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Impact of STATCOM and SSSC on synchronous generator LOE protection

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Abstract: Loss of excitation (LOE) protection is one of the most important protections of synchronous generators. Nowadays, application of an impedance relay with two negative offset operation zones to protect LOE is prevalent; this relay measures the output voltage and current of generator to detect LOE. On the other hand, utilization of flexible AC transmission systems (FACTS) devices in power systems for different applications is soaring; these devices cause changes in voltage and current signals in the utilized power system. Therefore, this paper is dedicated to investigate the amounts of changes in the current and voltage signals measured by the LOE relay when the static synchronous compensator (STATCOM) and static synchronous series compensator (SSSC) are used. Research results show that the changes in the measured signals manipulate the operation of the relay. It is also shown that partial LOE culminates in an under-reach of the relay. In surveys conducted, various operational conditions of the power system and FACTS devices are considered as well.

Key words: Generator loss of excitation (LOE) protection, static synchronous series compensator (SSSC), static synchronous compensator (STATCOM)

1. Introduction

A synchronous generator requires adequate DC voltage and current to its field winding to produce three-phase voltage. LOE can be caused by a short circuit, an open circuit, and a controlling problem or an operational error. When the LOE occurs the generator output voltage diminishes, which makes the generator absorb a great amount of reactive power. As a consequence, the armature winding current increases and causes unavoidable damage to the generator [1]. Therefore, a synchronous generator needs a safe and reliable protection system for LOE. Impedance relay is one of the most obvious and commonly used relays in protection of LOE. The current transformer (CT) and the voltage transformer (VT) of the LOE relay are connected to the generator terminal to continuously measure its impedance.

Nowadays, FACTS devices technology application in power systems faces an unremitting increase; because these devices change the signals of voltage and current in the power system, they vitiate the operation of relays like the LOE relays. Numerous researches have tackled this concept so far. A great part of the researches investigate different types of FACTS devices' effects on distance protection of transmission lines. In [2]–[4], the effects of series FACTS devices have been studied; these devices usually comprise thyristor controlled series capacitor (TCSC) and SSSC. Investigations of [5]–[7] have been devoted to probe the effects of shunt FACT devices on the distance protection of transmission lines that normally consist of static VAR compensator (SVC) and STATCOM. Studies in [8] and [9] have dealt with the effects of shunt-series FACTS devices' effects on the

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distance protection of transmission lines considering a unified power flow controller (UPFC) and generalized interline power flow controller (GIPFC). All the researches have shown that the presence of FACTS devices causes errors in the operation of distance relays of transmission line. It should be mentioned that in the majority of cases they result in under-reach of the relay.

A second part of the researches investigate the effects of FACTS devices on overcurrent (OC) protection. For instance, it has been shown in [10] that the presence of a fault current limiter (FCL) brings about a necessity for resetting the OC relay.

In the aforementioned two groups of researches, the synchronous generator and its protections have not been considered. In other words, because the distance and OC protections were the main objective of the researches a voltage source was used instead of a generator. Effects of STATCOM on synchronous generators protection have been recently investigated in [11]; in this research a 12-pulse STATCOM has been used; since the research has only used the STATCOM, it cannot inject/absorb active powers into/from the system. Most of the studies in LOE protection field deal with increasing LOE relay operation speed. In [12] a new method for LOE protection is presented. In the proposed method in this paper beside the LOE relay with 2 protection zones, another element is used for reactive power measurement. In this regard, also the reactive power injected by the generator can be measured, which increases the relay performance speed. In [13], it is shown that in a large power system the LOE in the generator is more dangerous for stability of power system. Load flow is utilized for that purpose in this paper. In [13], it is shown that LOE is accompanied by generator voltage drop, and using load power flow results, it is shown the LOE in the generator results in voltage collapse in the power system. Investigations in [14] showed LOE protection in isolated systems with an induction motor. In this paper it is shown that in some circumstances after LOE the relay does not detect LOE. In [15], the operation time of relay is reduced to 0.5 s, using fuzzy logic.

The current work investigates the effects of SSSC on LOE protection. Moreover, the effects of STATCOM on LOE protection are investigated to provide reliable data for comparing with the SSSC effects' results. For simulating the FACTS devices, an 48-pulse convertor is used that presents more feasible results for real applications. Different operation conditions of the system and the FACTS devices are considered in the simulations. It is shown that when LOE occurs, the generator output voltage gradually decreases. Although the FACTS devices curb the decrease in generator output voltage by injecting reactive power, they cause a delay in the operation of LOE relay or even lead to under-reaching of the relay under the worst condition, which is very dangerous for the generator. All the detailed simulations are carried out in the MATLAB/Simulink environment using the SimPowerSystems toolbox. This paper is organized as follows: Section (2) deals with LOE relay. In section (3), LOE relay is modeled. The FACTS devices' details and their modeling is presented in section (4). Impact of FACTS devices on LOE protection is shown in section (5). Finally, a few methods are presented to mitigate this detrimental delay in the operation of LOE relay in the presence of FACTS devices in section (6).

2. Loss of excitation (LOE) relay

The presented system in Figure 1 is used to investigate the operation mechanism of the LOE relay. The relay is connected to the terminal of the synchronous generator as shown in Figure 1. The right-hand side of the Bus-P shows the Thévenin equivalent circuit of the power system [1]. In the system shown in Figure 1, one can writ:

$$\vec{E}_T = |E_T| \angle 0^\circ, \vec{E}_G = |E_G| \angle \delta^\circ \tag{1}$$

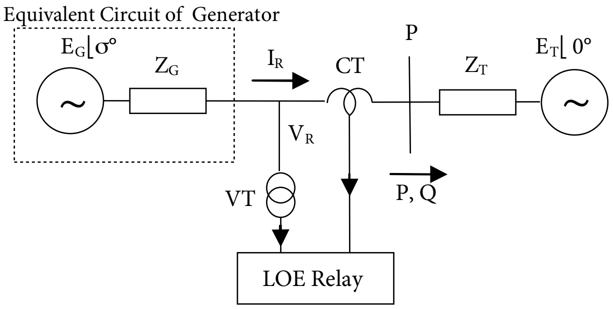

Figure 1. Equivalent system for studying LOE protection.

