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An Investigation of a New Method to Detect Loss of Excitation of Synchronous Generators

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ABSTRACT

Synchronous generators are one of the most important components of power systems. Problems a generator may face are internal faults, system disturbances, or operational hazards. The operation of a generator may easily be affected by faults within the machine itself as opposed to external disturbances occurring on the network to which it is connected. Generator protection must therefore be designed to react efficiently in both conditions. Loss of excitation (LOE) is a common fault in synchronous generators. The most common causes of LOE include the loss of field to the main exciter, accidental tripping of the field breaker, short circuits in the field circuit, and poor brush contact in the exciter. The most widely applied method to detect a generator loss of field condition on major generators is the use of distance relays to sense the variations of impedance as viewed from the generator terminals. This approach may not be able to distinguish between LOE and stable power swing (SPS). This paper further explores a new method proposed for LOE detection and corrects its shortcomings. It also presents a new approach for LOE detection that exploits a combined scheme based on the derivative of the terminal voltage and the derivative power angle of the generator. Comprehensive simulation studies are conducted on various generator conditions and system disturbances to determine the relay setting and to evaluate its performance. These studies demonstrate that the proposed strategy enhances the security and operation time of the LOE relay compared with some existing methods.

Article Info

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Detection, LOE relay Loss-of-excitation (LOE) fault, Stable Power Swing (SPS), Synchronous generator.

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I. INTRODUCTION

A. An Introduction to Power Systems

Secure and fast protection of a power system's components should be ensured to isolate the faulted area, minimize its effects on the nearby areas, and maintain system stability. The problem of the stability of a power system has been considered by electrical engineers in recent years. Increasing loads and deregulating a power system make the power system more complex than ever. Major blackouts due to power instability indicate the importance of this issue [1]. Due to the continuing growth of power systems such as in interconnections, use of new controls and technologies, and so on, different forms of system stability have emerged. Voltage stability and transient stability have become more problematic than in the past [1]. To prevent major blackouts such as August 2003's blackout in the northeast of the United States and August 1996's blackout from a western connection in North America that cost billions of dollars [2]-[5], real-time monitoring tools require the operator to take prompt action to correct problems.

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B. Motivation and Problem Description

The loss-of-excitation (LOE) condition of a generator in a power system may be caused by faults or unexpected problems in the automatic field voltage control in synchronous generators. A generator may completely or partially lose its excitation due to casual field breaker tripping, field open circuit, short circuits in the field winding, poor brush contact in the exciter, field circuit breaker latch failure, voltage regulator failure, or loss-of-excitation system ac-supply [3]. The LOE fault is mostly minor, but in very rare cases, a stimulus may be completely eliminated in a synchronous generator. LOE causes the generator to absorb a large amount

of reactive power from the power grid. Also, it causes the machine speed to go above the synchronous speed in which case the machine will start to operate like an induction generator, [6]-[14]. Due to LOE, the generator will start to consume reactive power in a very large amount from the power system, and this will result in a voltage drop.

This means an increasing reactive power demand on the neighboring system near the LOE generator. It also reduces the terminal voltage of the generator. LOE condition at a large generator, e.g. major fossil plants, can drag down nearby voltage of the system very fast and jeopardize the voltage stability of the rest of the power system. This can have a very serious impact on the power system if the system is not stable enough. A large increase in reactive power causes an increase in the stator currents, resulting in an overheating rotor, thermal heating in the rotor windings, loss of magnetic coupling between the rotor and the stator, and large voltage drop in the transmission system [5]-[14]. Therefore, it is necessary to identify the LOE fault on the synchronous generator in a power system as soon as possible. Furthermore, the effect of LOE on the stability of the power system and voltage stability must be determined in order to avoid voltage collapse.

Also, the loss of excitation causes the stator to overload and the rotor to overheat. The worst-case scenario for generator excitation is when the generator has a heavy load in which case there will be a higher probability of synchronization disappearing because the system impedance will be lower despite the high load and the final slip frequency of the system will be reduced [15]. During light loads, the generator may not lose synchronism and will operate as a synchronous generator depending on the principle of reluctance [16]. There is no determined time length the generator can operate without excitation [15], but to avoid possible voltage collapse resulting from reactive power demand and machine damage, secure fast and dependable LOE detection methods are required [17].

C. Literature Review

The conventional detection method, which is based on impedance measurement to detect LOE, is the most popular technique for LOE detection. The impedance scheme is the most utilized scheme for LOE detection. During an LOE event, Zones 1 and 2 are for detecting LOE with a full load and a light load, respectively. In other words, during heavy loads, the impedance trajectory enters the operating area faster than light loads. Also, Zone 2 is considered to be the backup of Zone 1, and during power swings, there is a high probability for the entrance of the impedance trajectory into Zone 2. When the measured impedance falls into the operating region, the relay function is picked up and, after a certain time delay to enhance the security of the power swing, a trip signal is sent to the generator's main breaker. The offset of the protection zones from the principle of the impedance plane is half of the transient reactance (X'_d /2). Two methods of LOE detection are presented in the SEL-300G relay manual [18]. These two cases are shown in Fig. 1.

