Impact of Fixed Series Capacitors and SSSC on the LOE Protection of Synchronous Generator

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Abstract - Loss of excitation (LOE) relay is prevalently used to protect synchronous generator. The widely used method for synchronous generator LOE protection is a negative offset mho relay with two zones. The basis of this relay is identical to mho impedance relay. In other words, this relay calculates impedance by measuring voltage and current at the generator terminal. On the other hand, the presence of series compensation, changes measured voltage and current signals during loss of excitation. This paper reveals that the presence of series compensators such as fixed series capacitors (FSCs) and static synchronous series compensator (SSSC) causes a significant delay on the performance of generator LOE relay. It is also shown that the presence of SSSC causes the LOE relay to be under-reached. Different operating modes of the power system, the SSSC and also different percentages of series capacitive compensations have been considered in the modeling. All the detailed simulations are carried out in the MATLAB/Simulink environment using the SimPowerSystems toolbox.

Keywords: Generator loss of excitation (LOE) protection, Flexible AC transmission system (FACTS), Static synchronous series compensator (SSSC), Fixed series capacitors (FSCs)

1. Introduction

Synchronous generators need a controllable DC power supply for its field winding to produce the three phase voltage. Synchronous generator LOE or its significant reduction less than allowed value can cause abnormal conditions and speed deviation from synchronous speed. If this condition continues, generator will be damaged due to heating of rotor and stator [1]. Nowadays, for protecting synchronous generator excitation system, negative offset mho distance relay is used which is connected to the terminal of synchronous generator. This relay calculates the impedance using measured values by the current-transformer (CT) and the voltage-transformer (VT) connected to the generator terminal. With steady increase of consumption and load in power systems, FACTS devices technology has been considered to overcome this problem. There are various FACTS devices for different applications categorized as series, shunt and series-shunt to the power system. Since these FACTS devices change the voltage and current of the power system, they disturb the performance of protective relays which are continuously measuring voltages and currents in power system. In general, researches can be put under three distinct categories.

The first category consists of researches which investigate the effect of series FACTS devices (such as Thyristor Controlled Series Capacitor (TCSC) and SSSC) on the performance of transmission line distance relay. In [2] and [3], the effect of TCSC on transmission line protection has been investigated which the considered transmission line relay is the distance relay. Regarding the results of investigations presented in [2], it is shown that the effect of TCSC on the performance of relay depends on the TCSC mode. Investigations in [4] also show the effect of SSSC on the trip characteristics of the distance relay. This paper delineates that the zero sequence of injected voltage by SSSC divides trip characteristics of relay into two distinct parts.

The second group contains researches which tackle the effect of shunt FACTS devices (such as Static Synchronous Compensator (STATCOM) and Static VAR Compensator (SVC)) on the performance of distance relay. The effect of STATCOM on the calculated impedance by mho impedance distance relay has been shown in [5]. In this paper, steady state model is used for STATCOM and results show that the presence of STATCOM in fault loop causes the relay to be under-reached. Investigations in [6-8] show the effect of SVC and STATCOM on the calculated impedance by distance relay.

The third group consists of researches which investigate the effect of series-shunt FACTS devices on the performance of distance relay. The effect of Unified Power-Flow Controller (UPFC) on the distance protection is shown in [9]. Research results show that series part of UPFC (or SSSC) has more effects on the calculated impedance by relay rather than the shunt part (or STATCOM). The effect
2. Loss of Excitation (LOE) Relay

Loss of excitation in synchronous generator means that field winding is either short or open circuited (completely or partially). When a synchronous generator loses its field winding, it acts like an asynchronous generator which works with speed higher than synchronous speed. Under these circumstances, generator receives reactive power from power system which can dramatically reduce the system voltage. If this condition continues, the generator will be damaged due to the heating at the rotor and stator. Armature current may even reach two or threefold larger than the nominal value; so that, a separate relay is considered for synchronous generator LOE protection to prevent the damages to the generator. The relay used to detect LOE is a kind of impedance relay which is located in the generator terminal. To investigate how the relay operates, the system shown in Fig. 1 is considered. In this system, the CT and the VT of the relay are located in the generator terminal and the therein equivalent circuit of the power system is on the right side of bus-P. In the system shown in Fig. 1, one can write:

\[ \vec{E}_T = |E_T| \angle 0^\circ, \quad \vec{E}_G = |E_G| \angle \theta^\circ \]  

where,

- \( \vec{E}_T \) is the terminal voltage of the generator,
- \( \vec{E}_G \) is the generated voltage.

The basis of LOE relay is identical to mho distance relay. Both of them detect the fault by measuring the ratio of the voltages and currents.