where

$$\frac{\vec{E}_T}{\vec{E}_G} = \frac{|E_T|}{|E_G|} e^{-j\delta} = qe^{-j\delta} \tag{2}$$

in which

$$\vec{E}_T = \vec{E}_G q e^{-j\delta}, \, q = \frac{|E_T|}{|E_G|} \tag{3}$$

The current (I_R) equals

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

where

$$\vec{Z} = \vec{Z}_G + \vec{Z}_T \tag{5}$$

The voltage of relay emplacement is as follows:

$$\vec{V}_R = \vec{E}_G - \vec{Z}_G \vec{I}_R$$

In this case, the measured impedance by LOE relay will be as follows:

$$\vec{Z}_R = \frac{\vec{V}_R}{\vec{I}_R} = \frac{\vec{E}_G - \vec{Z}_G \vec{I}_R}{\vec{I}_R} = \frac{\vec{E}_G}{\vec{I}_R} - \vec{Z}_G \tag{6}$$

Applying (4) in (6) results in

$$\vec{Z}_R = \frac{\vec{E}_G}{\frac{\vec{E}_G (1 - qe^{-j\delta})}{\vec{Z}}} - \vec{Z}_G = \frac{\vec{Z}}{1 - qe^{-j\delta}} - \vec{Z}_G \tag{7}$$

According to (7), the calculated impedance by the LOE relay depends on two parameters, q and δ. The pushing path denoting the impedance vector location versus the variations of δ from 0 to 360 degrees and also under different q values of 0 to 1 is shown in Figure 2. The impedance varies in the transient interval of the generator operation too. The relationship between the impedance and slip (S) of the rotor speed is shown in Figure 3.

When the generator is operating under synchronous condition $(S = 0)$, then its impedance equals X_d. When S increases the generator impedance equals $X_d^{'}/2$. Variations in the location of the denoting point of impedance vector versus the S variations posit on the Z_s circle. To make this subject more clear, granted that a partial LOE occurs and $q = 0.1$ p.u., the relay characteristic is shown as a circle with corresponding diameter of 0.1 (Figure 2) and its center positing on the Z_s circle regarding the different S values (Figure 3). It is obvious that the design and construction of a relay whose characteristics depend on S values is very demanding and difficult. However, regarding the investigations in [1], [16]–[19], the presented relay characteristics in Figure 4 provide the best results for a vast bunch of LOEs; this relay is well known as a Berdy [12] relay, which has two distinct zones; both of the zones have a negative offset of $X'_d/2$ as shown in Figure 4. Diameters of Zone 1 and 2 are 1.0 p.u. and X_d, respectively. Zone 2 should have a delay in operation because when a fault occurs in the transmission line the calculated impedance by LOE relay temporarily enters this zone and it should not respond to this temporary fault. However, Zone 1 has immediate response characteristics.

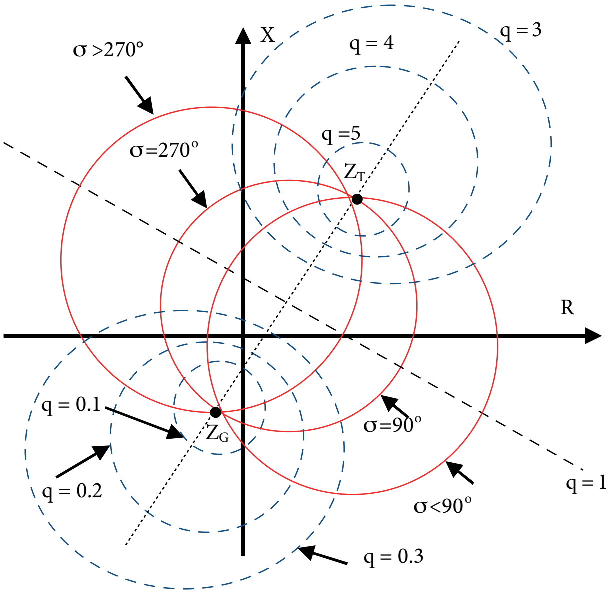

Figure 2. Locus of Z_R as a function of q and δ.

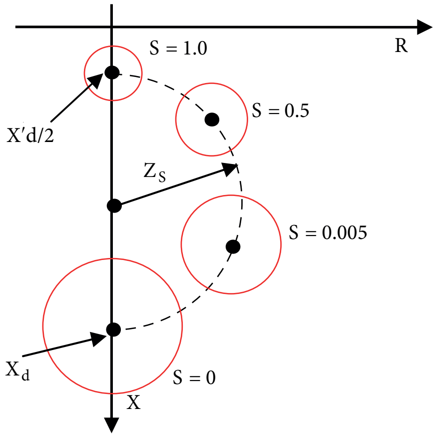

Figure 3. Locus of Z_R as a function of slip (S).

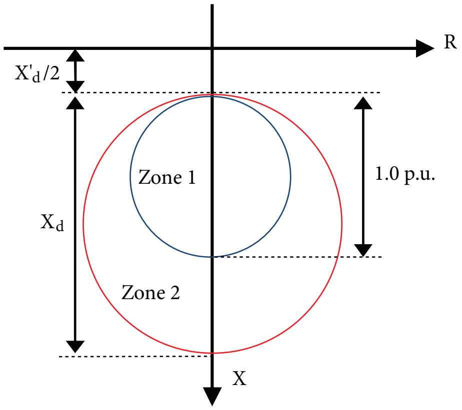

Figure 4. Operational characteristic of LOE relay.

