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The Influences of UPFC on the Performance of LOE Protection of Synchronous Generator

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ABSTRACT

The primary protection of the power system is a synchronous generator loss of excitation (LOE) protection which is used to measure impedance. The impedance is calculated at the generator terminal by measurement of current (I) and voltage (V). The relay performance is conducted using the impedance trajectory nature. The R-X impedance measurement technique is used for assessing a synchronous generator's LOE performance. Different Flexible AC Transmission Systems (FACTS) devices have been used to improve the power system performance, although the main disadvantage of this FACTS controller is that it malfunctions the LOE relay by changing the impedance. The existence of a UPFC causes a delay in the operation of the LOE relay and causes conditions such as overreach and under-reach. This article examines UPFC's influence on the LOE relay. The mitigation technique is also implemented using Simulink/MATLAB.

Keywords— Synchronous generator protection, LOE, FACTS Devices, UPFC, positive and negative offset mho relay.

1. INTRODUCTION

For the stability and reliability of the power system, the transmission line protection is mandatory. The impedance measurement technique is required for this protection. The relays were invented to measure impedance when faulty or abnormal conditions occur. When the system voltage is abnormal, it will decreases, and hence the amount of current will increases. The impedance is inversely proportional with the current, whereas it is directly proportional with the voltage. If this impedance falls below the set value, the impedance trajectory of the fault falls into the trip area. Depending on the duration of the impedance trajectory, the relay will transmit a trip signal to the CB (circuit breaker). For this impedance measurement, the mho relay is used.

Different types of failures and abnormal conditions affects the relay operation. LOE is one of the phenomena, which causes due to several factors such as damage to the exciting system, power failure or short circuit in the exciting system winding. The mho offset relay is used for LOE protection [1]. Nowadays one need to implement the FACTS devices in the transmission line for the sustainable performance of the power system. FACTS equipment is categorized into series, shunt, series-series and series-shunt equipment based on the FACTS controller's connection to the transmission line. TCSC (Thyristors Controlled Series Capacitor) and SSSC (Static Sync. Series Compensator) are two types of series FACTS, whereas two types of FACTS controllers are STATCOM (Static Synchronous Compensator) and SVC (Static Var Compensator).

The capability for power transfer is improved by FACTS devices in the transmission network. The network's control and stability were enhanced by series/shunt compensation. They are also used to optimize losses and manage congestion [2]. The R-X, R-X with directional element, V-I P-Q and G-B schemes are used for the LOE protection. The R-X and R-X with directional element schemes are mainly used for rapid detection of LOE condition [3-6]. For STATCOM system, the analytical results for normal and L-G faults conditions are same [7]. The disadvantage of this system is that STATCOM delays detection of failure; STATCOM increases the R-X ratio [8, 9]. The positive offset mho relay is invented and modeled; the impact of STATCOM has been studied on this type of relay [10, 11]. The line protection in SSSC's presence is inspected, which having the disadvantage of overreaching of relay [12, 13]. In previous work [14-19], the performances of relays with several shunt FACTS controllers were studied. The subsynchronous resonance is reduced by a UPFC damping controller in a fractional order [20].

The combination of SSSC and STATCOM is known as UPFC. SSSC and STATCOM have an impact on the LOE relay. It shows that the performance of the relay was delayed [21]. To reduce the delay, you have to make proper settings in the relay. The simulation results and the mitigation technique for complete and partial LOE are studied in this article. Several research pieces are conducted on different FACTS devices and their impact on LOE protection. In prior work, the impact of TCSC [22], SVC [23] and GIPFC [24] on distance protection is assessed.

2. SYNCHRONOUS GENERATOR LOE PROTECTION

A. LOE of synchronous generator

The P and Q (active and reactive power) is supplied by the synchronous generator to the grid. Considering the complex power, both P and Q are combined. P is taken from the turbine while Q comes from the field winding of the generator. Due to the following conditions, the LOE condition occurs in the synchronous alternator: field loss to the main exciter, intentional tripping of the breaker, SC (short circuit) in field winding, poor brush contact, failure in CB latch and the loss of ac supply to the excitation system [25].