$X_d \equiv$ Generator direct-axis reactance

$X_s \equiv$ The sum of the step-up transformer reactance and system reactance

$X' \equiv$ Generator transient reactance

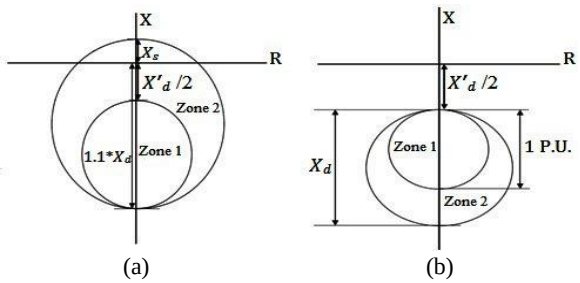


Fig.1. Loss-of- excitation protection: (a) positive-offset mho element and (b) negative-offset mho element

The conventional method shows mal-operation during severe stable power swing (SPS) conditions; for instance, a severe fault near the generator [15]. It was reported in a NERC technical reference document that 13 out of 290 generator tripping resulted from LOE mal-operation during such disturbances [17]. Besides, the additional elements can be introduced to implement the protection function, such as directional element, under-voltage element, over-current element, minimum excitation limit, steady-state stability limit, etc.

What is certain is that conventional methods are unable to detect SPS. Therefore, methods should be created that do not have the problems of impedance methods. The techniques used to detect LOE are described in Section 2.

II. LOSS OF EXCITATION FAULT

A .Techniques Proposed

As discussed in Section 1, the conventional method is not reliable during SPS conditions. In addition, it requires a time delay that results in more stress in the generator and the network. Therefore, other techniques have been proposed to eliminate these pitfalls. In [15], a new method of LOE detection is introduced based on the fuzzy set theory. It depends on the concept of the conventional LOE detection method, which relies on the variations in the terminal voltage and apparent impedance. This method works when the voltage range is between 0.5 and 0.8 p.u, so if the system is strong, it will not work. Its performance depends on the strength of the system and a lot of data is required.

A setting-free approach to detecting LOE of a synchronous generator is presented in [18]. This approach does not need threshold settings, so it does not depend on system parameters. This approach relies on the resistance variations because it has

a fixed polarity during LOE (it remains negative). This method discriminates between LOE and a disturbance by setting a time delay before tripping. The performance of the method is evaluated during peak hours, off-peak hours, and disturbances for a 2-bus system. The results show that it is faster than the conventional method. In [19], a new strategy is presented to detect a synchronous generator's LOE. This method depends on the value and duration of voltage and reactive power amount.

Its performance has been compared with the conventional method and the proposed method in [15] for different loading conditions, generator ratings, and system configurations. The index presented in [19] has difficulty discriminating between SPS and LOE. Also, a solution is presented in [20]. The discrimination between SPS and LOE is based on the variations in the fast Fourier transform coefficient of the three-phase active power at the relay location. Therefore, the delay associated with the other methods is avoided through an additional threshold value. The second threshold is the active power based on the FFT coefficient. When the indicators are calculated and they exceed two threshold values, the LOE fault is detected; otherwise, it shows an SPS condition on the grid. There are several techniques based on magnetic flux variations in the air gap ([21], [22]), but these techniques have been criticized because, to measure the machine flux, the search sensors coil should be utilized but there is, naturally, no desire to install it due to the damage to the generator [20]. A new method based on PMU measurement in the presence of flexible alternating current transmission systems (FACTS) is presented in [23], but this method needs measurement synchronization and lots of information. The algorithms presented in [18] and [20] start their calculations with the initial condition that the terminal voltage of the machine is less than 0.95 p.u. When the system is strong or there are several generators on the same bus, the generator's terminal voltage does not reach 0.95 or less. This indicates that the calculations are not started by the algorithm and LOE will not be recognized. Also, these methods have not been studied in a larger system.

B. Contribution

This paper presents an event to find LOE occurrence and distinguish it from SPS. The proposed approach detects the LOE event using the rate of variations in the generator's terminal voltage and output angle power. The proposed method is investigated for different conditions and parameters. It is examined by considering various parameters of the generator, system disturbances, and the structure of the system under the existing conditions. Also, according to the studies, a comparison is made to identify two SPS and LOE approaches. In the second part, the strategy of the proposed method for LOE detection is discussed. Also, the concept of strategy and its algorithm are explained in this section. In Section 3, the studied system and its components include different parts of the generator and loads based on the proposed strategy. The proposed index identifies faults based on the relevant algorithm and according to the simulation. Section 4 addresses the concluding points of the proposed method.

C. Synchronous Generator Modeling for LOE Transient Analysis

Synchronous generators supply almost all the electric power we consume today. The rotor of a synchronous generator needs to be driven by a source of mechanical power or a prime mover and the field winding needs to be fed by a source of DC power to provide active and reactive power to the power system. These exclusive combinations of electrical and mechanical equipment need to be protected against different kinds of faults. Generator faults are always considered to be serious since they can cause severe and costly damage to insulation, windings, core, shafts, and couplings [1]. Generally, there are two types of excitation systems – rotating and static. Rotating systems use a dc or an ac generator as the source, but static systems apply rectifiers as sources that are directly fed from the generator terminals via a step-down transformer. Today, most excitation systems are ac or static types because of their fast response capability. When a generator loses its excitation, the rotor current gradually decreases and the field voltage decays by the field time constant as well. As mentioned in the previous section, in this case, the generator operates as an induction generator and draws reactive power from the power system instead of generating reactive power.

Considering the generator active power output equation:

$$Pe = \frac{Eq.Us}{Xd+Xs}\sin\delta \quad (1)$$

where P_e is the active power output to the system, E_q is the generator internal voltage behind the d-axis synchronous reactance, Us is the equivalent system voltage, X_d is the d-axis synchronous reactance, X_d is the system impedance, and δ is the angle between E_q and U.

The active power output is proportional to the system voltage, the generator internal voltage, and its sine. As the generator internal voltage E_q is a function of field voltage, the generator active power output is a function of field voltage as well.