The measured impedance by LOE relay will be as follow:

\[ V_R = E_G \angle \theta = -Z_G I_R \]  

In this case, the calculated impedance by relay equals:

\[ Z_{x,\text{rel}} = \frac{E_G - Z_G I_R}{I_R} = \frac{E_G - Z_G}{I_R} \]  

Applying (4) in (7) results in:

\[ Z_k = \frac{E_G(1 - qe^{-j\theta})}{Z_G} Z_G \]  

When LOE occurred or the generator lost its internal voltage, the \( E_G \) diminishes to become zero; therefore, in (3), \( q \) gradually goes to \( \infty \). Replacing \( q = \infty \) in (8), then \( Z_k = -Z_G \). In other words, it shows that after LOE and reducing the amount of \( E_G \) to zero (this reduction is not conducted instantly and regarding to generator’s outputs, the time is different) the amount of calculated impedance by relay equals to \( -Z_G \). According to this fact, the protection area related to LOE relay is considered in negative part of R-X diagram. This area is shown in Fig. 2. This figure shows the relay operation zones according to [1, 12-14]. These zones contain two circles. The diameter of Zone 2 is \( X'd \) and the Zone 1 has a 1.0 p.u. (generator base) diameter. Both zones have a negative offset equal to \( X'd/2 \). The 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. But the Zone 1 has immediate response characteristics.

The basis of LOE relay is identical to mho distance relay. Both of them detect the fault by measuring the
impedance. Thus, their main components are the same, too. The performance of LOE relay is as follows:

At the first step, outputs of the CT and the VT connected to the generator terminal are sampled after passing through low pass filters. The obtained samples are converted into the voltage and current phasor using phasor unit. In phasor unit, Full Cycle Discrete Fourier Transform (FCDFT) method combined with mimic filter is used. Finally, the output impedance of relay is obtained from

\[ Z = \frac{V}{I} \]

that is an imaginary value. We used the SymPowerSystems and Simulink of MATLAB to model the power system, SSSC and distance relay. To verify modeling of LOE relay the studied system in [1] is used (example 13.7). This system is shown in Fig. 3. Ancillary information to this system is given in [1]. Supposing LOE at \( t = 1 \text{ s} \) in the equivalent generator, output voltage, active and reactive power of generator are shown in Fig. 4. According to the results, loss of excitation and consequently absorbing reactive power by the generator dramatically reduces the generator voltage. The measured impedance by the LOE relay is shown in Fig. 5. The results show that the calculated impedance by the relay enters the Zone 1 at \( t = 3.304 \text{ s} \) and the relay detects the loss of excitation after 2.204 s. It can be seen that the results from our simulations are closely matched to the results presented in Ref. [1]. To further validation of the model, the relay and the power system were simulated using EMTP software. Results of simulations with EMTP are shown in Fig. 5; regarding these figures, it is shown that both the EMTP and MATLAB simulations present the same results which in conjunction with aforementioned results of Ref [1] will be an adamant verification to the proficiency of MATLAB simulations results.

### 3. Investigation and Modeling of SSSC

It has been always obvious that power transfer in long transmission lines is primarily limited due to line impedance. Series capacitive compensator was proposed several decades ago to compensate a part of inductive impedance of transmission line and consequently to increase power transfer. Recently another method has been used, called Static Synchronous Series Compensator (SSSC). This compensator contains 48-pulses converters converting DC voltage to AC voltage with appropriate switching. The obtained AC voltages are injected into the transmission line through series transformers with line. The basic difference between SSSC and FSCs is that the output voltage of SSSC can be constant for different current values of transmission line. Also, SSSC (unlike FSCs) can work under inductive mode like an inductor. The controller of SSSC is shown in Fig. 6. It calculates the reference angle according to the three phase voltage, \( V_{B1} \), and using 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 Phase Locked Loop (PLL) too. Phase shift as \( +\pi/2 \) or \(-\pi/2 \) is obtained from the feedback signal of \( V_{Re} \). 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 \( V_{Re} \) is compared to the
measured injected voltage \( |V_{inj}| \) and the amplified error is added to the synchronization signal \( \theta = \omega t \) as a correcting angle [15, 16].

4. Impact of SSSC on the LOE Protection

The single-line diagram of the system which is used for the investigations is shown in Fig. 7. In this figure, the SSSC is connected to the middle of the line. This system consists of two synchronous generators connected to each other through transmission lines. The G1 and G2 have a rating of 2100MVA and 1400 MVA, respectively. Both generators contain excitation system, hydraulic turbine, governor and PSS. The calculated impedance by LOE relay assuming loss of excitation in G1 at \( t = 10 \) s is shown in Fig. 8. It is shown that the presence of SSSC causes 0.19 s delay time in relay performance. In the simulations, the reference voltage of SSSC was set to be 0.18 p.u. and SSSC had a capacitive compensation mode. The magnitude of injected voltage by SSSC is shown in Fig. 9. According to the figure, the value of output voltage follows the reference voltage. After loss of excitation, the output voltage of SSSC is increased to its maximum value to prevent further loss of transmitted power. According the results, the presence of SSSC reduces the speed of voltage drop and causes delay in relay performance. Results for different operation modes of system and different values of SSSC nominal power are investigated and the following results are obtained:

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

2) In all the cases, increasing the nominal power of SSSC increases the amount of delay in relay operation.