Take into account that the generator is in sync with the grid. Now apply LOE to the generator, but the generator tried to stay in synchronization with the grid, and this is done by running the machine as a power generator. The induction generator is operated asynchronously. The induction generator runs at higher speed than synchronous speed. Because of this asynchronous operation, the reactive power is absorbed from the grid by the system. However this operation is good only for the strong grid. If the grid is weak then the entire system collapses which causes the overheating of stator winding and insulation failure. Therefore a loss of excitation protection is to be considered in order to avoid this condition. The specially developed mho relay is used for this protection. The offset mho relay is mostly used. This protection prevents the generator from becoming destroyed.

B. LOE relay

The LOE relay is equivalent to mho distance relay. The operation of these two relays is based on impedance measurement. The performance of relays is identified depending on the measured and set value of impedance. The performance of the relays is explained as follows: The initial step is to obtain the instantaneous values of I and V (i.e. I_R and V_R) from CT and PT. The Fast Fourier Transform (FFT) extracts the fundamental magnitude and phase values of these I_R and V_R values. These values are used to detect L-L faults. The sequence filter is used to find components of V and I for positive, negative, and zero sequence. These sequence components are used to detect ground fault. Now set the parameter of the mho circle. By using logic gates, we can determine the relationship between a measured and a set impedance value.

For the LOE protection, five schemes may use i.e. P-Q, V-I, G-B, R-X, and R-X with directional element scheme. Among all techniques, the R-X and R-X with directional scheme are the best methods to track the trajectory of fault impedance. Impedance calculation needs R (resistance) and X (reactance) of the system under defective conditions. Figure 1 shows the relay operation. For measurement purposes, the relay transmits the I_R and V_R signals from CT and PT. The voltage of the terminal (E_T) is given as,

$$\vec{E}_T = |E_T|\angle 0°, \vec{E}_G = |E_G|\angle \theta° \quad (1)$$

Where,

$$\frac{\vec{E}_T}{\vec{E}_G} = \frac{|E_T|}{|E_G|} e^{-j\theta} = qe^{-j\theta} \quad (2)$$

Wherein,

$$\vec{E}_T = \vec{E}_G q e^{-j\theta}, q = \frac{|E_T|}{|E_G|} \quad (3)$$

The relay current (I_R) is stated as,

$$\vec{I}_R = \frac{\vec{E}_G - \vec{E}_T}{\vec{Z}_G + \vec{Z}_T} = \frac{\vec{E}_G\left(1 - qe^{-j\theta}\right)}{\vec{Z}} \quad (4)$$

Where,

$$\vec{Z} = \vec{Z}_G + \vec{Z}_T \quad (5)$$

The relay voltage (V_R) is calculated as follows:

$$\vec{V}_R = \vec{E}_G - \vec{Z}_G \vec{I}_R \quad (6)$$

The relay impedance is stated as:

$$\vec{Z}_R = \frac{\vec{V}_R}{\vec{I}_R} = \frac{\vec{E}_G - \vec{Z}_G \vec{I}_R}{\vec{I}_R} = \frac{\vec{E}_G}{\vec{I}_R} - \vec{Z}_G \quad (7)$$

From eq. (4) and (7), Modified relay impedance calculated as,

$$\vec{Z}_R = \frac{\vec{V}_R}{\vec{I}_R} = \frac{\vec{E}_G}{\frac{\vec{E}_G\left(1-qe^{-j\theta}\right)}{\vec{Z}}} - \vec{Z}_G = \frac{\vec{Z}}{\left(1-qe^{-j\theta}\right)} - \vec{Z}_G \tag{8}$$

Here, E_G is generator voltage and E_T terminal voltage. Z_G and Z_T are generator and terminal impedance.

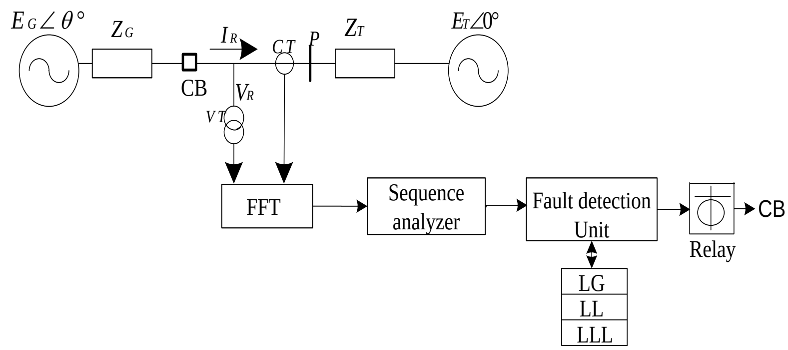

Figure 1 Study system with LOE relay arrangement

Regarding LOE, the E_G tends to zero and, consequently, the magnitude of the relay impedance is the same as that of a generator with an opposite polarity. The protection area of the LOE relay is deliberated accordingly in the negative part of the R–X diagram.