3. Modeling of LOE relay

As seen in the previous section, the LOE relay requires the voltage and current of its installation location to detect the LOE. For this purpose, the CT and VT are installed at the terminal of the generator to measure the current and voltage. Since the main frequency of system is required to calculate the impedance, the outputs of the CT and the VT are passed through a low-pass filter to remove the extra harmonics. The obtained signals are sampled and then converted to phasors by the phasor unit. The phasors of measured signals are calculated using different methods. The used method in the phasor unit is mostly full cycle discrete Fourier transform (FCDFT) [20]. The obtained phasors are entered into the impedance calculating unit and according to (6) that is an imaginary value. To verify modeling of the LOE relay the studied system in [1] is used (example 13.7). This system is shown in Figure 5. There are four 555MVA generators in this system, each of which contains an excitation system and power system stabilizer (PSS). Ancillary information to this system is given in [1]. Supposing LOE at t = 1 s, output voltage, and active and reactive power of the generator are shown in Figure 6.

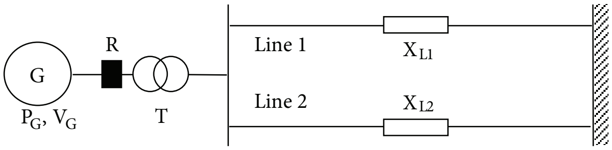

Figure 5. Sample system [1].

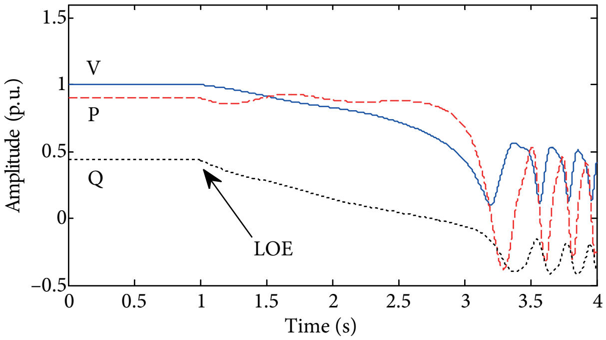

Figure 6. Outputs of generator after an LOE at t = 1 s.

According to the results, LOE and consequently absorbing reactive power by the generator dramatically reduces the generator voltage. The measure impedance by the LOE relay is shown in Figure 7. The figure shows that the calculated impedance by the relay enters Zone 1 at t = 3.304 s and the relay detects the LOE after 2.204 s.

4. Investigating and modeling of SSSC/STATCOM

Always it has been obvious that with appropriate series/shunt compensation, transmittable power in the steady state can be increased and also voltage profile along the transmission line can be controlled. The most important compensators include SSSC and STATCOM, which are widely used in power systems. The single-line diagram of the system used for the investigations is shown in Figure 8. In this figure, the SSSC/STATCOM is connected to the middle of the transmission line. The system, connected in a loop configuration, is interconnected through transmission lines and two transformers. The generator models include a speed regulator and an excitation system as well as a PSS.

4.1. Analysis and modeling of SSSC

It has been always obvious that power transfer in long transmission lines is primarily limited because of line impedance. A static synchronous series compensator (SSSC) was proposed to compensate a part of reactance of the transmission line and consequently to increase power transfer. This compensator contains 48-pulse converters. It consists of four 3-phase, 3-level inverters and four phase-shifting transformers. The four

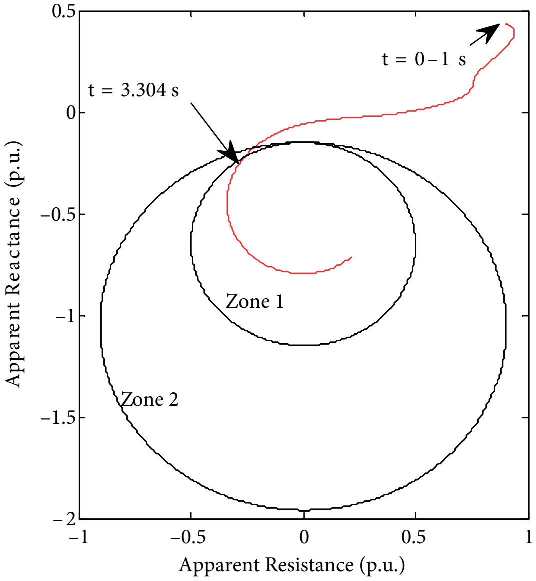

Figure 7. Impedance trajectory calculated by LOE relay after an LOE at t = 1s.

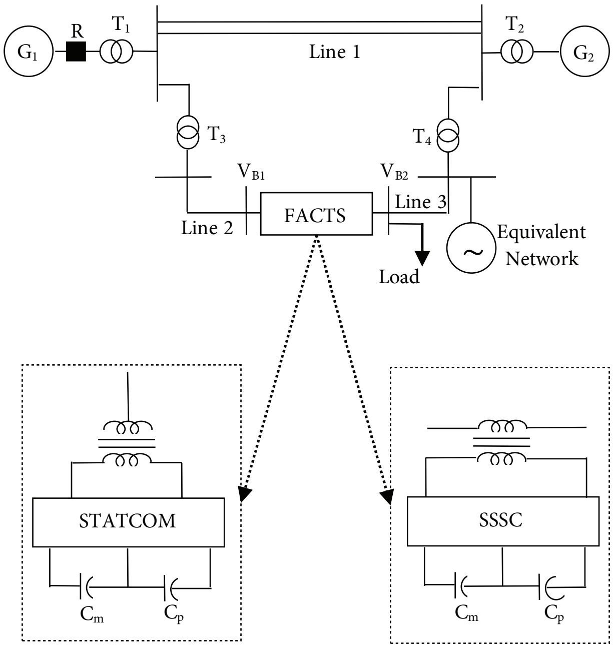

Figure 8. Sample system with SSSC/STATCOM.

