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A Novel Approach to Detect the Synchronous Generator Loss of Excitation

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***Abstract*—Loss of excitation (LOE) event threatens both the generator and power system stability. Several methods have been proposed for LOE detection, most of which are based on the impedance trajectory. Such approaches may not be able to distinguish between LOE and stable generator swing (SGS). Thus, allocating an operation time delay is usually used to overcome the LOE relay misoperation due to SGS. This paper presents a new approach for the LOE relay. The proposed strategy exploits a combined scheme based on derivative of both the terminal voltage and the output reactive power of the generator. Comprehensive simulation studies are accomplished for various generator conditions and system disturbances to determine the relay setting and to evaluate its performance. The performed studies demonstrate that the proposed strategy enhances both security and operation time of the LOE relay, as compared with some existing methods.**

***Index Terms*— Loss of excitation detection, stable generator swing, synchronous generator, system disturbance**

I. Introduction

GENERATORS are amongst the most important elements of a power system and their fast and secure protection is crucial. One of the generator failures is loss of excitation (LOE) which may occur due to auxiliary equipment faults, unintended breaking of field breaker, short or open circuit in excitation system and slip rings flashover. After a synchronous generator loses excitation, it operates similar to an induction generator with oscillating voltage, current and output power, and it also requires a considerable amount of reactive power which should be provided by the nearby generators. The remaining generators may not be able to provide such amount of reactive power due to their limitations. Therefore, LOE not only can damage the generator and its associated mechanical prime mover, but also it threatens the power system stability [1-3].

LOE may lead to some subsequent events for the synchronous generator, including stator winding overload, rotor thermal damage, stator end-core damage and mechanical failure. In addition, the LOE event causes the faulty generator to absorb a large amount of reactive power from the power system which can lead to the power system voltage instability [2]. Therefore, LOE should be quickly detected to prevent power system instability and to mitigate the subsequent generator damages.

The earliest form of the LOE protection employs an undercurrent or undervoltage relay. These relays which are connected to the field circuit may misoperate for some cases [2]. An approach for LOE detection is introduced in [4] based on a single phase negative–offset mho element. The approach has been improved by combining a positive–offset mho element and a directional unit. The mho element characteristic is considered outside of the generator steady state stability characteristic to prevent generator instability. Meanwhile, the directional element provides security for close-in external faults [5]. Although this approach provides a good performance, but in some conditions its operation speed is not acceptable.

To decrease the LOE relay operation time and to increase its security against stable generator swings (SGS), an impedance-based relay including two negative-offset mho elements as the LOE relay characteristic is proposed in [6]. The impedance-based approaches may misoperate for SGS condition caused by a close-in short circuit fault when the generator absorbs reactive power from the system [7-8]. Since the estimated impedance can temporarily enter into the LOE relay characteristic under such condition, a time delay is usually considered to prevent misoperation. Although this improves the LOE relay security, the delay leads to more stresses on the generator and power system [8-11].

To enhance the performance of LOE detection algorithm and especially to discriminate the LOE event from SGS, some other techniques have been proposed:

- Neural network-based algorithms [12] and [13] which require considerable amount of training data from various conditions. Since these methods are dependent on the test system characteristics, they may not perform properly when applied to diverse systems. Training the associated network might also be time consuming.
- Utilization of the rate of change of reactance [14] which improves the impedance relays operation. However, the set points are depended upon the machine and system parameters.
- Fuzzy logic-based technique [3] which utilizes the impedance trajectory and generator terminal voltage to improve conventional method performance for LOE detection. The performance of this algorithm is generally acceptable, while it can still be improved.

This paper presents a new strategy to detect LOE event

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which securely discriminates it from SGS. Contrary to the existing impedance-based approaches, the proposed strategy realizes the LOE event using the rate of change of both the generator terminal voltage and generator output reactive power. The proposed strategy is comprehensively examined for diverse system conditions and parameters including various generator parameters and initial conditions, system configurations and disturbances. In addition, its performance is compared with that of two existing approaches. Performed studies demonstrate that the proposed strategy is able to successfully distinguish between SGS and LOE events. Meanwhile, the strategy operates much faster than the studied existing approaches.

The rest of this paper is organized as follows. Section II describes two impedance-based and fuzzy logic-based approaches to be compared with the proposed strategy. Section III presents the studied system and its components including generator controllers and also elaborates the proposed LOE detection algorithm. In section IV, the strategy performance is compared with that of the existing studied approaches for different conditions.

II. Existing LOE Protection Methods

Several methods have been presented for LOE protection, which mostly utilize the impedance trajectory seen by the generator LOE relay. Among these methods, a conventional impedance-based technique [6] as one of the fastest methods and a fuzzy logic-based algorithm [3] as one of the newest reported approaches are implemented in this paper to compare their performance with that of the proposed strategy.