In some cases, the presence of SSSC causes the relay not to operate. In other words, the presence of the SSSC causes LOE relay to be under-reached. For example, the results for \( E_f = 0.1 \) (it is not completely short circuited), \( P_{G1}=0.7 \) and \( V_{G1}=1.0 \) p.u. are shown in Fig. 10. As it is seen in Fig. 10, the relay does not detect the LOE, 90 seconds after loss of excitation. The output voltage of generator (G1) is
shown in Fig. 11. It can be seen from Fig. 11, that the presence of SSSC prevents the voltage drop and causes the relay not to detect the LOE. Results show that when generator’s output active power is less than 0.7 p.u. and also $E_f$ is between 0.1 and 1.0 p.u., the relay experience under-reach. The amount of generator’s voltage considered as 1.0 p.u. in these analysis. For smaller amounts of voltage, the $E_f$ area decreases. For example, when $P_{G1} = 0.7$ p.u. then $V_{G1} = 0.98$ p.u., the relay is under-reach when $E_f$ be between 0.16 and 1.0 p.u. The current of generator armature for $E_f = 0.1$ p.u., $P_{G1}$ & $V_{G1} = 1.0$ p.u and $V_{Ref} = 0.18$ p.u is shown in Fig. 12. It can be seen from Fig. 12 that assuming the LOE, the presence of SSSC causes the generator (G1) armature current to be overloaded for longer time and this will gradually cause damage to the armature winding.

5. Impact of FSCs on the LOE Protection

One of the most commonly used methods to increase the transmitted power of transmission line is FSCs compensation. In this section, the effect of FSCs compensation in LOE relay performance is shown. In this investigation, the studied system in [1] is used. Calculated impedance for 50% compensation when LOE occurs at $t = 1$ s, is shown in Fig. 13. Two cases are considered in this figure. In the first case, only transmission line 1 (L1) is compensated but in second case, both transmission lines (L1&L2) are 50% compensated. The output voltage of generator for both cases is shown in Fig. 14. As seen in this figure, the

![Fig. 11. Generator (G1) terminal voltage after an LOE at t=10 s.](image1)

![Fig. 12. Generator (G1) armature current after an LOE at t=10 s.](image2)

![Fig. 13. Apparent impedance trajectory calculated by LOE relay after an LOE at t = 1 s.](image3)

![Fig. 14. Generator terminal voltage after an LOE at t = 1 s.](image4)
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FSCs compensation reduces the speed of voltage drop and causes a significant delay in relay operation. The results are given in Table 1 for different operating modes and different compensation values. According to Table 1, the following results are obtained:

1) With a fixed output voltage of generator and constant compensation percentage, reducing the generator output active power, increases the delay in LOE relay operation.
2) With a fixed voltage and output active power of generator, increasing the compensation percentage, increases the LOE relay operation time.
3) With a fixed output active power of generator and compensation percentage, reducing the output voltage of generator decreases the delay in LOE relay operation.
4) Increasing the number of compensated transmission lines, increases the LOE relay operation time.

The maximum amount of delay is attained when compensation for both transmission lines is 70%, output active power and voltage of generator are 0.5 p.u. and 1.02 p.u. respectively. The calculated apparent impedance by LOE relay in this case, is shown in Fig. 15.

Similar to SSSC section, it is assumed here that the value of excitation voltage is $E_f = 0.1$ p.u. and results are shown in Fig. 16. As seen in Fig. 16, the delay is 1.93 s. Decreasing the short circuit percentage of excitation voltage, increases the delay. For example, for $E_f = 0.4$ p.u. the delay increased to 4.87 s. The calculated apparent impedance in this case, is shown in Fig. 17.

5. Conclusion

In this paper, the effect of SSSC and FSCs compensation on the performance of LOE relay is investigated. The results show that the presence of SSSC causes the delay in relay operation. The amount of this delay depends on operating conditions of power system and output rating of SSSC. In all the cases, increasing the nominal power of SSSC increases the delay in relay operation. The results show that when excitation voltage is not completely short circuited, the presence of SSSC causes the LOE relay not to operate. In other words, the relay will be under-reach. Also in this paper, the effect of FSCs compensation in relay performance is investigated. The results show that increasing the compensation percentage, increases the amount of delay. Since synchronous generator LOE increases the armature current, the relay should detect LOE quickly to prevent the severe damage to the armature winding. It is necessary that the delay resulted from series compensation to be reduced by using improved techniques.

References


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