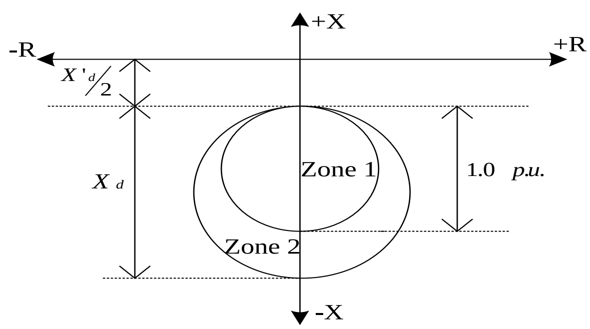

Figure 2 Negative offset mho relay

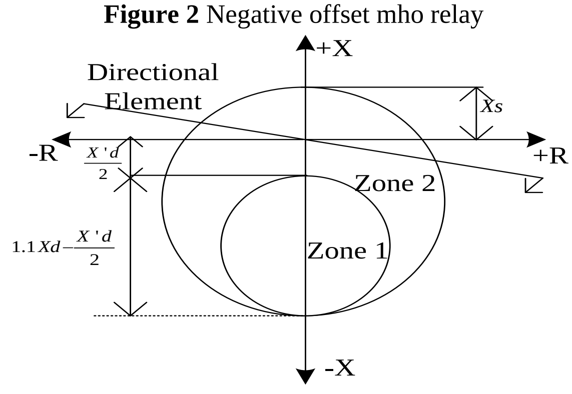

Figure 3 Positive offset mho relay

The negative offset relay mho with two zones, i.e. zone-1 and zone-2, is shown in Figure 2. The zone-1 Diameter will be 1 p.u. And zone-2 is the same as the X_d. The negative offset for $X'_d/2$ is used to limit the relay trip when the system is in a small transient condition. The two zones R-X with directional element technology are shown in figure 3. Zone-1 has the negative offset of $X'_d/2$. Zone-1 diameter is $(1.1X_d - X'_d/2)$. Xs is offset for zone-2, which corresponds to the sum of the system and transformer reactance. Zone-2 diameter is $(1.1\ X_d + X_s)$. The directional element is used to block a relay in normal operation and power swing. In normal operating conditions, the impedance trajectory is outside the zonal area, although it passes inside the zones under defective conditions. This distinguishes the relay between fault and power swing conditions.

3. UNIFIED POWER FLOW CONTROLLER

There are two types of FACTS devices, first type consisting of reactive impedances and transformers for tap-changing using conventional thyristor valves for the purpose of the control. This type includes the thyristor controlled FACTS devices like SVC, TCSC, TCVR and TCPAR. Another kind of FACTS is self-commutating, VSC (voltage-sourced converters). The FACTS devices such as STATCOM and SSSC are in the second group of FACTS devices, known as voltage source controlled FACTS devices. UPFC is developed by STATCOM and SSSC and was invented by Gyugyi in 1991. UPFC exchanges both P and Q for AC as well as absorbing and generating Q automatically and providing Q compensation without reactors and condensers. UPFC offers dynamic compensation and control in real time.

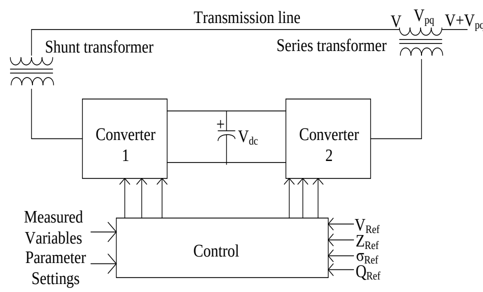

Figure 4 Employment of UPFC by two back to back VSC

UPFC works in all four quadrants of the P+jQ complex plane. The third-generation FACTS device is used for power flow control, power transmission capacity improvement, angle stability and damping of the system and for controlling P and Q flow. Figure 4 shows implementation of UPFC, converter 1 is STATCOM and converter 2 is SSSC. Both converters are connected with the dc link. By using the correct swing operation, UPFC can be used as a single STATCOM or SSSC [1].
The impedance of the line is one of the UPFC's controllable parameters. The UPFC has its particular impedance; the existence of UPFC increases the system's total impedance. This affects the LOE relay performance. LOE relay malfunction occurs and unable to discriminate between fault and power swing.