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 controller of the SSSC is shown in Figure 9. It calculates the reference angle according to the three-phase voltage, V_{B1}, and using a phase locked loop (PLL). The angle of transmitted current is obtained from the PLL output and transmitted current of transmission line or SSSC. The magnitude of SSSC output voltage is obtained from measured V_{B2} and using $V_{B2} - V_{B1}$ too. Phase shift as $+\pi/2$ or $-\pi/2$ is obtained from the feedback signal of V_{Ref}. The small steady angle $\Delta\alpha$ is added to phase shift as $+\pi/2$ or

$-\pi/2$ to absorb power from the system to compensate losses of converters. The magnitude of injected voltage (V_{inj}) is controlled by a simple closed-loop PI controller. The magnitude of V_{Ref} is compared with the measured injected voltage (V_{inj}) and the amplified error is added to the synchronization signal $(\theta = \omega t)$ as a correcting angle [21,22].

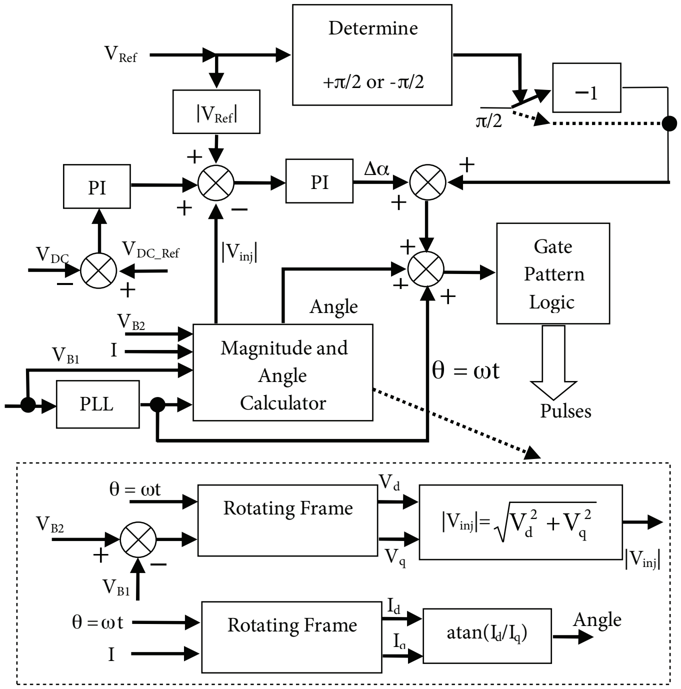

Figure 9. Control systems used for SSSC converters.

4.2. Analysis and modeling of the STATCOM

The synchronous compensator (STATCOM) is a static synchronous generator that works as a shunt compensator of reactive power. This compensator is able to control inductive or capacitive current independent of AC voltage of the system. In this investigation, 48-pulsed voltage source converters are used for modeling the STATCOM. The control system used for the STATCOM converters is shown in Figure 10. In this controller, output current of the STATCOM is decoupled into its reactive current (I_q) and active current (I_d) components. The value of the reactive current component (I_q) is compared with source reactive current $(I_{q\,Ref})$. The error produced this way after proper amplification gives angle α. This angle defines required phase shift between the output voltage of the converter and the voltage of the AC system, which is necessary for charging (or discharging) storage capacitance to a required DC voltage level. The I_q limit computation part is to limit the value of the output current to the rated value of the converters. This part is used in practical applications and has not been considered in most of the literature; therefore, it leads to an unlimited output of the STATCOM and also its effect on the power system becomes unreal. The STATCOM has two different operation modes: voltage control mode, where the switch shown in Figure 10 is in position "a", and constant reactive power generation mode, where the switch is in position "b" [21–23].

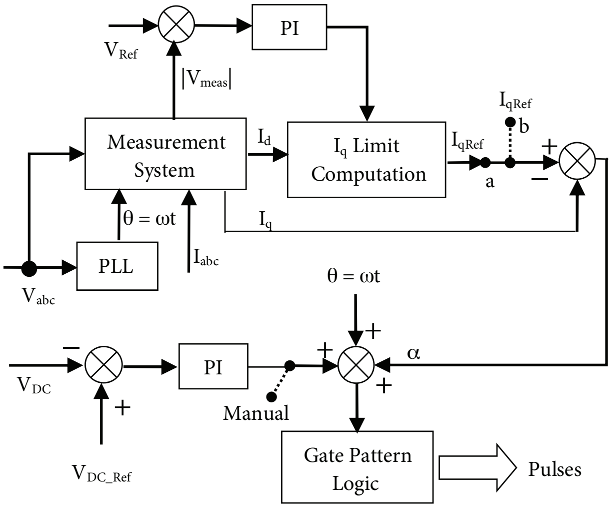

Figure 10. Control systems used for STATCOM converters.

5. Impact of the SSSC/STATCOM on LOE protection

The calculated impedance by the LOE relay assuming LOE in G1 at t = 10 s is shown in Figure 11 (a). It is shown that the presence of the SSSC causes 1.06 s (14.74 s–13.68 s) delay time in relay performance. It is assumed that the delay of Zone 2 is larger than 1.06 s. In the results, the reference voltage of the SSSC is considered 0.2 p.u. (the unit of V_{Ref} is per unit, which is based on the system voltage) and the SSSC has a capacitive compensation mode. The magnitude of injected voltage by the SSSC is shown in Figure 12. According to the figure, the value of output voltage has followed the reference voltage. It was also seen that V_{Ref} for the SSSC, which is applied by the operator, has the most impact on the system. For instance, the results for different V_{Ref} are shown in Figure 11 (b). When SSSC has inductive series compensation, it has different effects on the relay performance. The results for two different amounts of V_{Ref} are shown in Figure 11 (b). According to the figure, for $V_{Ref} = –0.08$ the presence of the SSSC increases the speed of relay performance. In other words, the presence of the SSSC causes LOE relay to over-reach. Since the reactance of the transmission line is increased in this case, the speed of generator voltage drop is increased. In contrast, for $V_{Ref} = –0.18$, the SSSC causes a delay in relay operation.