In the steady-state, the operation point is the point where the mechanical power input equals the electrical power output. When the mechanical power increases, the load angle δ increases. The maximum mechanical power can increase until the load angle reaches δ=90°, after which the mechanical power will be greater than the electrical power and the generator will lose synchronism as there is no equilibrium point between mechanical power input and electrical power output. For the same reason, when the mechanical power input is fixed and the maximum electrical power output

decreases due to the field voltage reduction, the load angle δ increases as the intersection of mechanical power and electrical power moves up to the peak. The generator electric power output versus the load angle is shown in Fig. 2.

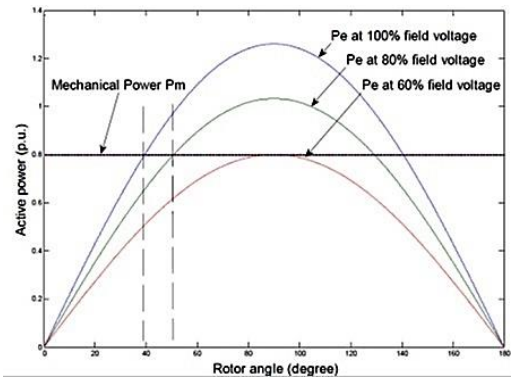


Fig. 2. Generator active power – angle diagram

When a generator operates at δ =90°, any increase in mechanical power or decrease in electrical power will lead to the generator's loss of synchronism. As a result, the generator will operate asynchronously as an induction machine, typically with a 2% to 5% slip, and will draw the reactive power from the system for the excitation instead of generating reactive power to the system [24]. Normally, a generator's field voltage cannot be measured directly, so to detect the LOE, the protection scheme applies the generator's terminal voltage, current, power angle, active power, or reactive power output as the input value and calculates the generator characteristic values to determine the LOE fault.

III. GENERATOR CAPABILITY LIMITATION

A. Generator Capability Curve

First of all, the generator capability is limited by the rated MVA, which represents the generator maximum continuous output in the steady-state without overheating. However, concerning the voltage stability and long-term stability, it is essential to consider the reactive power capability which is limited by field current limit, armature current limit, and stator end region heating limit [25]. The generator thermal limits are shown in Fig. 3.

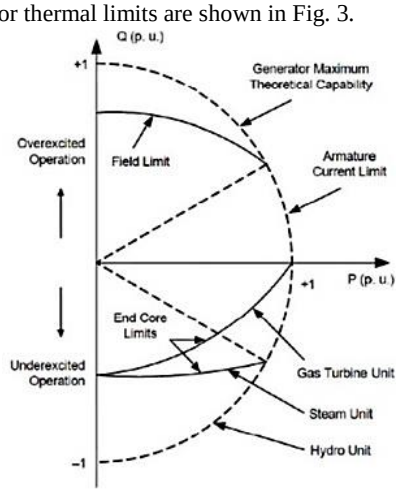


Fig.3. Generator operation thermal limits [26]

B. Dynamic Performance of a Synchronous Generator during LOE

The field circuit of a synchronous generator needs to be excited by a direct current supply in order to keep the generator in synchronism with the power grid and to keep the voltage constant. Basically, synchronism between the power system and the generator is maintained due to the interaction of fluxes produced by the stator and rotor windings [27]. Excitation can be provided in many ways including rotating dc exciters with commutators, rotating alternator rectifiers, or static supplies. Power and torque pulsation due to the LOE conditions will be more severe in a generator with a rectifier bridge supply than in a generator supplied by a dc exciter [28]. After LOE occurs, a decrease in the field current will reduce the electromagnetic torque, while the mechanical torque from the prime-mover cannot change immediately, thus the rotor will accelerate. Under such a condition, the generator speed will be above the synchronous speed and the synchronous generator will operate as an induction generator. Due to the slip between the rotating magnetic fields of the stator and the rotor, ac currents are induced in the field winding body and damper windings [27]. Because of the reactive power drawn by the LOE generator, the system voltage is immediately reduced while the armature current of the generator is increased [29]. Under such circumstances, disturbance in the power system would take place.

Since the rotor of large turbo-generators is not laminated, instead of being machined from a steel alloy forging, under an LOE condition, substantial heat will be generated by eddy currents [27]. Excess rotor heat is likely to affect the integrity of the field windings, insulation, wedges, or retaining rings [28]. Damage to the generator may occur in a timescale of between 10 seconds and several minutes.

A generator converts mechanical energy into electrical energy, so the input power is the mechanical prime mover, e.g. diesel engine, steam turbine, water turbine, and so on. Regardless of the prime mover type, the rotor velocity must remain constant to maintain a stable system frequency. The transient analysis of a synchronous machine is thus concerned with determining transient fluxes and currents and their influence on the electrical and electromechanical behavior of the machine.

The electromechanical equation for a synchronous generator follows directly from equating the inertia torque (equal to the moment of inertia j times the angular acceleration) to the net mechanical and electric torque acting on the rotor. Thus, we have

$$\mathrm{j}\frac{\mathrm{d}^2\theta}{\mathrm{d}^2\mathrm{t}} = \mathrm{T}_{\mathrm{mech}} - \mathrm{T}_{\mathrm{elec}} \qquad (2)$$

where

θ= the angular position of the rotor

T_{mech} = the mechanical accelerating shaft torque applied to

the rotor

T_{elec} = the electromagnetic torque acting to decelerate the rotor

The equation, like those that follow, is written with a certain generator in mind.