A. Impedance-based Method

Fig. 1 illustrates the impedance-based LOE relay characteristic which includes two offset mho elements [6]. LOE detection for a heavily loaded generator is very important due to the severe stresses which would be imposed on the generator and power system in this condition. The estimated impedance usually passes through zone-1 under such condition. Therefore, a low time delay setting should be considered for this zone to prevent the subsequent damages to the generator and system. The zone-2 characteristic can detect LOE occurrence for a lightly loaded generator. Furthermore, it operates as the zone-1 backup. Since during SGS condition, entrance of the impedance trajectory into the zone-2 characteristic is more probable, a longer operation time is usually considered for this zone to prevent the LOE relay misoperation against SGS [15].

B. Fuzzy Logic-based Method

A LOE detection algorithm based on the fuzzy inference mechanism (LOEP-FIM) has been proposed to increase the relay security against system disturbances and to decrease the operation time [3]. This technique exploits the impedance trajectory in conjunction with the generator terminal voltage. First, the phasor values of current and voltage signals are calculated using an appropriate algorithm, e.g. discrete Fourier transform (DFT). Afterwards, apparent impedance should be

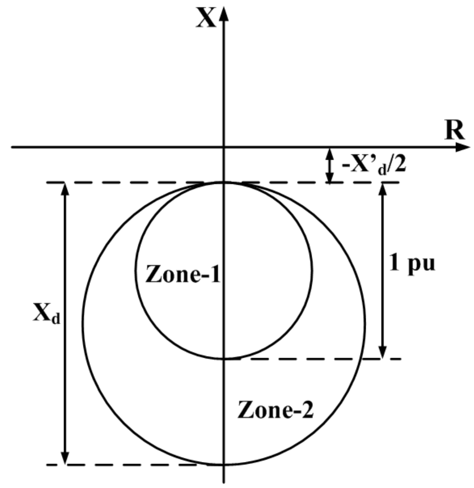

Fig. 1. Typical two-zone LOE relay characteristic

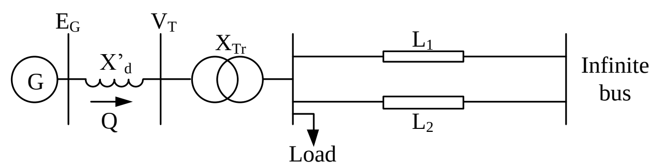

Fig. 2. Simulated system to investigate performance of LOE detection methods

calculated and per-united based on the generator rated current and voltage. The apparent impedance and terminal voltage are fed to the LOEP-FIM to make a decision between trip, alarm, and no trip.

III. Proposed LOE Protection Strategy

A. Studied System

Fig. 2 shows a sample power system which is modeled using DIgSILENT software [16]. This is similar to the system configuration investigated in [3]. In the studied system, a generator is connected to a strong power grid through an intermediate transformer and two parallel lines. Moreover, standard models of IEEEG1 and ESDC1A have been employed to simulate the generator governor and excitation system, respectively [17-18]. To be able to investigate the performance of the proposed strategy for a longer duration after system disturbance occurrence, no protective relays are modeled in the studied system. The system, the generator and the corresponding controller parameters are given in Appendix.

B. Strategy Concept

Any change in the power system configuration or load leads to the generator terminal voltage and power variations. The generator voltage and output power variations depend on the excitation system and governor control modes which are considered as voltage and output active power control, respectively. Using the terminal voltage V_T and reactive power Q, an appropriate index is suggested whose value and duration can be used to discriminate between LOE and other system events.

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After occurrence of a short circuit on the generator excitation winding terminal, which results in the LOE event, a decaying DC current flows through the excitation winding. Accordingly, the generator output voltage gradually decreases, as illustrated in Fig. 3-a for a LOE event at 2 s. This results in a negative terminal voltage derivative, Fig. 3-b. Under such a condition, the generator begins to absorb reactive power from the power system and the generator output reactive power decreases, Figs. 3-c and 3-d. Consequently, the derivative signs of both terminal voltage and reactive power are the same. In addition, the value of *dQ/dt* is noticeable, even for a relatively long duration after the LOE event.