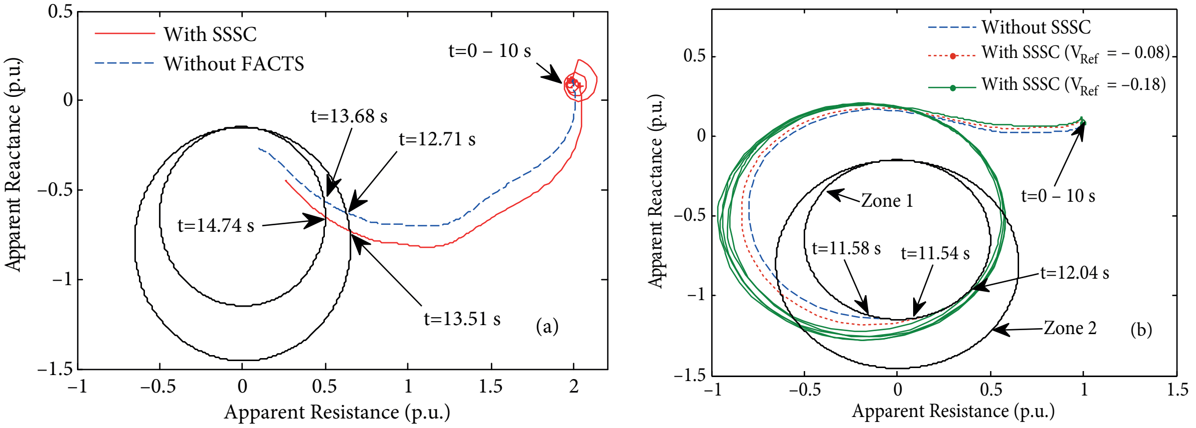

Figure 11. Impedance trajectory calculated by LOE relay after an LOE at t = 10 s and SSSC in compensative mode (a), in inductive mode (b).

Supposing that LOE occurs at t = 10 s, the calculated apparent impedance by relay, with the presence of the STATCOM, is given in Figure 13. It is seen from the figures that presence of the STATCOM caused 1.04 s delay in relay operation. The output reactive power of the STATCOM is given in Figure 14. It is shown in the figure that after loss of excitation, the STATCOM increased the reactive power injection to its maximum value to prevent voltage drop of the system. The output voltage of G1 is shown in Figure 15. It can be seen from Figure 15, that the presence of the SSSC/STATCOM prevents the voltage drop and causes the relay not to detect the LOE.

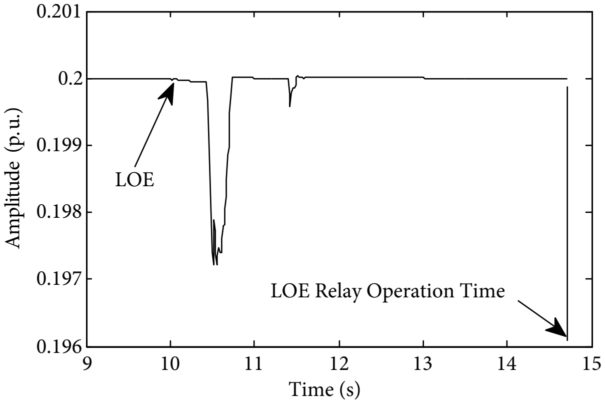

Figure 12. The magnitude of injected voltage by SSSC after an LOE at t = 10 s.

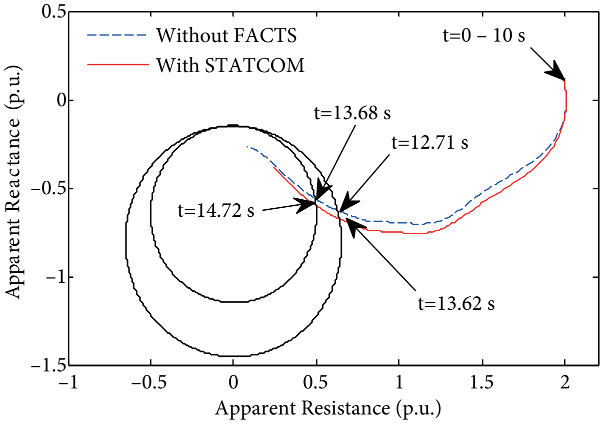

Figure 13. Apparent impedance trajectory calculated by LOE relay after an LOE at t = 10 s.

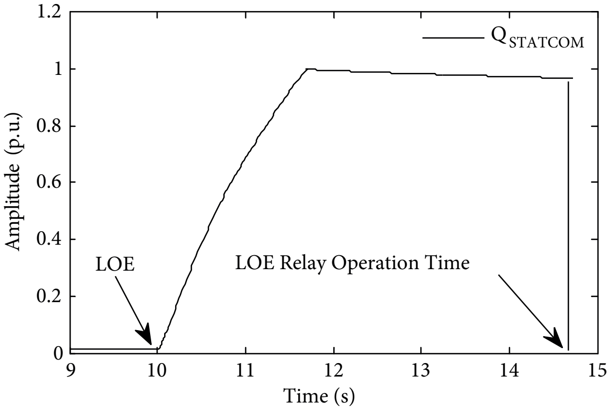

Figure 14. Reactive power injected by the STATCOM.

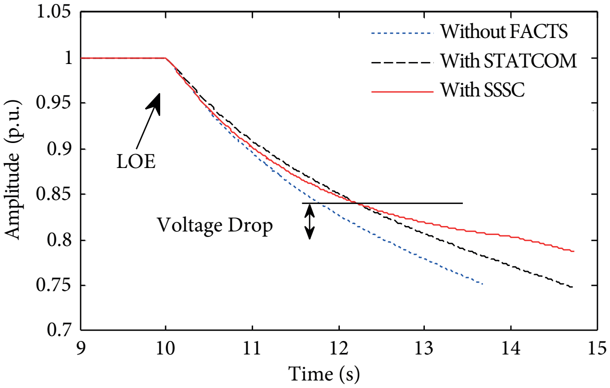

Figure 15. Generator 1 (G1) terminal voltage after an LOE at t = 10 s.