The UPFC scheme includes SSSC and STATCOM control. The block diagram of SSSC control is shown in figure 4. The current measurement block is used to obtain direct I_d axis and I_q current components. I_q's zero here. Similarly, V_q is the quadrature axis voltage extracted from voltage measurement block. The error between V_q and V_{qref} is given to V_q - voltage regulator and finally, this output is provided to the PWM modulator. PLL's output is Θ (phase angle) which is also specified to the PWM modulator. The output is accompanied by the development of pulses.

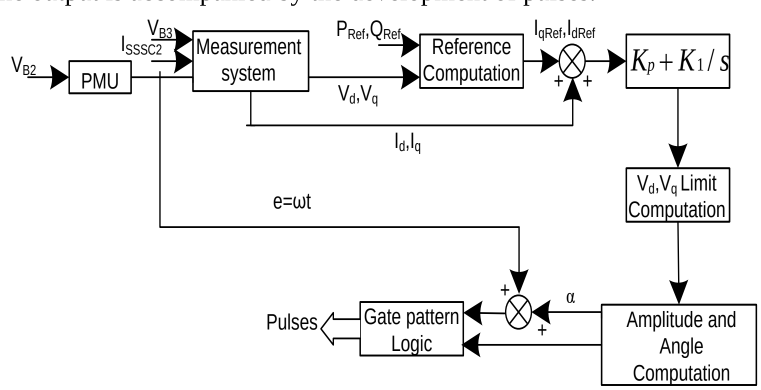

Figure 4a SSSC control system

The STATCOM control is shows Figure 4b. The three-phase alternating current of STATCOM gives to d-q transformation block to get direct current (I_d) and quadrature axis current (I_q). I_{qref} is obtained in PLL followed by positive sequence voltage measurement (current is quadrature by voltage), I_d and I_q are supplied to block I_q Limit calculations in order to achieve α (firing angle). In order to improve dynamic performance, the dc capacitor voltage regulator must be added. The final signal (Θ + α) is supplied to the logic block for the gate pattern by adding all the signals.

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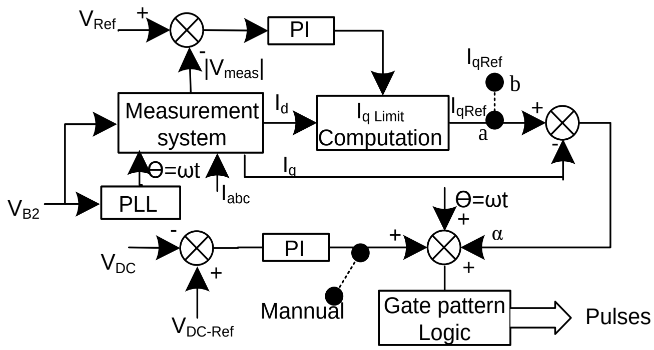

Figure 4b STATCOM control system

4. STUDY SYSTEM WITH SIMULATION RESULTS

A. Case 1: Study system without UPFC

The double-line study system without UPFC is shown in Figure 5. Through three phase transmissions, the system comprises 2 generators, with 2100 MW of voltage and 1400 MW of capacity. The system consists of 2 transformers with 1000 MVA and 800 MVA ratings. This five-bus system uses four lines with 300 km length of L_1, 140 km length of L_2 and L_3 and 50 km length of L_4 with their respective X_{L1} to X_{L4} reactions.

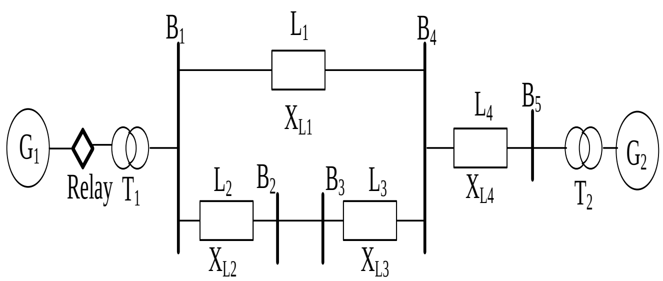

Figure 5 System without FACTS device

Figure 6a shows the tripping signal of the relay, at t = 11.58 sec, the trip signal provided to CB, Figure 6b shows the impedance trajectory of the LOE relay. The impedance trajectory is outside of both zones during the normal condition. In the case of a failure, the fault impedance trajectory enters the zones at particular time. Then the relay is operated by sending trip signal to CB and the faulty part of the remaining system is isolated. In this case, the impedance trajectory enters zone 1 at 11.58 sec.