Fig. 4-a illustrates the simulated generator terminal voltage V_T after a 100 MW load rejection at 2 s, with power factor of 0.8. It suddenly increases because of the voltage drop reduction across both the transmission lines and also the transformer and generator impedances. Therefore, a positive rate of change in terminal voltage initially results, as shown in Fig. 4-b. Due to the time delay of the excitation system and AVR and also the turbine and governor, the generator internal voltage E_G and also the angle difference between E_G and V_T (δ) are almost constant at the instant of disturbance occurrence. Thus, the generator output reactive power Q should suddenly decrease based on (1):

$$Q = V_T\left(\frac{E_G}{X'_d}\cos\delta - \frac{V_T}{X'_d}\right) \qquad (1)$$

where V_T and E_G are the per-united generator terminal and internal voltages, and X'_d is the generator transient reactance. It should be noted that the reduction of reactive current leads to a lower generator internal voltage [19] and more reduction of Q is resulted. As illustrated in Fig. 4-c, the sudden reduction of Q at the instant of load rejection agrees with the discussed theory. Fig. 4-d shows the reactive power derivative, which is negative after the load rejection. It should be noted that the reactive power is calculated using the three phase voltages and currents.

$$Q = imag(V_1 \times I_1^* + V_2 \times I_2^* + V_3 \times I_3^*) \qquad (2)$$

Fig. 5 illustrates the multiplication of the voltage derivative and the reactive power derivative for both cases under study, which is used as an index to discriminate between a LOE event and other system disturbances. As illustrated in Fig. 5-a, the index is equal to a large negative value at the instant of load rejection. Subsequently, the generator terminal voltage and reactive power mildly change due to dynamic response of the generator and its associated controllers. This initially results in a positive value, about 9, which diminishes quite fast in about 20 ms. Afterwards, the index remains within the range of -0.2 and +0.1. In fact, it does not exceed beyond +0.1 for a long duration. On the contrary, the calculated index is always equal to a noticeable positive value for the LOE event, Fig. 5-b.

Consequently, if the suggested index value remains more than a large positive threshold for a predefined duration, a LOE event occurrence can be concluded. This approach has

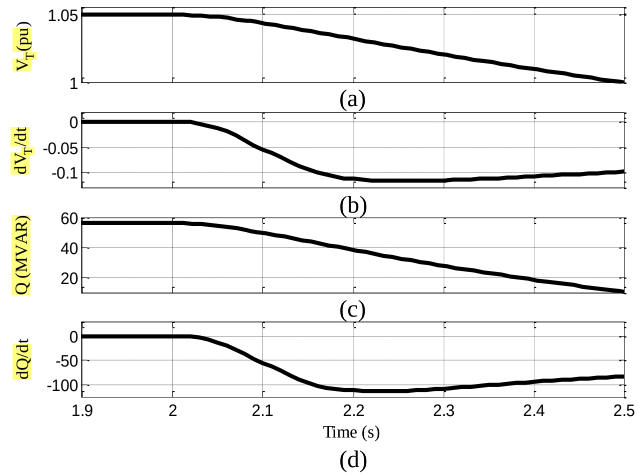

Fig. 3. Generator output variables after LOE

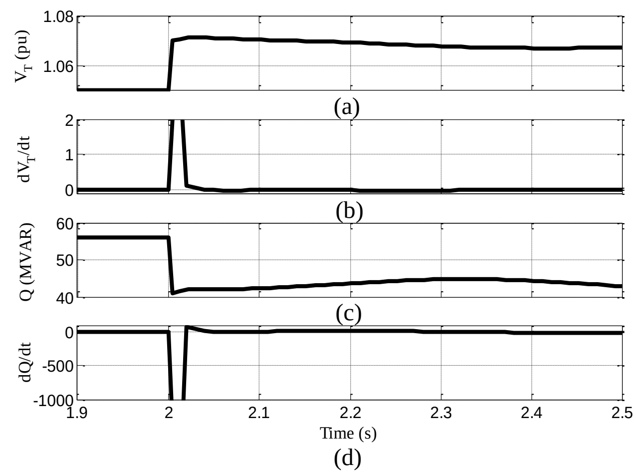

Fig. 4. Generator output variables after sudden reduction of system load

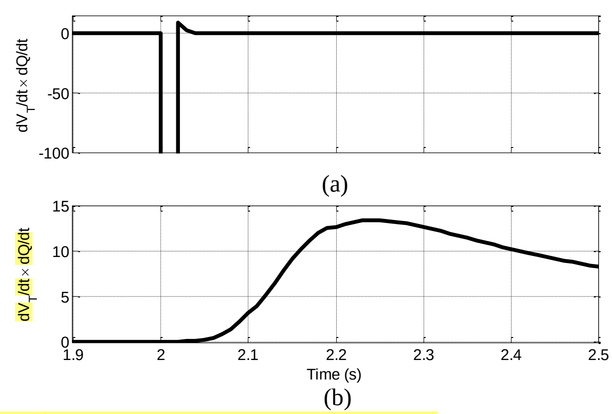

Fig. 5. Index value for LOE and load rejection events

been examined by comprehensive studies on several other power system disturbances such as short circuit events and power swings. As such, the generalization of the method has been confirmed by the obtained results.

C. Strategy Algorithm

The flowchart of the proposed strategy to recognize the LOE event is illustrated in Fig. 6. The generator terminal voltage drops after LOE event for both cases of short-circuit or open-circuit of the excitation winding.