The results for different operation modes of system and two different values of SSSC nominal power are given in Table 1 and the following results are obtained:

1) With a fixed output voltage of the generator, decreasing the output active power of generator increases the LOE relay operation time.

2) With a fixed output power of the generator, output voltage variations of the generator do not have much effect on the delay in LOE relay operation time.

Table 1. Performance of LOE relay with the SSSC/STATCOM.

1.02 p.u.			1.0 p.u.			0.98 p.u.			Generator terminal voltage
1.0 p.u.	0.7 p.u.	0.5 p.u.	1.0 p.u.	0.7 p.u.	0.5 p.u.	1.0 p.u.	0.7 p.u.	0.5 p.u.	Generator output active power
0.63 s	0.82 s	1.06 s	0.60 s	0.79 s	1.01 s	0.57 s	0.74 s	0.93 s	Delay time (s) with ±200 MVA SSSC
0.58 s	0.78 s	1.04 s	0.49 s	0.71 s	0.91 s	0.51 s	0.66 s	0.87 s	Delay time (s) with ±200 MVA STATCOM

In the studies, the effect of parameters of the transmission line and also FACTS devices' nominal power are analyzed and the below results are obtained:

1) In all cases, increasing the nominal power of the SSSC/STATCOM has increased the amount of delay in LOE relay operation.

2) In all cases, increasing the impedance values of the transmission line has increased the amount of delay in LOE relay operation.

The results in Table 1 are obtained while a complete LOE occurred ($E_f = 0$ p.u.). It is assumed that the amount of excitation voltage is $E_f = 0.1$ p.u. and it is not completely short circuited and the calculated impedance by LOE relay is shown in Figure 16 (V_{G1} & $P_{G1} = 1.0$ p.u.). According to Figure 16, the SSSC and STATCOM make a delay duration of t = 2.43 s and t = 1.87 s in the relay operation, respectively. According to the results, in this case the amount of delay is remarkable compared with the results in Table 1. The operating time of the relay is so important that in [15] by using fuzzy logic the authors reduced the operating time of the relay as much as 0.5 s, which in comparison with this time, the delay caused by SSSC/STATCOM devices is significant. The current of armature for $E_f = 0.1$ p.u., P_{G1} & $V_{G1} = 1.0$ p.u. is shown in Figure 17. It can be seen that assuming the LOE, the presence of a SSSC/STATCOM causes the generator armature current to be overloaded for a longer time and this will cause damage to the armature winding gradually.

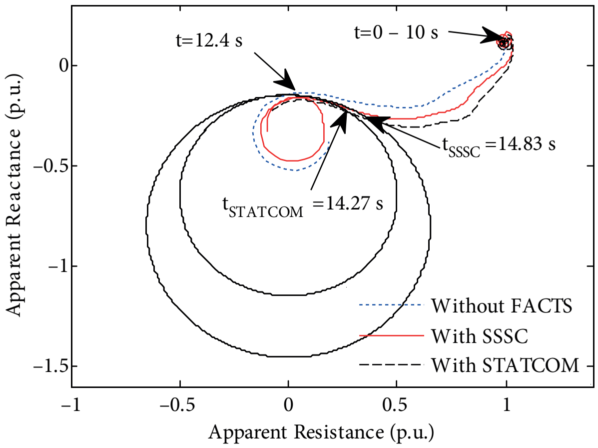

Figure 16. Apparent impedance trajectory calculated by LOE relay after an LOE at t = 10 s and $E_f = 0.1$ p.u.

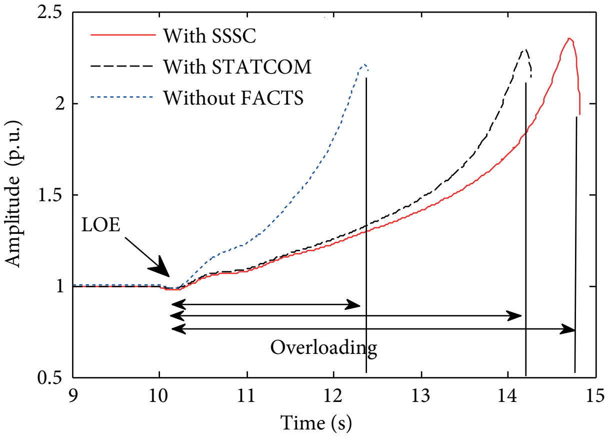

Figure 17. Generator (G1) armature current after an LOE at t = 10 s.

In some cases, the presence of a SSSC/STATCOM causes the relay not to operate. In other words, the presence of a SSSC/STATCOM causes the LOE relay to under-reach. For example, the results for $E_f = 0.2$ p.u., P$_{G1}$ = 0.4 p.u. and V$_{G1}$ = 1.0 are shown in Figure 18. As seen, the relay has not detected the LOE, 190 s after LOE. The output voltage of the generator (G1) is shown in Figure 19. It can be seen that the presence of a SSSC/STATCOM prevents the voltage drop and it causes the relay not to detect the LOE. Results show that when the generator's output active power is less than 0.4 p.u. and also E_f is between 0.2 and 1.0 p.u., the relay experiences under-reach. The amount of the generator's voltage is considered 1.0 p.u. in these analyses. For smaller amounts of voltage, the E_f area decreases. For example, when P$_{G1}$ = 0.4 p.u. then V$_{G1}$ = 0.98 p.u., and the relay experiences under-reach when E_f is between 0.26 and 1.0 p.u.