It is often convenient to express the rotor angular position $\boldsymbol{\delta}$ in terms of a synchronous rotating reference frame as

$$\theta = \frac{2}{\text{poles}}(\omega t + \delta) \tag{3}$$

where ω is the synchronous electric frequency and δ is the electrical angle between a point on the rotor and the synchronous reference frame. δ is often taken equal to the synchronous-machine power angle, so, Eq. (4) becomes as follows for a generator with two poles:

$$j\frac{d^2\delta}{d^2t} = T_{mech} - T_{elec} \tag{4}$$

Known as the swing equation, it can be solved for the electromechanical dynamics of the synchronous machine. The key to its use is the accurate representation of the torques acting on the rotor. The mechanical shaft torques must be determined from a representation of the dynamics of the prime mover (or load in the case of a motor).

Since this model results in an expression for electric power output (4) as a function of the rotor angle, it is convenient to rewrite Eq. (5) in terms of power. This can be done by multiplying by the rotor mechanical velocity ω_m.

Since for most situations of practical interest, deviations of ω_m from synchronous speed are very small, ω_m can be replaced by the synchronous rotor velocity $\omega_s = (2/poles)\omega$, giving

$$j\omega_s\frac{d^2\delta}{d^2t} = P_{mech} - P_{elec} \tag{5}$$

In the LOE condition, the load angle (i.e δ) fluctuates and reaches the maximum and then decreases. It, then, shows that the power system is stable. At that moment, due to the inherent permanence of the power system, the derivative of the load angle ($d\delta/dt$) is zero. As a result, the fluctuations will be smaller and smaller. It should be noted that while the load angle is different, if the derivative of the load angle ($d\delta/dt$) is zero at a certain moment, stability will be guaranteed. If the load angle increases indefinitely, it will imply that the power system is unstable. To find the derivative of the load angle ($d\delta/dt$), both sides of (6) with $d\delta/dt$ are multiplied as follows:

$$j\omega_s\left(\frac{d^2\delta}{d^2t}\right)\frac{d\delta}{dt} = (P_{mech} - P_{elec})\frac{d\delta}{dt} \tag{6}$$

or

$$\frac{1}{2}j\omega_s\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 = (P_{mech} - P_{elec})\frac{d\delta}{dt} \tag{7}$$

Using Eq. (7) and performing some trigonometric derivatives and integrating, the derivative of the load angle can, finally, be found as follows:

$$\frac{d\delta}{dt} = \sqrt{\int_{\delta_0}^{\delta}\left(\frac{2}{j\omega_s}\right)(P_{mech} - P_{elec})d\delta} \tag{8}$$

Before LOE occurs, δ_0 is the load angle and at this time $d\delta/dt=0$. As soon as LOE happens, $d\delta/dt$ is no longer zero, and the load angle changes. When $d\delta/dt=0$, i.e., the load angle stops and the generator operates in a new stable condition with motor performance.

$$\frac{d\delta}{dt} = \int_{\delta_0}^{\delta}\left(\frac{2}{j\omega_s}\right)(P_{mech} - P_{elec})d\delta = 0 \tag{9}$$

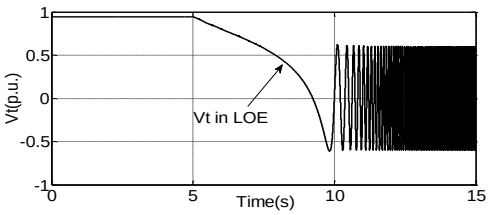
It should be noted when $d\delta/dt = 0$, the synchronous generator will not stay at rest with a connection to the power system at the first time. However, according to balancing available in the power system, the maximum load angle is reduced during the subsequent fluctuations. That is, the power system is stable and the generator will achieve a new operating point with the motoring function often known as the swing equation, it can be used to solve for the electromechanical dynamics of the synchronous-machine. The key to its use is the accurate representation of the torques acting on the rotor. The mechanical shaft torques should be determined from the presentation of the dynamics of the prime mover (or the load in the case of a motor).The basic electromechanical equation, the so-called swing equation, states that the product of a rotor moment of inertia times its angular acceleration is equal to the net torque applied to the rotor (mechanical shaft torque and electromagnetic torque). Under steady-state conditions, the net torque is zero and the rotor remains at constant (synchronous) speed. Transient analysis is performed to investigate the nature of the transients resulting from a disturbance and whether or not the stable steady-state operation will be reestablished.

C. The Proposed Strategy Concept

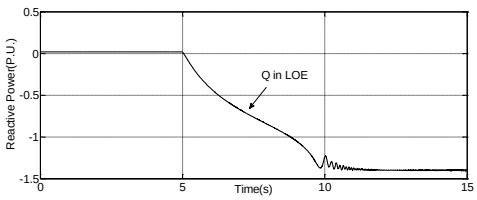
When LOE occurs, due to the mechanical inertia, the mechanical input and load angle keeps constant temporarily. The reactive power output decreases to zero quickly and the generator starts to import the reactive power from the system. The generator's internal voltage decays because of the field voltage reduction, and the phase current goes up due to a large amount of reactive power imported. As already mentioned under LOE conditions, a synchronous generator will continue providing pulsing active power and draw a large amount of reactive power from the grid, which can jeopardize the system's voltage stability [30].

After a short-circuit fault on the generator's excitation winding terminal, which leads to LOE, the dc current flowing through the excitation winding disappears. Therefore, the output voltage of the generator slowly decreases, as shown in Fig. 4(a), and LOE occurs in 15 s. In such a situation, the generator starts to absorb reactive power from the grid, and the

reactive power of the generator begins to decrease. Consequently, the signals derived from the terminal voltage and reactive power are the same (Fig. 4(b)). In addition, the speed of the generator is increased and this will increase the power angle (δ). The load angle variations and speed are depicted in Figs. 5(a) and (b) after LOE occurs.