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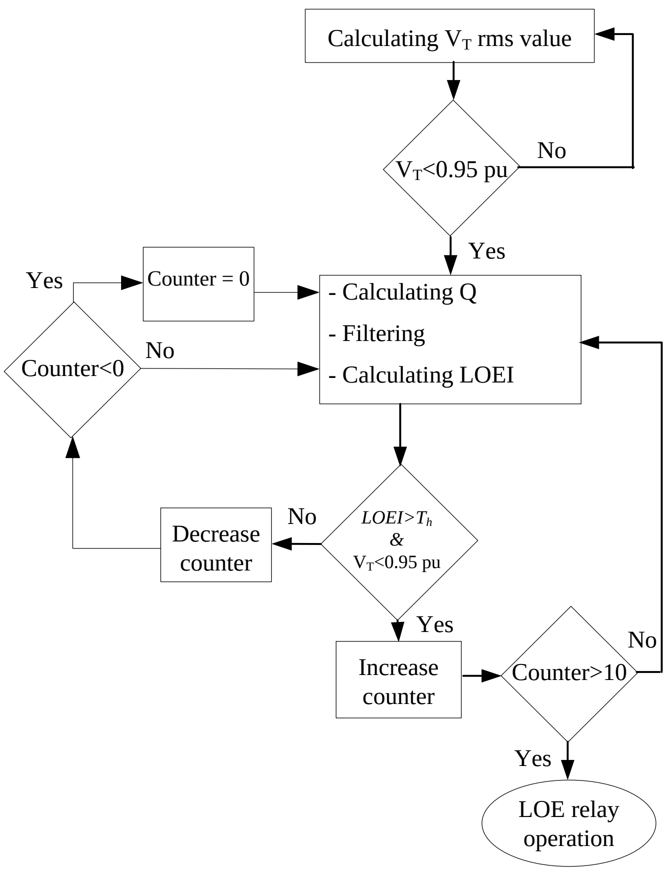

Fig. 6. Flowchart of the proposed LOE relay

Thus, an undervoltage unit with the setting of 0.95 pu is used as the fault detection unit. After the fault detection operation, the output reactive power is computed using the current and voltage phasors which are calculated based on DFT [20]. Subsequently, the reactive power in conjunction with the rms value of the generator terminal voltage are sampled at the frequency of 10 Hz. The strategy exploits the derivative of the sampled signals. Thus, to cancel unfavorable oscillations occurring after power system disturbances, e.g. after clearing a system short circuit fault, a second order Butterworth low pass filter with cutoff frequency of 5 Hz is utilized.

Subsequently, the proposed loss of excitation index (*LOEI*) is calculated by

$$LOEI = 10^5 \times [Q^{(k)} - Q^{(k-1)}] \times [V_T^{(k)} - V_T^{(k-1)}] \qquad (3)$$

where Q and V_T are the output reactive power and the terminal voltage values, respectively. The kth sample is denoted by the superscript k. It is noted that the terms $[Q^{(k)} - Q^{(k-1)}]$ and $[V_T^{(k)} - V_T^{(k-1)}]$ represent the derivatives of reactive power and terminal voltage, respectively. In addition, a large constant value, i.e., 10^5 is used to make the *LOEI* value more visible. The LOE event is detected if the calculated *LOEI* is greater than an adjusted threshold T_h for ten samples. If *LOEI* exceeds the T_h value for a few samples and then becomes less than T_h before LOE relay operation, the resetting process starts which decreases the counter. Operation of the proposed LOE relay depends on T_h setting whose proper value selection is discussed in the following section.

IV. Evaluation of the Proposed Strategy

The objectives of this section are (i) to evaluate the proposed strategy performance against LOE event and also power system disturbances including SGS, load rejection and line outage, (ii) to determine an appropriate setting value for T_h, and (iii) to compare the performance of the proposed strategy with that of the two existing approaches. To approach these objects, several scenarios are examined with different system configurations, generator rated powers and generator loading conditions. The studied system of Fig. 2 and the corresponding implemented LOE approaches are modeled appropriately.

A. Generator LOE

Since the *LOEI* value might be dependent on the power system configuration and the pre-disturbance generator output power, various cases are studied in the following subsections.

1) Case study

The studied generator has the rated power of 187.5 MVA, rated voltage of 11.5 kV and works at the full load condition of output active and reactive powers of 140 MW and 56 MVAR, respectively. Figs. 7.a and 7.b illustrate V_T and Q, respectively when a short circuit fault occurs on the excitation winding terminal at 5 s. As shown, both of these values are decreasing. Fig. 7.c shows *LOEI* index which is zero before the system disturbance. Meanwhile, *LOEI* has a positive value after the LOE event which agrees with the discussed concept. The proposed strategy can correctly realize the LOE event for this case.