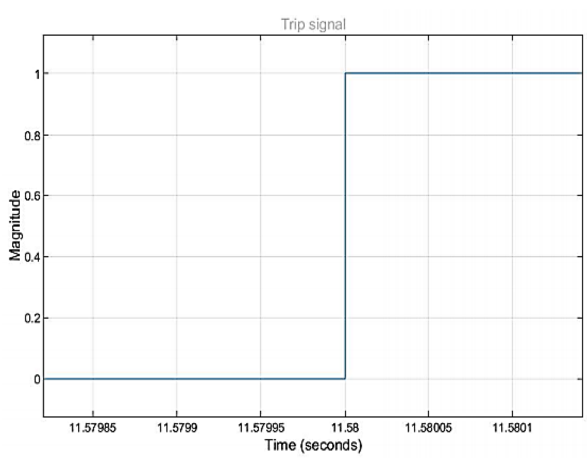

Figure 6a Trip signal of a system without UPFC

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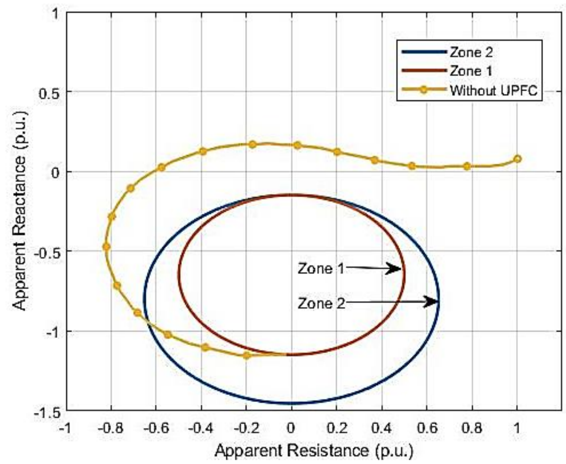

Figure 7b LOE relay impedance trajectory

B. Case 2: Study system with UPFC

Figure 7 shows the study system in the existence of UPFC between buses B_2 and B_3. The presence of UPFC causes the damage of armature winding. Figure 8a shows the trip signal. The LOE condition is applied at t = 10 sec, the impedance enters into zone 1 at a time of 12.27 sec which is more than the system without UPFC. The delay of 12.27 - 11.58 = 0.69 sec occurred in the response of the LOE relay which is shown in fig.8b.