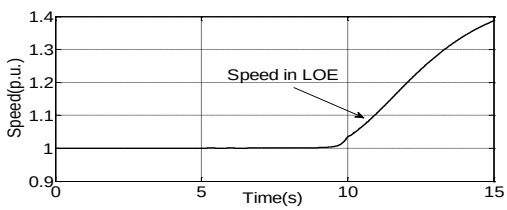


(a)

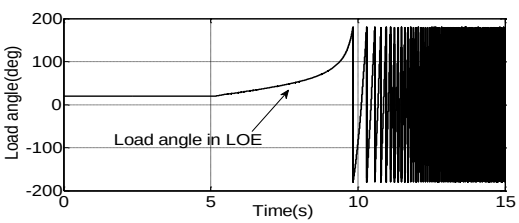


(b)

Fig.4. The generator's terminal voltage and Q after LOE



(a)



(b)

Fig.5.The generator's speed and load angle after LOE

If the voltage changes in two consecutive, samples of this quantity will be equal to:

$$\Delta V = V_k - V_{k-1} \quad (10)$$

In addition, the value of dv/dt is significant, even for a relatively long time after the LOE event.

In this case, after the LOE event, the output voltage of the generator gradually decreases, and ΔV becomes negative. Also, we will have for δ after the LOE event:

$$\Delta\delta = \delta_k - \delta_{k-1} \quad (11)$$

According to Figure 4(a), it can be said that after the LOE event, the value of Δδ is positive and it will increase. Also, dδ/dt is positive.

With the multiplication of derivatives of the two sides (1) and (2), we will have:

$$\Delta V * \Delta\delta = (V_k - V_{k-1}) * (\delta_k - \delta_{k-1}) \text{ and:}$$

$$(dV/dt) * (d\delta/dt) = (d(V_k - V_{k-1})/\mathrm{dt}) * \left(\frac{d(\delta_k - \delta_{k-1})}{\mathrm{dt}}\right) \quad (12)$$

It should be noted that the terms $(V_k - V_{k-1})$ and $(\delta_k - \delta_{k-1})$, respectively, represent the derivatives of the terminal voltage and the rotor angle, respectively. Regarding the voltage and load angle variations, in the LOE event, Eq. (12) indicates an index in that the direction is negative and its value is increasing. By applying the changes in Eq. (12), which is considered as Loss of Excitation Detection Index (LOEDI), is obtained as below.

$$\text{LOEDI} = K_G * ((dV/dt) * (d\delta/dt)) \quad (13)$$

Various permutations of the electrical quantities are multiplied to one another for better detectors as expressed in Eq. (3). K_G is an amplified quantity to increase the detection index value and it depends on the index parameters and $k_G = 10^5$. If the calculated index is larger than the specified threshold *Th* for five samples, the LOE event will be detected. The LOE relay function depends on the *Th* settings. The function of this logic is that after starting the algorithm if the value of the LOEDI increases from *Th*, one unit is added to the Loss Of Excitation Detection Counter (LOEDC); otherwise, it will be reduced by a unit. If the LOEDI value reaches the final value (N), LOE occurs and the relay trip signal is issued. The parameter *N* represents the maximum value of the LOEDI to ensure the occurrence of LOE.

C. Strategy Algorithm

Fig. 6 shows the flowchart of LOE detection to calculate the initial values where terminal voltage, apparent power, and power factor are given as inputs. Then, the load angle (δ) of the machine can be calculated. Generator terminal voltage decreases after LOE due to the short circuit or open circuit in the excitation winding. Therefore, the voltage of 0.95 per-unit is considered a fault. After the fault detection operation, the terminal voltage of the generator is first determined. Subsequently, the generator power angle changes are specified. Given that this algorithm uses the derivative of sample signals from the voltage and rotor angles, we use a low-pass filter to eliminate negative fluctuations to obtain the indicated signals. Using this method, it accurately distinguishes LOE and Sustainable Power Swing (SPS). To calculate *Th*, the following should be considered. Due to the fact that the rotor voltage and power angles are almost constant and do not

change under normal generator conditions, the LOEDI changes are negligible.

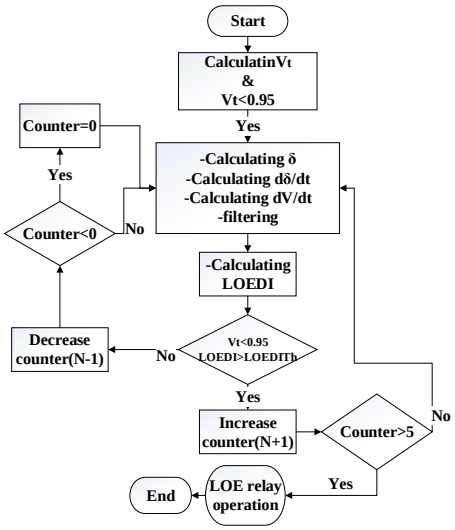


Fig.6.The flowchart of the proposed LOE relay

In addition, the simplified trip logic diagram on the LOEDI index is shown in Fig. 7.

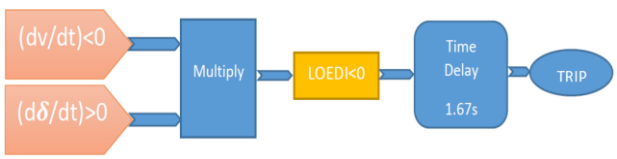


Fig.7.The Trip logic for LOEDI

Eventually, the phase angle of the generator's internal voltage remains positive in half of the period depicted. According to [31]-[37], the power system swing frequency range is 0.3-7 Hz. In this paper, the minimum value (0.3 Hz) will be considered as the network swing frequency. The longest time period for the expected angle oscillation is then 1/0.3 s or 3.33 second as shown in Fig. 8. The delta variation will change its polarity after half a cycle or 1.67s.