2) Comprehensive studies

Due to dependency of the *LOEI* value to power system parameters, pre-disturbance system conditions including (i) generator rated power, (ii) generator initial output power, and (iii) system configuration are varied to investigate the strategy performance and to determine the proper value of T_h. The simulation results for the above mentioned conditions are summarized in Table I.

As illustrated in Table I, the value of *LOEI* is dependent on the generator rated power. This is justifiable due to high reactive power changes of large generators during LOE event. Based on the performed studies, the least value of *LOEI* is 25. As a result, the proper value of T_h is considered to be 20.

B. System Disturbances and SGS Events

The objective of this study is to examine the proposed strategy and the adjusted T_h value when the studied system is subject to system disturbances and SGS events.

1) Transmission line outage

To evaluate the performance of the proposed relay subject to system disturbances, the modeled generator with the rated power of 187.5 MVA is studied. The output active and

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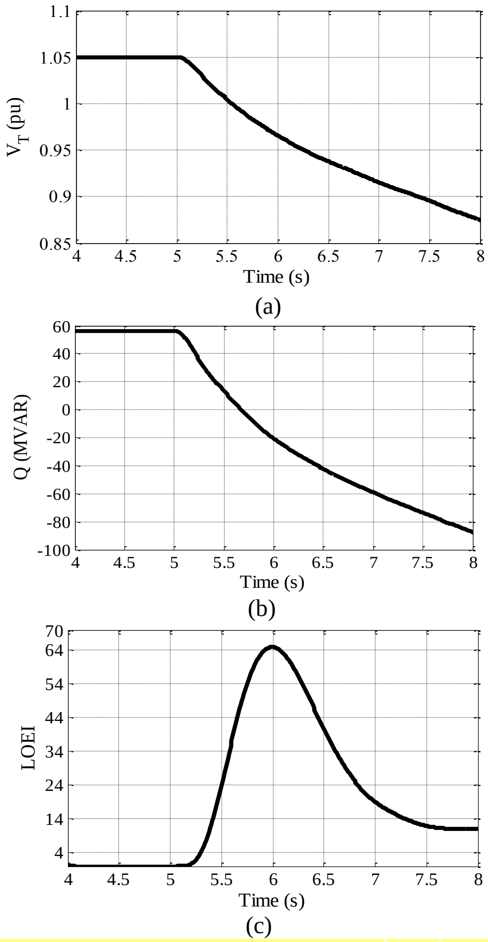

Fig. 7. (a) Terminal voltage, (b) reactive power, and (c) *LOEI* value for LOE event under the generator full load condition

TABLE I
OBTAINED *LOEI* VALUES FOR DIFFERENT LOSS OF EXCITATION EVENTS

Generator rated power [MVA]	System configuration	Generator initial loading		*LOEI* first peak value
		P [MW]	*Q* [MVAR]	
125	L_1 and L_2 in service	90	42.34	26
	L_1 and L_2 in service	40	41	25
	L_2 out of service	90	39.48	25
154	L_1 and L_2 in service	120	55.00	39
	L_1 and L_2 in service	40	54.44	34
	L_2 out of service	40	50.00	33
187.5	L_1 and L_2 in service	140	56.00	65
	L_1 and L_2 in service	45	54.31	60
	L_2 out of service	45	50.00	58
210	L_1 and L_2 in service	168	69.72	111
	L_1 and L_2 in service	80	67.28	71
	L_2 out of service	168	54.91	106

reactive powers of generator are 100 MW and 56 MVAR, respectively. As a case study, a switching event is considered for one of the transmission lines, i.e., L_1.As illustrated in Fig. 8, after outage of L_1, *LOEI* value is always less than the T_h value with a large margin. Consequently, the proposed method provides secure operation for this disturbance.

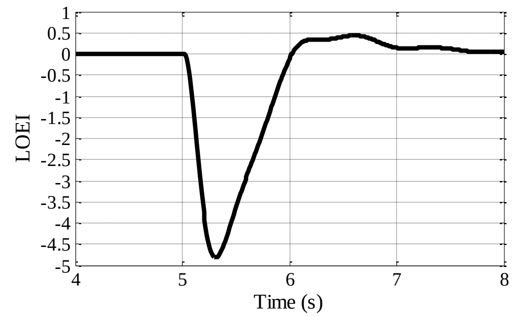

Fig. 8. *LOEI* value after L_1 outage

2) Stable generator swing

The conventional impedance-based LOE algorithms may misoperate during SGS where the generator is operating under a leading power factor [8]. Therefore, the performance of the proposed algorithm is investigated under this condition. To do so, it is assumed that the generator absorbs 56 MVAR reactive power from the system. To generate an SGS event, a three phase short circuit fault at the middle of transmission line L_1 is considered which is cleared after 100 ms. The computed generator terminal voltage and reactive power along with the related filtered values are illustrated in Figs. 9-a and 9-b, respectively. As shown in Fig. 9.c, the calculated *LOEI* has a large negative value during both the short circuit and the generator swing time intervals, except a very short time interval (less than 0.1 s) which may become a small positive value. Even during this interval, the obtained *LOEI* is much less than the T_h value. Thus, this event is not classified incorrectly as a LOE event.