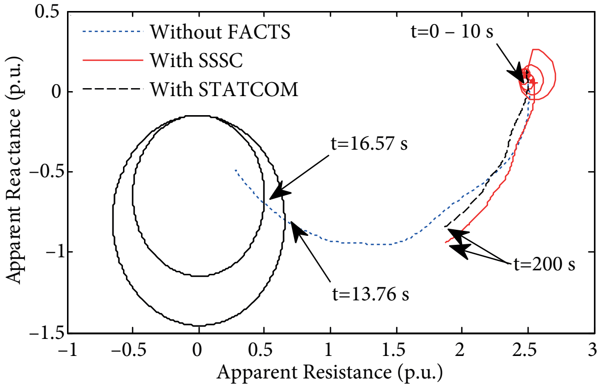

Figure 18. Apparent impedance trajectory calculated by LOE relay after an LOE at t = 10 s (the presence of the SSSC/STATCOM causes LOE relay to under-reach).

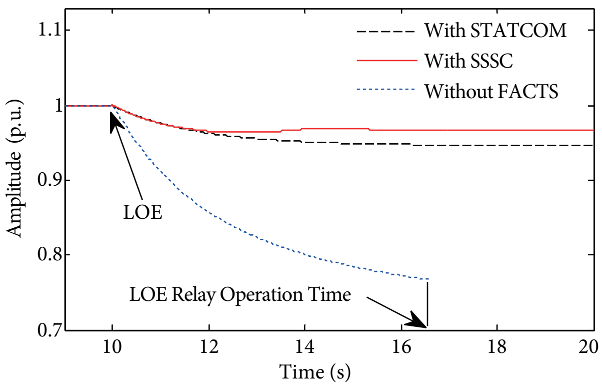

Figure 19. Generator (G1) terminal voltage after an LOE at t = 10 s.

It should be mentioned that the worst condition happens when the LOE does not work due to the presence of a SSSC/STATCOM. On the other hand, the presence of a SSSC/STATCOM causes error in LOE operation only when the generator output is less than 0.4. In this case, although presence of a SSSC/STATCOM prevents the voltage drop and it causes the relay not to detect the LOE, the generator output is kept normal because its power is low. For example, for the case study shown in Figure 18, the outputs of the generator are shown in Figures 20 and 21. Regarding the armature current, it is seen that the SSSC curbs the increase in armature current and the damper winding current as well. Although it is superficially shown that the SSSC prevents any damage to the generator, the indispensable damage is hidden due the fact that the presence of the SSSC causes the LOE in the generator not to be detected properly. There are special conditions when the presence of a SSSC/STATCOM causes delay in relay. These conditions occur when the generator output active power is very close to its nominal value. Results of simulations dedicated to this phenomenon are shown in Figures 22 and 23. It is shown that the presence of a SSSC/STATCOM causes this result; the currents of field winding and damper windings stay in the overload condition more than where there are no FACTS devices in the network.

After operation of the LOE relay, the generator is separated from the circuit and production of power declines. In other words, the supply and demand are not equal and consequently the frequency is changed. The results are shown in Figure 24. As seen in the figure, after the trip of the generator at t =10, the frequency has been maintained in the allowable limit, because the presence of FACTS devices increases the available transfer capability of the system and therefore the system is stable after relay operation and isolating of G1. Without

FACTS devices the system goes to frequency instability with generator tripping. Under this condition, the frequency returns to the nominal value after reducing the consumption.

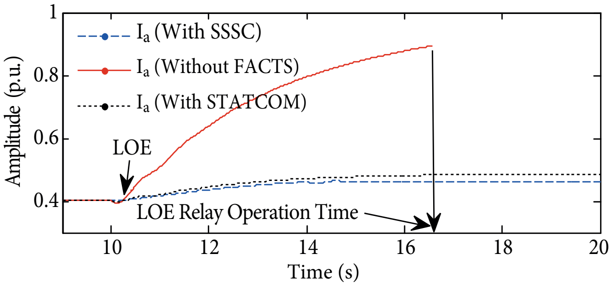

Figure 20. Generator (G1) armature current after an LOE at t = 10 s.

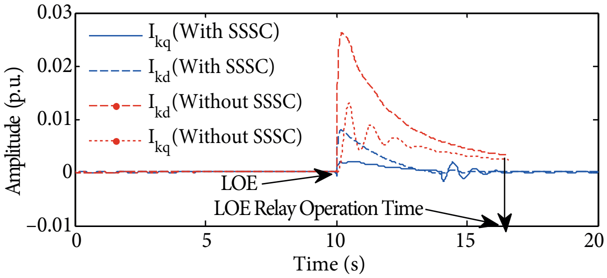

Figure 21. Generator (G1) damper winding current after an LOE at t = 10 s.

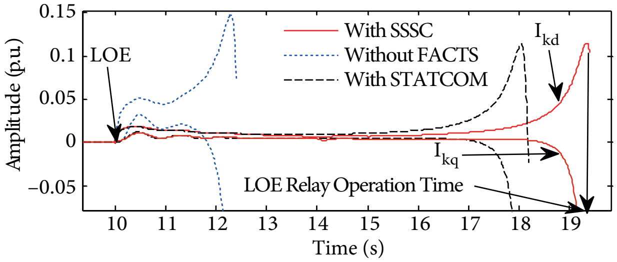

Figure 22. Generator (G1) damper winding current after an LOE at t = 10 s.

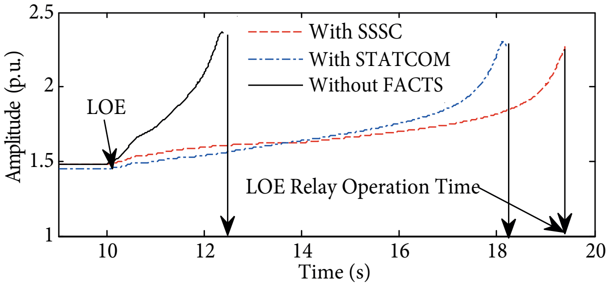

Figure 23. Generator (G1) field winding current after an LOE at t = 10 s.

6. Mitigation impact of SSSC/STATCOM on LOE protection

Different methods of reducing relay operation delay are suggested as follows:

1) Using a neural network algorithm to develop a logical relationship between the output reactive and active powers of the SSSC/STATCOM and the delay to control the relay.