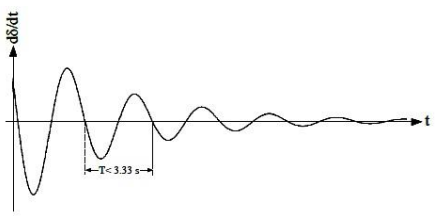


Fig.8. The dδ/dt oscillations during the slowest power swing [31]-[36]

IV. Evaluation of the Proposed Strategy

Given that the amount of LOEDI may depend on the configuration of the generator's power system and output power, different items will be studied in the following sections. Table 1 presents the different loadings of the generator for simulation conditions. Simulation with different loads and under the conditions of complete interruption of LOE excitation and reduction of PLOE excitation in MATLAB/SIMULINK software has been done completely.

TABLE I

The Loadings of the Generator

Loading (p.u.)							
S=P+JQ P.U.							
L1	0.1+j0.2	L5	0.5+j0.4	L9	0.9-j0.2	L13	0.5-j0.6
L2	0.1+j0.3	L6	0.7+j0.2	L10	0.7-j0.5	L14	0.3-j0.6
L3	0.3+j0.4	L7	0.8+j0.4	L11	0.6-j0.4	L15	0.3-j0.4
L4	0.3+j0.5	L8	0.9+j0.3	L12	0.5-j0.2	L16	0.1-j0.2

A.Case Study

The studied network is a single machine infinite bus (SMIB) shown in Fig. 9. The full power network data is presented in [23]. The simulation model includes a salient-pole generator 250 MVA connected to a common bus via connection step-up transformer. The common bus connects to the infinite bus via a 100-km transmission line. The transformer's primary side voltage is 20 kV and its secondary side voltage is 230 kV. The generator model comprises a synchronous generator, a hydro turbine with a governor, an automatic voltage regulator (AVR), and a power system stabilizer (PSS). The exciter used in the model is a static exciter that is a standard IEEE type ST1A. The power supply for the exciter is obtained from the generator terminal voltage via a step-down transformer and controlled rectifier. In this type of exciter, the inherent time constant is very small and it can operate without a stabilizer [32]. But in this model, PSS is implemented to accelerate the stabilization.

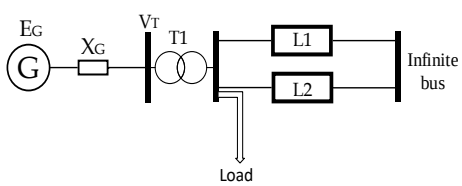
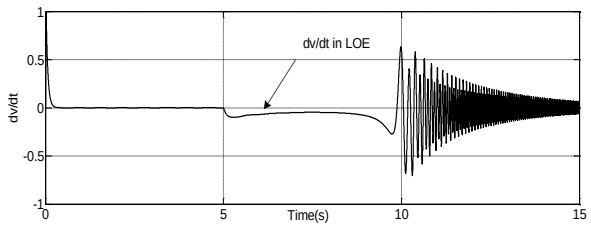
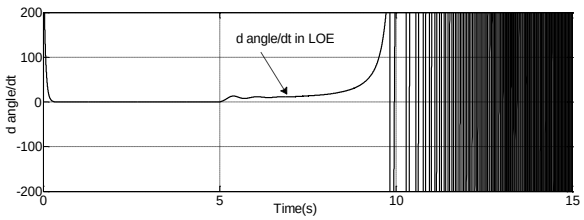


Fig.9. The simulated system to investigate the performance of the LOE detection methods

The generator data and control system data are listed in Appendix A. In this case, based on the mentioned model, the simulation was performed according to the system specifications. After the LOE event, the signal generated by the voltage and the power angle derivative are shown in Fig. 10(a) and (b). This figure shows that after the LOE occurs, the output voltage decreases, and the power angle output increases. The signal generated by the voltage is negative while the power angle signal is positive. The main idea is to use the index mark to detect the error after simulating the analysis based on the positive or negative signals after the LOE occurs. The simulation is performed in 15 seconds and after 5 seconds of the threshold.



(a)



(b)

Fig.10. The generator's derivative terminal voltage and derivative angle power after LOE

One of the main outputs of the simulation is the LOEDI index. Fig. 11 shows the LOEDI after the LOE occurs. The positivity or negativity of the index is considered a very important parameter. The LOEDI value is, initially, zero before the LOE occurs and its value is negative after the LOE occurs. As a result, if the index is negative, an LOE has occurred. The LOE relay must operate and issue a stop command.

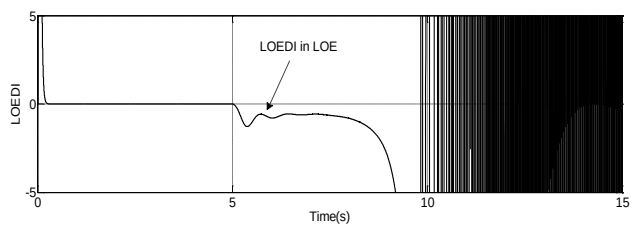


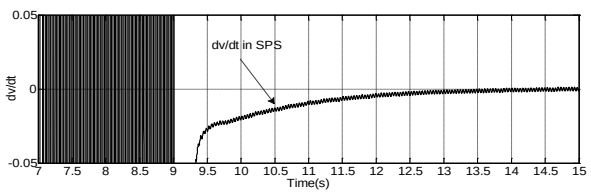
Fig.11. LOEDI after LOE

Next, the algorithm performance is tested under swing conditions since this is the main reason behind conventional relay mal-operation. A stable power swing is defined as an oscillatory disturbance that is controlled by the power system. After the disturbance is removed, the system will remain stable. For example, a fault on any line within the system that is cleared after a designated time will potentially give rise to an SPS.