3) Comprehensive studies

The generator swing characteristics consisting of the swing frequency, swing amplitude, and damping duration are mainly dependent on the generator parameters, pre-fault output power, the location and type of the system short circuit fault, and the duration of fault. To make sure that the proposed strategy would remain stable during different SGS events, comprehensive simulation studies are carried out under the various mentioned conditions. Table II illustrates rare cases for which the *LOEI* value exceeds the set threshold. As given in Table II, for stressed power system circumstances where the generator is highly loaded and/or it absorbs high amount of reactive power from the system, and especially for a long fault clearing time, the *LOEI* value may increase beyond the T_h value. However, its duration for the worst case, which is a very improbable condition, is 800 ms. To activate the proposed strategy, the *LOEI* value should remain more than T_h for at least one second, i.e., 10 samples with the sampling frequency of 10 Hz. Thus, comprehensive case studies show the strategy is correctly blocked for all of the studied SGS events.

As illustrated in Table II, the time interval for which the *LOEI* value is more than T_h increases when the pre-fault generator active and reactive power and also fault duration are increased. To investigate the proposed approach performance in more details, the *LOEI* value and the time interval for which $LOIE>T_h$, are illustrated in Table III for various loading conditions of the 187.5 MW generator. As shown in this table,

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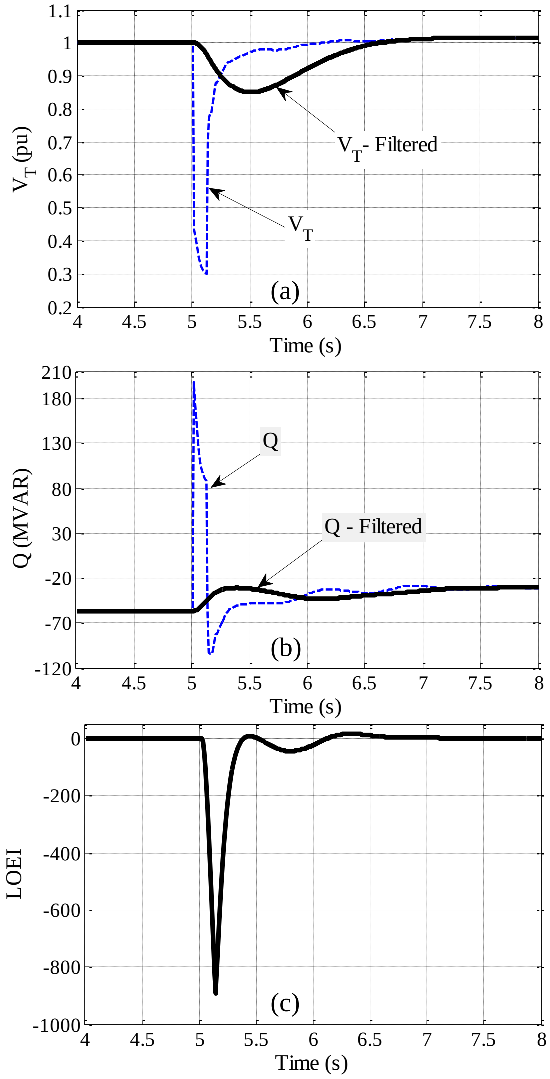

Fig. 9. (a) Generator terminal voltage and its filtered value, (b) generator output reactive power and its filtered value, and (c) calculated *LOEI* for the SGS event

for the generator lightly loaded conditions, the proposed strategy is not even activated. However, for the generator heavily loaded cases, the *LOEI* value might become more than T_h for a short interval which is much less than pre-defined set value (1 s). It should be noted that maximum feasible active power of the studied 187.5 MW generator at the real site environmental condition is about 140 MW and its associated maximum reactive power is about 30% of the rated power (56 MVAR). Thus, even for the highest feasible case of generator loading, the proposed approach correctly remains stable against a SGS event caused by a long-duration three-phase fault.

Comprehensive simulation studies clearly show that the calculated *LOEI* value may rarely increase above the threshold value while its duration is often much less than 1 s. Consequently, the proposed strategy guarantees the LOE relay security even against severe generator swings.