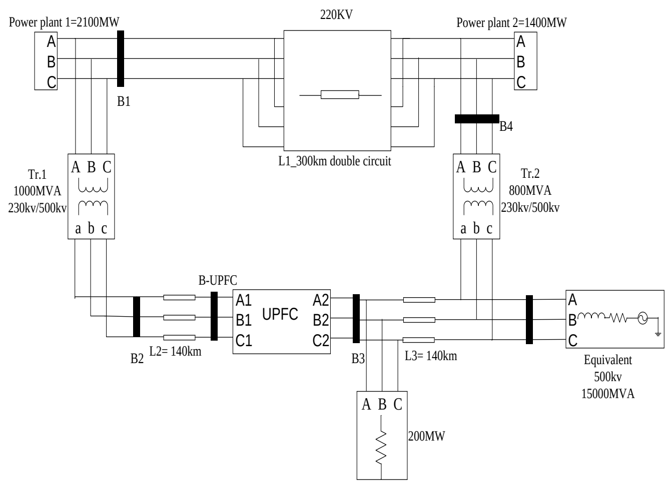

Figure 8 Study system with UPFC

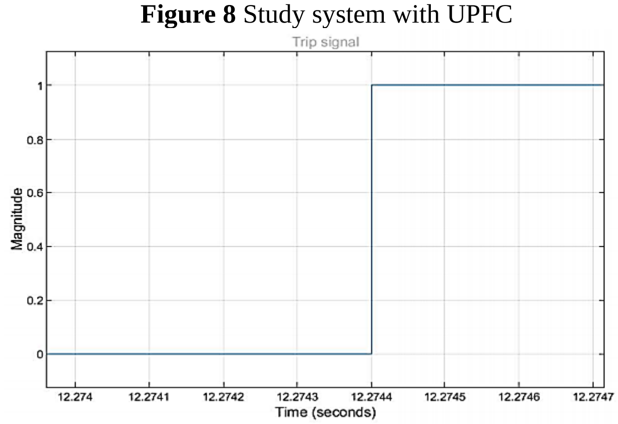

Figure 8a Trip signal of a system with UPFC

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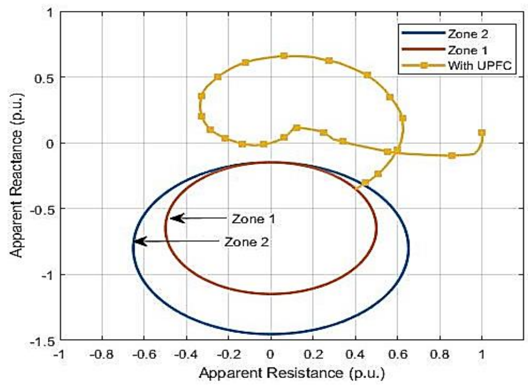

Figure 8b Impedance trajectory of the system with UPFC

C. Case 3: LOE at 10S and field voltage = 0 p.u. (Complete LOE condition)

Figure 9 shows individual impedance trajectories of SSSC, STATCOM, UPFC, and system without UPFC. The LOE condition is applied at t = 10 sec in the simulation with E_f = 0 p.u. The impedance trajectory of individual STATCOM enters in zone 1 at t = 11.82 sec and t = 12.03 sec for SSSC. The delay due to SSSC is more than STATCOM because the LOE condition drops the system voltage and SSSC helps the system for compensation of this voltage drop by injecting Q therefore the delay will get increases.

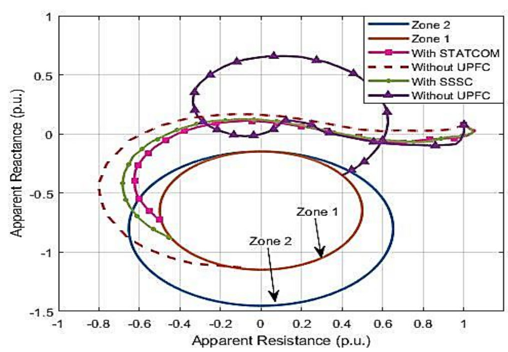

Figure 9 Impedance trajectories, LOE at 10 sec, field voltage= 0 p.u.

D. Case 4: LOE at t = 10S and field voltage = 0.1 p.u. (Partial LOE condition)

Figure 10 shows the impedance trajectories for the given condition. The simulation results prove that the processing time of the LOE relay gets increases due to partial LOE. The partial LOE is a condition when the grid partially fulfils the reactive power demand which will fall the generator terminal voltage. The tripping of relay for a system with STATCOM is provided at 13.217 sec, for SSSC is at 12.625 sec, for UPFC is at 13.786 sec and system without UPFC, it is at 11.6657 sec. The decreasing value of generator P surges the delay. Also, the ratings of UPFC affects on the relay performance by increasing delay in the performance of relay.

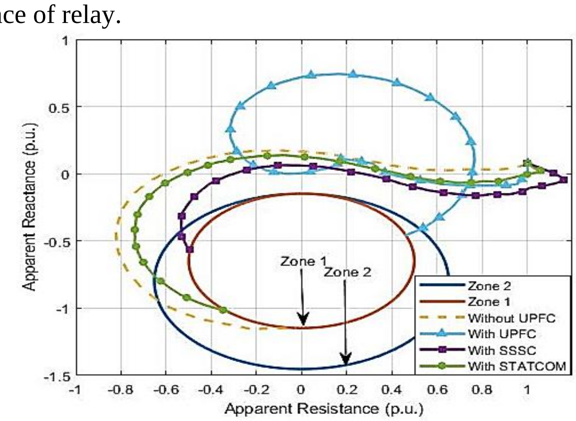

Figure 10 Impedance trajectory, LOE at 10 sec, field voltage = 0.1 p.u.