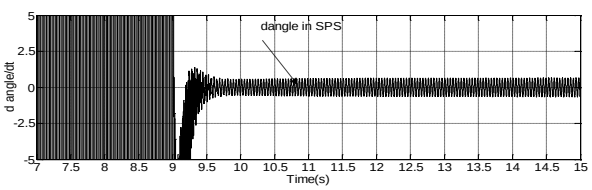
For security evaluation of the proposed index, non-loss of field disturbances was applied to the simulated system. There were no trip commands generated, so the index can be considered a secure index. The proposed algorithm can correctly identify the LOE event. Since the LOEDI index depends on power system parameters, such as generator power, output power, and power system, if a short-circuit fault occurs and a stable power swing (SPS) is generated, the simulation results show that in the event of SPS, the LOEDI will be swinging.

In this case, if the generator is fully excited, a three-phase short circuit to the ground fault will occur within 2 seconds (in 7 s to 9 s). The simulation was performed for 15 seconds with a 5-s threshold. After a 1.67-s delay (10.67 s), the derivative of the voltage will be negative and fluctuate, and the power angle derivative will have low-amplitude oscillations; consequently, the magnitude of their increment, which is the LODEI index, will also be positive. A stable power swing is defined as an oscillatory disturbance that is controlled by the power system. After the disturbance is removed, the system will remain stable. For example, a fault on any line within the system that is cleared after a designated time will potentially give rise to an SPS.

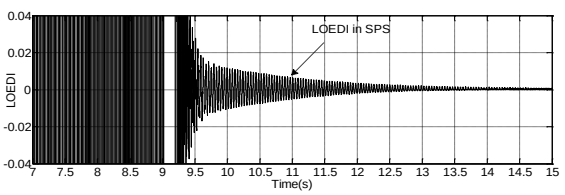
In Fig. 12(a)-(c), the derivative of the voltage, the derivative of the power angle, and the LOEDI index are shown when the SPS occurs. The value of the LOEDI index is zero before the fault. Therefore, the index after oscillation will occur after 1.67 seconds (in 10.67 s). By changing the sign from positive to negative in a half-cycle, we realize that no LOE has occurred. Therefore, if this indicator is not negative, an SPS has occurred and the LOE relay will not give a trip. This will be a way to distinguish between the two errors (LOE and SPS).



(a)



(b)

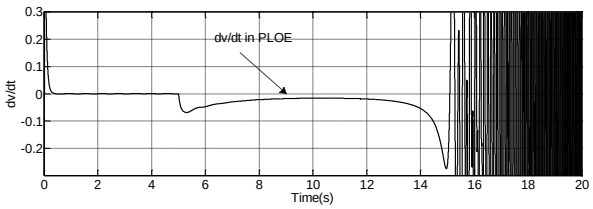


(c)

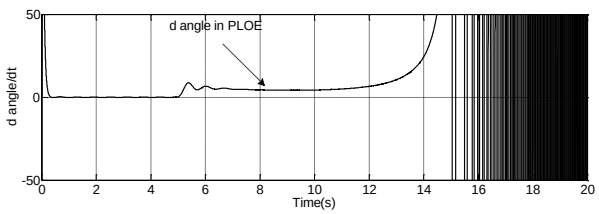
Fig.12. The generator's derivative terminal voltage, derivative angle power, and LOEDI after SPS

By reducing the generator excitation, we repeat the simulation and check the output of the output signals. For example, suppose that the generator excitation is reduced to

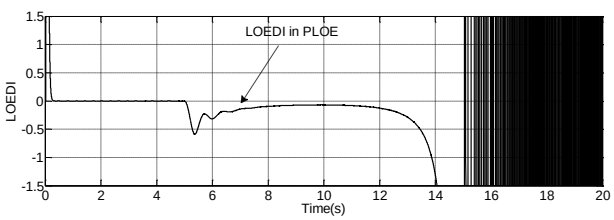
0.4 p.u. (PLOE). According to the simulation outputs, we conclude that the voltage derivative in this case is negative and the power angle is positive. The corresponding index will also be negative. This result is similar to when the generator has full excitation. It detects and operates the error rate after 1.67 seconds. Figs. 13(a),(b),(c) present the simulation results. The behavior of the generator shows that the index detects the LOE error and cuts off the command relay correctly and in the shortest time in PLOE mode. The simulation is performed in 20 seconds and after 5 seconds of the threshold.



(a)



(b)



(c)

Fig.13. The generator's derivative terminal voltage, derivative angle power, and LOEDI after PLOE

Whether the index is positive or negative is considered a very important parameter in determining the LOE. Initially, the value of the LOEDI indicator is zero before the PLOE occurs, and the LOEDI value is negative after the PLOE occurs. Therefore, the index is similar to the time when the LOE occurs in the previous section. As a result, if the index is negative, an LOE has occurred. In this case, the LOE relay must act and issue a stop command. Therefore, in the PLOE mode, the LOEDI indicator correctly detects the LOE event and commands the LOE relay to prevent damage to the generator. Similar to this case, with a reduction in excitation to 0.4 p.u. (PLOE), the road performance will be the same as the previous part of LOE.

In the next case, we examine the behavior of the generator under heavy load conditions. Given that the generator is under a lot of stress in these conditions, it is crucial to detect the fault in the shortest possible time. The simulation is done with the previous specifications. According to Table II, different simulated loads and the LOEDI index signal were investigated in two modes (LOE and PLOE). The results are shown in Fig. 14.

