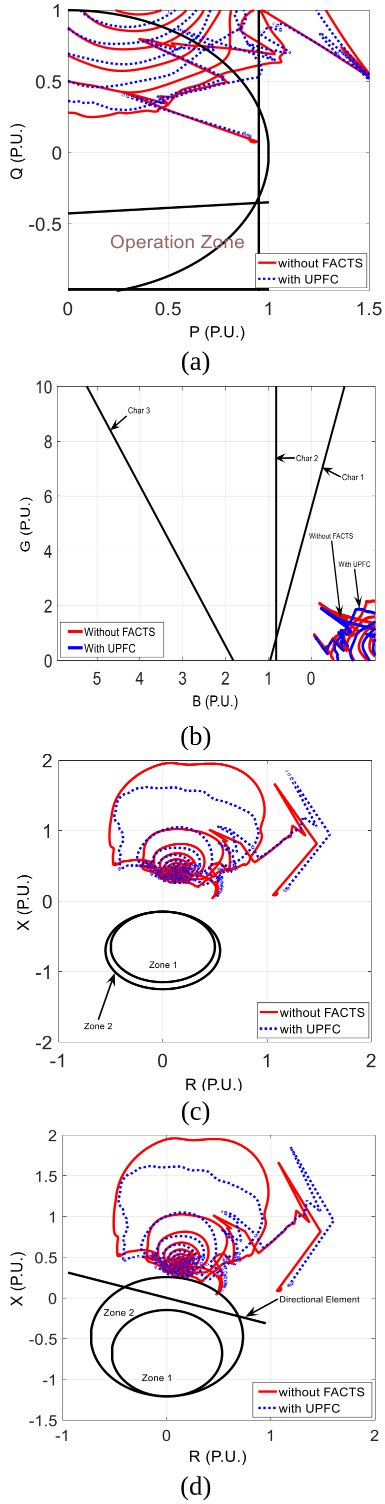


Figure 13. The performance of four schemes during the external fault in inductive load (a) seen P-Q trajectory in GCC (b) seen admittance trajectory in G-B diagram (c) seen impedance in negative mho offset (d) seen impedance in mho directional

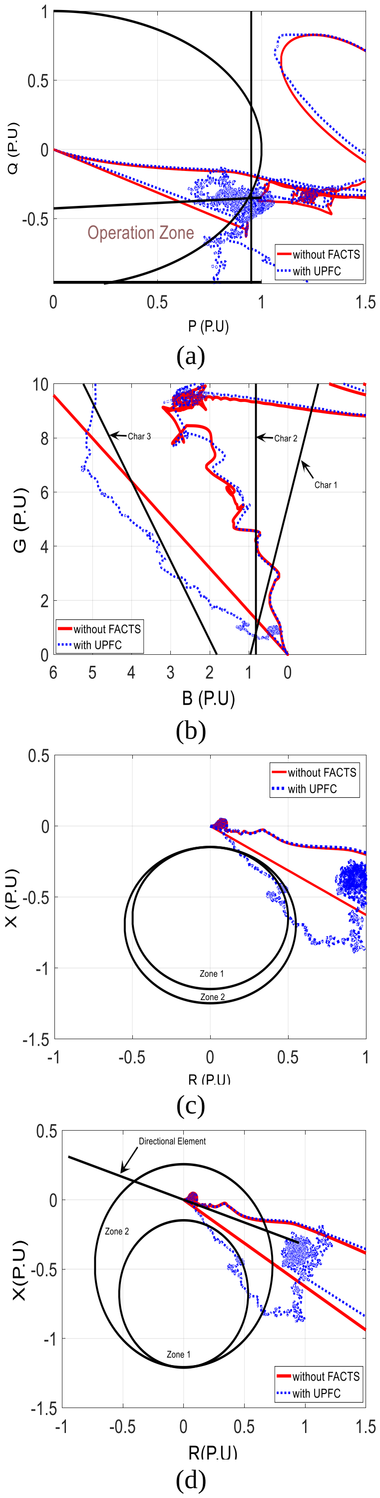


Figure 14. The performance of four schemes during the SPS in capacitive load (a) seen P-Q trajectory in GCC seen (b) seen admittance trajectory in G-B diagram (c) impedance in negative mho offset (d) seen impedance in mho directional