The proposed approach security is also evaluated under various line outage and load rejection events. For these cases, *LOEI* is always less than T_h, and thus the approach properly

TABLE II
OBTAINED *LOEI* VALUES FOR DIFFERENT SGS EVENTS

Generator rated power [MVA]	Fault duration [ms]	Generator pre-fault output		LOEI duration above threshold [s]
		P [MW]	*Q* [MVAR]	
125	200	90	42.34	0.3
	200	90	-40.43	0.8
154	200	120	55.00	0.32
	300	120	55.00	0.75
	200	120	-55.68	0.8
187.5	200	140	56.00	0.3
	100	140	-56.00	0.25
210	200	165	60.77	0.4
	300	165	60.77	0.55
	200	165	-61.01	0.8

TABLE III
LOEI AND ASSOCIATED VALUES FOR DIFFERENT SGS EVENTS

Generator pre-fault output power		LOEI peak value	LOEI duration above threshold [s]
P [MW]	*Q* [MVAR]		
140	56	60	0.3
130	50	50	0.21
120	43	40	0.085
110	37	33	0.07
100	31	26	0.05
90	25	22	0.025
80	19	18	0
70	14	16	0
60	8	12.5	0
50	3	11	0
40	0	8	0
40	-2	7.8	0
50	-8	8	0
60	-13	8	0
70	-19	10	0
80	-24	11	0
90	-30	15	0
100	-35	20	0
110	-40	30	0.065
120	-45	48	0.12
130	-50	80	0.23
140	-55	140	0.33

distinguishes the mentioned disturbances from the LOE event. Table IV shows the summarized results of the strategy for two disturbances, a line outage and a 100 MW load rejection.

C. Comparative Analysis

To evaluate the proposed method, its performance is compared with that of the two existing techniques described in Section II. The first approach, which is impedance-based, utilizes two zones with adjusted delays of 0.1 and 0.5 s for zone-1 and zone-2, respectively. Furthermore, the second approach, i.e., the fuzzy logic-based method, exploits both the impedance and generator terminal voltage parameters. For

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TABLE IV
OBTAINED *LOEI* VALUES FOR SYSTEM DISTURBANCES

Generator rated power [MVA]	System disturbance	Initial output power		LOEI duration above threshold [s]
		P [MW]	*Q* [MVAR]	
187.5	L_1 outage	140	56.00	0
	Load rejection	140	81.90	0

this approach, the alarm threshold X_{1set}, trip threshold X_{2set} and time delay t_{set} values are considered equal to 0.35, 0.65 and 200 ms, respectively [3]. These two approaches are modeled to study their performance under various conditions.

Both of the approaches need to measure the impedance seen from the generator terminal. Since LOE event is a low speed phenomenon, all electrical variables including voltage, current and calculated impedance change gradually. Fig. 10 illustrates the impedance trajectory for an LOE event at 5 s. The calculated impedance enters into the LOE zone-2 and zone-1 characteristics 3.86 and 6 s after occurrence of the LOE event, respectively. Consequently, the impedance-based LOE approaches are intrinsically slow. On the other hand, the proposed method uses the rate of change of variables. Therefore, it operates much faster than the studied methods, as illustrated in Table V for the 154 MVA generator.

In addition, the security of the proposed strategy is compared with that of the other studied approaches. As summarized in Table V, the proposed method is correctly stable against SGS, even while the generator absorbs a large amount of reactive power. Whereas, both existing approaches incorrectly operate under such a condition, especially when a properly set minimum excitation limiter is not employed. It should be noted that the LOEP-FIM method is activated in the first studied case of SGS, too. However, it has become stable due to the considered time delay recommended in [3]. It should be noted that the generators are operated at the maximum feasible active power based on the actual site environmental condition, which is for example 120 MW for the 154 MVA generator.

Accordingly, as compared with the two studied approaches, which are improved LOE techniques, not only the proposed strategy operates much faster, but also it remains stable against generator swings. Therefore, the strategy can be practically employed for generator protection, especially due to the (i) fast operation, (ii) algorithm simplicity, and (iii) secure operation.

D. Discussion

The impedance-based LOE relay with the widely used characteristic, Fig. 1, was initially recommended at 1949 when the generator X_d value was in the range of 1.1 to 1.2 pu [4], [6]. Under such a case, the relay could properly discriminate generator normal operating conditions from a LOE event. In the more recent generator designs, this reactance has been increased to about 2.0 pu; however, the relay setting concept has not been changed in many utilities. Thus, the LOE relay is prone to maloperation when a mildly loaded generator is