2) The impedance path calculated by the relay can be expressed in terms of active and reactive power. This method can develop a relationship between two diagrams regarding the following equations (according to Figure 1) [1]:

$$R = \frac{P \times (V_R)^2}{P^2 + Q^2} \tag{8}$$

$$X = \frac{Q \times (V_R)^2}{P^2 + Q^2} \tag{9}$$

When the SSSC/STATCOM has not been added to the power network, values of P and Q will be identical to the output active (P_G) and reactive power (Q_G) of the generator, respectively. Therefore, adding a FACTS device to the transmission line reduces output powers of the generator. In other words, some part of the output powers used by the network are produced by the FACTS devices. From the viewpoint of power, it can be stated that the FACTS devices manipulate the LOE protection operation by changing the power balance. Now, knowing the reactive/active power of FACTS devices and adding it to the generator reactive/active power, one can eliminate or at least reduce the FACTS devices' effects on LOE protection. In other words, to calculate the impedance (8) and (9) can be used, where $P = P_G + P_{FACTS}$ and $Q = Q_G + Q_{FACTS}$, where P_G, Q_G = generator output active and reactive power and P_{FACTS}, Q_{FACTS} = SSSC/STATCOM output active and reactive power, respectively. Considering this method, the results of simulation for the maximum delay of Table 1 (P_{G1} = 0.5 p.u. then V_{G1} = 1.02 p.u) are shown in Figure 25. Regarding the results shown in the figure it is seen that the delays were reduced to 0.41 s (with SSSC) and 0.25 s (with STATCOM) from the initial values of 1.06 s (with SSSC) and 1.04 s (with STATCOM).

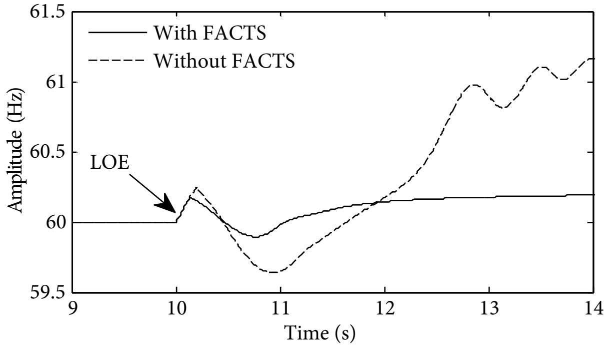

Figure 24. The frequency of Generator 1 (G1) after an LOE and tripping G1 at t = 10 s.

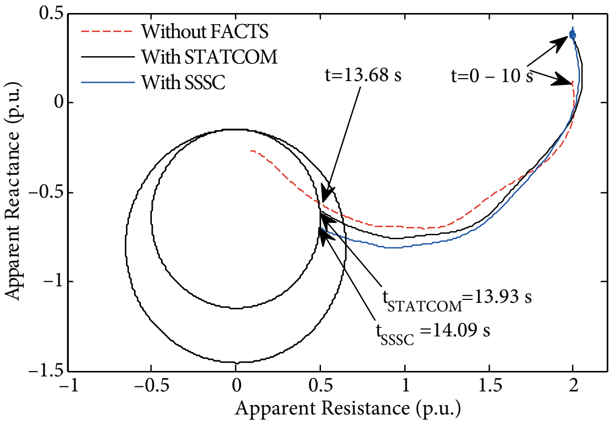

Figure 25. Apparent impedance seen by LOE relay after an LOE at t = 10 s.

7. Conclusion

In this paper, the effect of a SSSC and STATCOM on the performance of a LOE relay is investigated. The results show that the presence of a SSSC/STATCOM causes a delay in relay operation. The amount of this delay depends on the operating conditions of the power system and nominal power of the SSSC. For example, in the presence of a SSSC/STATCOM, decreasing the output active power of the generator increases the delay in relay performance. In all cases, increasing the nominal power of the SSSC/STATCOM increases the delay in relay operation. The results show that when excitation voltage is not completely short circuited, the presence of a SSSC/STATCOM causes the LOE relay not to operate. In other words, the relay experiences under-reach.

Since synchronous generator loss of excitation increases the armature current, the relay should detect LOE quickly to prevent severe damage to the armature winding. According to the delay due to series compensation, it is necessary in future research to reduce the delay using improved techniques.

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Appendix

A list of some sample system parameters are given in Table 2.

Table 2. Parameters of the generator, transmission line, and the transformer.

Component	Parameters
Generators	S_{G1}=1000 MVA, S_{G2}=1200 MVA, V_{G1}=V_{G2}=13.8 kV
	X_d=1.305, X'_d=0.296, X''_d=0.252 (p.u.)
	X_q=0.474, X''_q=0.243, X_l=0.18 (p.u.)
	T'_d=1.01, T''_d=0.053, T''_{qo}=0.1 (s)
	Rs=2.5844e-3 (p.u.), H=3.7 (s), F= 60 (Hz)
Transformers	S_{T1}=1000 MVA, 13.8/230 kV, S_{T2}=1200 MVA, 13.8/230 kV, S_{T3}=1000 MVA, 230/500 kV, S_{T4}=800 MVA, 230/500 kV
	R_1=0.002, L_1=0, R_2=0.002, L_2=0.12 (p.u.)
	R_m=L_m=500 p.u.
	T_1 & T_2: D1/Y_g and T_3 & T_4: Y_g /Y_g winding connection
Distributed transmission lines	L_1=65 km, L_2=L_3=50 km
	Line 1: Double Circuit R_1=0.068, R_0=0.284, R_{0m}=0.216, L_1=1.31e-3, L_0=4.02e-3, L_{0m}=2.43e-3 ohm/km
	Line 2=Line 3: R_1=0.0255, R_0=0.3864, L_1=0.9337e-3, L_0=4.1264e-3, C_1=2.74e-9, C_0=7.751e-9 ohm/km
Equivalent network	3-phase short circuit level=15,000 VA, Base voltage= 500 kV, X/R ratio= 10