6. Guidelines to select LOE protection scheme

Table 3 summarizes the performance of four LOE protection schemes during the LOE, PLOE, SPS, and external three-phase fault in the presence of FACTS device. According to Table 3, R-X, R-X directional, P-Q, and G-B schemes detect LOE and PLOE in the presence and the absence of FACTS device. The operation times of relay in LOE and PLOE conditions are considered in presence of UPFC since the UPFC causes more delay time in the operation of a LOE relay. R-X, R-X directional and G-B schemes detect SPS with capacitive load unintentionally in absence of UPFC in transmission line. On the other hand, the UPFC could affect the R-X, the R-X directional, and the G-B schemes. Furthermore, it prevents to detect the SPS condition with capacitive load. P-Q scheme leads to unnecessary detection with capacitive load during SPS situation in presence and absence of UPFC. R-X scheme's mal-operation occurs in presence of UPFC during a three-phase fault with capacitive load. The R-X directional, G-B and P-Q schemes, depending on loads, could cause mal-operation of LOE relay in the presence and the absence of UPFC. The R-X scheme during capacitive load and absence of UPFC prevents to detect three-phase fault situation. In many cases, the negative offset and the setting of the zone diameter of R-X scheme make this scheme more conventional than other three schemes.

Table 2. LOE protection schemes comparison during LOE, PLOE, SPS and external faults

Condition	Compensation device	Protection schemes							
		R-X	Operation time of R-X	R-X directional	Operation time of R-X directional	P-Q	Operation time of P-Q	G-B	Operation time of G-B
LOE	With FACTS	Y	4.717	Y	3.844	Y	5.745	Y	5.433
	Without FACTS	Y	4.121	Y	3.274	Y	4.101	Y	3.890
PLOE	With FACTS	Y	6.461	Y	6.282	Y	7.535	Y	6.673
	Without FACTS	Y	4.902	Y	4.560	Y	4.638	Y	4.610
SPS (Inductive Load)	With FACTS	N		N		N		N	
	Without FACTS	N		N		N		N	
SPS (Capacitive Load)	With FACTS	N		N		Y		N	
	Without FACTS	Y		Y		Y		Y	
Fault (Inductive Load)	With FACTS	N		N		N		N	
	Without FACTS	N		N		N		N	
Fault (Capacitive Load)	With FACTS	N		Y		Y		Y	
	With FACTS	Y		Y		Y		Y	

Y :Yes ; N: No

7. Conclusion

This paper investigates four conventional schemes of LOE protection in a compensated power system with UPFC. Accordingly, the behavior of R-X, R-X directional, G-B, and P-Q trajectories through LOE, PLOE, SPS, and external three-phase fault with and without UPFC are discussed. Moreover, the effect of operation modes of the UPFC on the LOE scheme is analyzed. The results show that the presence of FACTS devices in the transmission line causes time delay to detect the LOE in compare with the absence of UPFC. In addition, the P-Q and R-X schemes detect the LOE longer than other schemes. On the other hand, during the PLOE, the time delay of detection is larger and the presence of UPFC causes more delay. In this situation, P-Q and R-X mho offset schemes detect the PLOE longer than the other schemes. Besides, the performance of the LOE relay are studied during the SPS and external three-phase fault with different load conditions. When an external fault happens in a heavy loading condition, the generator may trip and it causes a mal-operation of the LOE relay. The R-X directional scheme is selected as more reliable and stable scheme of LOE protection in the presences of UPFC. The R-X directional and

G-B schemes could detect the LOE situation sooner than the other scheme. In conclusion, R-X directional and G-B schemes are more appropriate schemes for the LOE detection and discrimination of LOE situation against other external faults.

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