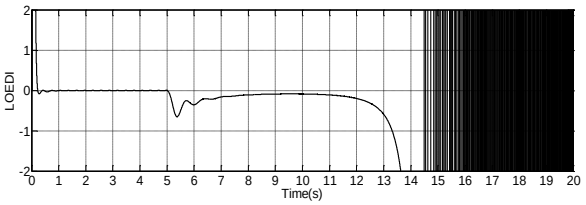


Fig.14. LOEDI after LOE and PLOE in the heavy load case

Fig. 14 shows that the system will oscillate in 9.6 seconds in the LOE mode, as well as in PLOE mode after 13.6 seconds. Simulation with different loads indicates that the proposed algorithm will operate without error affecting the behavior of different loads in LOE detection and will operate after 1.67 seconds if the index is negative.

Examining different modes under heavy and light load conditions in both LOE and PLOE conditions (0.2,0.4) are presented in Table 4. The simulation results indicate that the type of load in the fault detection is not affected by the LOEDI index and the index is independent of the load. It also detects LOE by reducing the excitation by 20% and 40% with different loads of the proposed algorithm. One of the important features of the index is the detection of partial reduction of excitation.

TABLE II

Supplementary Data of the Simulated Generator

Type of Loading (P.u.)		P.F	Mode of LOE
Heavy loading	L8=0.9+j0.3	Laging	LOE,EF=0
			PLOE,EF=0.2
			PLOE,EF=0.4
Heavy loading	L10=0.7-j0.5	Leading	LOE,EF=0
			PLOE,EF=0.2
			PLOE,EF=0.4
Light loading	L2=0.1+j0.3	Laging	LOE,EF=0
			PLOE,EF=0.2
			PLOE,EF=0.4
Light loading	L16=0.1-j0.2	Leading	LOE,EF=0
			PLOE,EF=0.2
			PLOE,EF=0.4

V. COMPARISON OF THE PROPOSED METHOD WITH OTHER LOE DETECTION METHODS

The performance of the LOE-DVA method for the case study synchronous generator, loading at S= 0.5-j0.4 p.u [33], was evaluated and compared with the following methods.

- Positive offset
- Berdy
- LOE protection based on fuzzy inference mechanism (LOE-FIM)
- LOE protection based on flux method (LOE-FBM)
- LOE protection based on flux method combined with negative sequence current (LOE-FVNSC)
- LOE-TDFM

The results are presented in Table III.

TABLE III

The Comparison of Different LOE Detction Methods

Relay type	Trip Time(s)
Positive Offset	11.2s
Berdy	10.4s
LOE-FIM	9.1s
LOE-FBM	3.1s
LOE-FVNSC	3.1s
LOE-TDFM	1.7s
LOE-DVAM	1.67s

According to the methods in Table III, Fig. 15 depicts the faster performance of the LOE-DVAM relay.

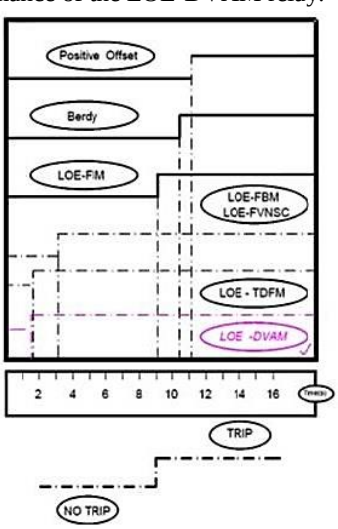


Fig.15. Various relay performance comparison

VI.CONCLUTION

In a synchronous generator, fault detection is one of the most important parameters to prevent serious damage to the generator. This paper introduced a new method for LOE and SPS detection. This method quickly detects faults, distinguishes between different faults (LOE, SPS), and prevents malfunction of the fault detection relay. The method is based on the generator's output signals, which use the terminal voltage derivative and the generator's power angle derivative. Using simulation in the MATLAB software, the behavior of the signals before and after the occurrence of the LOE error was investigated. The simulation output shows various behaviors caused by changes in the system, such as reduced generator excitation, short-circuit fault, and network load changes. Thus, according to this theory, an index is defined as LOEDI, which recognizes the LOE fault based on the calculation of the output voltage derivative signals. The LOEDI index detects the LOE fault within 1.67 seconds and reports the LOE detection relay. Table III shows that our proposed method outperforms all other methods. In the LOE fault detection method, comprehensive simulation studies for different system conditions and generators were examined by designing and simulating the synchronous generator simulation circuit. The results of these studies have shown that the proposed strategy is faster and more accurate. The algorithm distinguishes the LOE fault from the stable power swing (SPS) and prevents the relay from malfunctioning. It also prevents damage to the generator if the LOE occurs with the correct operation. With the proposed method, the protection and security of the synchronous generator as the most important device of power grids increases, and the LOE detection time is reduced.

APPENDIX

System data
Positive sequence equivalent impedance 0.0068+j0.096 p.u. (230kV, 200 MVA)
System voltage 230 kV, L-L, RMS
System frequency 60 Hz

Generator data	Transformer data	Transmission lines
S=200MVA, f=60 HZ H=3.2 s, V=13.8 KV Xd= 1.305pu, Xq=1.274 pu X'd= 0.3 pu, X'q= 0.243pu X"d= 0.23 puX"q= 0.24 pu T'do=5 s, T'qo=1.01 s T d=, T q= 0.09s Rated power factor 0.9 lagging	Rated MVA 210 MVA Rated voltage 13.8/230 kV Uk=12.5 % Connection mode DY11	L_1=L_2=100 km V=230 KV Z- = Z+ =0.042+0.139 Ohm/Km Z0 =0.159+0.736Ohm/ Km

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