E. Case 5: LOE at 10S, field voltage = 0.2 p.u., and generator output active power = 0.2 p.u.

Figure 11 shows the above-mentioned R-X scheme. In this case the impedance trajectory of the UPFC system does not enter any LOE relay zone and therefore the LOE relay will not travel and experience under the current phenomenon and thus proper generator protection will not occur.

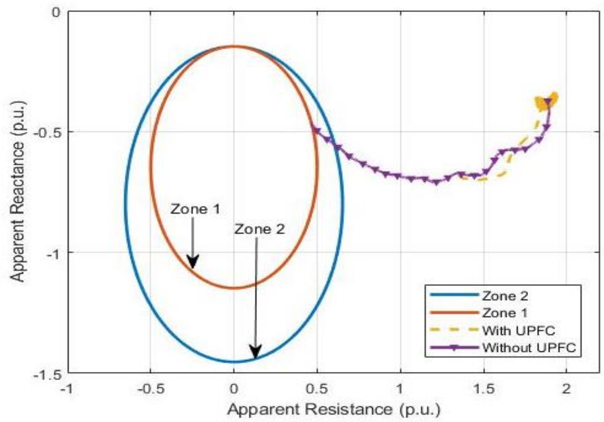

Figure 11 Impedance trajectories, LOE at 10 sec, field voltage= 0.2 p.u.

5. MITIGATION TECHNIQUE

The disadvantage from the above cases is that the LOE relay malfunctions as UPFC impedance is not added to the system impedance. The mitigation approach basically adds the value of the P and Q of UPFC to the P and Q of generator respectively, so that total power is shown in the below expression.

$$P = P_G + P_{UPFC} \quad (9)$$

$$Q = Q_G + Q_{UPFC} \quad (10)$$

From the above equations, the value of resistance and reactance is calculated as follows:

$$R = \frac{P*(V_R)^2}{P^2+Q^2} \quad (11)$$

$$X = \frac{Q*(V_R)^2}{P^2+Q^2} \quad (12)$$

This relay design medication minimises the previous disadvantages. The impedance relay in the presence and absence of UPFC having E_f = 0.2 p.u. is shown in Figure 12. The active power of the generator is 0.8 p.u. The condition of mitigation is applied here. The only thing to notice is that this technique increases the delay in the LOE relay performance. The trip time for a system without UPFC is 12.62 sec and for a system with UPFC is 12.99 sec, so the delay is 0.37 sec. In this way technique helps to remove the phenomenon under reach.

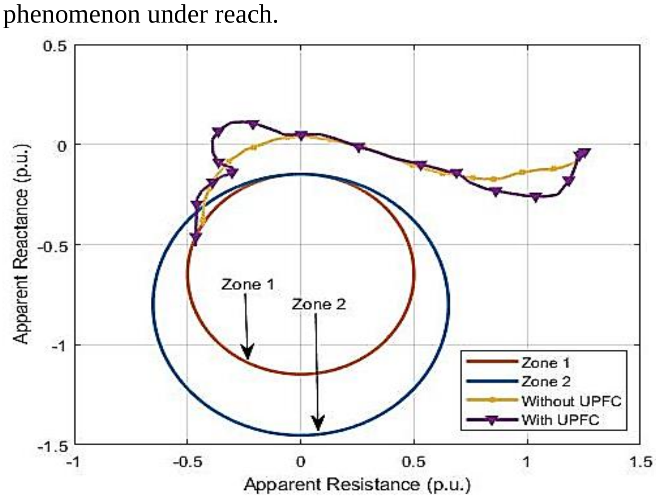

Figure 12 Impedance trajectories, with and without UPFC

6. CONCLUSION

This article illustrates the influence of UPFC on the synchronous generator LOE protection with the help of SIMULINK/MATLAB software. The simulation results for several conditions states that the delay of performance of LOE relay gets increases due to a decrease in generator active power and an increase in ratings of UPFC. The impedance of the transmission line gets decreases with increasing delay. Due to this, the abnormal conditions like overreaching and underreaching takes place which results in maloperation of LOE relay. Hence one needs to modification in the relay setting and this is done by adding ratings of UPFC into system ratings. The complete and partial LOE conditions also considered in this article. The future scope of this work is to minimize the performance delay time. Also to study the influence of other third-generation FACTS devices (like IPFC, GIPFC) on generator LOE protection.

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