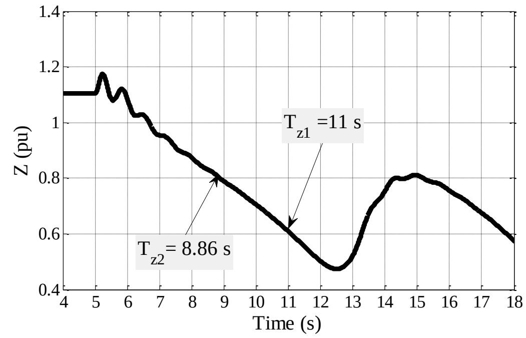

Fig.10. Apparent impedance amplitude versus time after LOE

TABLE V
COMPARATIVE ANALYSIS

Events	Generator initial loading		Conventional impedance-based relay	LOEP-FIM	Proposed method
	P [MW]	*Q* [MVAR]			
LOE	120	55	Trip after 4.36 s	Trip after 3.49 s	Trip after 1.6 s
LOE	40	55	Trip after 7.46 s	Trip after 6.02 s	Trip after 1.66 s
SGS	120	55	No Trip	No Trip	No Trip
SGS	120	-48	Trip after 0.7 s	Trip after 0.4 s	No Trip

operated on the under-excited mode. For example, the LOE relay may unacceptably operate for the studied 210 MVA generator with X_d=2.64 pu and X'_d=0.21pu when the generator absorbs more than 0.36 pu reactive power. This is not a rare condition and may occur during both normal operation or system contingencies. It should be noted that a reduced relay characteristic may jeopardize the LOE relay operation under generator lightly loaded conditions [6]. On the contrary, the security against running the generator under severe under-excitation condition is intrinsically guaranteed by the proposed approach. Furthermore, based on the comprehensive simulation studies, it is concluded that the proposed strategy appropriately distinguishes between the LOE event and other system disturbances.

A minimum excitation limiter (MEL) can be exploited to increase the stability of conventional LOE relays during an SGS [17]. MEL is a control loop added to the generator AVR to boost the excitation current and move the operating point back toward the excitation system limit. Our studies illustrate that MEL with properly adjusted parameters can enhance the conventional LOE relay security for an underexcited generator subjected to stable swings. However, the relay stability using the MEL function suffers from the following items:

- Influence of MEL on the impedance based LOE relay performance is severely sensitive to even a minor change of the adjusted parameters.
- The settings are dependent on the generator parameters that are determined with some uncertainties. In addition, they also depend on the system Thevenin impedance to which the generator is connected.
- Proper settings of the MEL parameters, especially time constants, require accurate and comprehensive simulation

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studies.

It should be noted that our studies show MEL does not have an adverse influence on the proposed LOE detection approach to properly operate for a LOE event.

A benefit of the conventional impedance based LOE relay is to prevent possible overheating of the end windings in the event of MEL failure. Thus, the proposed approach can be supplemented by the conventional LOE relay with the proper zone and specially time delay setting to provide such a benefit.

As illustrated in Table I, a larger generator rated power results in a higher *LOEI* value. Consequently, to enhance the proposed approach security, the T_h value can be selected adaptively based on the generator rated power, its associated controllers and the system to which the generator is connected.

To be able to provide a systematic approach, some further studies in a more complex system, shown in Fig. 11 is performed. The simulation parameters for the 187.5-MW generators, transformers and transmission lines are similar to those of Fig. 2.

Setting parameters of the proposed relay include the T_h value and the time delay, i.e., the number of samples for which the loss of excitation index (*LOEI*) is larger than the T_h value. The T_h value and the corresponding time delay should be respectively obtained based on the worst case of LOE events and the worst case of system disturbances. Table VI shows the obtained proposed index for the LOE occurrence in G_1. As illustrated, the value of *LOEI* depends on the generator loading and the network configuration. It could be concluded that:

- Less initial loading of the generator leads to less *LOEI* first peak value.
- A stronger network to which the generator is connected results in a lower LOEI value. Because, the rate of change of the generator terminal voltage decreases in such a condition.
- More paralleled generator decreases the generator terminal voltage fluctuations after a LOE event. Thus, the LOEI value also decreases for this case.

Accordingly, to adjust the T_h value, the worst case can usually be studied for the LOE event under the following conditions:

- Minimum acceptable output power of the generator
- Minimum equivalent Thevenin impedance for the busbar connected to the line end
- Maximum number of paralleled generators

It should be noted that for the abovementioned conditions, the least voltage variation would appear across the generator terminal that decreases the obtained *LOEI* value.

Furthermore, to adjust the time delay for the proposed approach, its sensitivity to the system and generator conditions is investigated for various stable generator swings (SGSs).

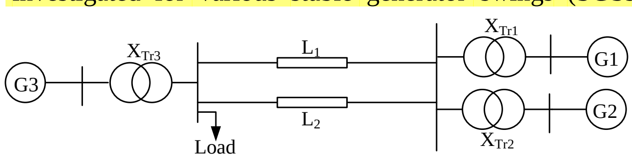

Fig. 11. The simulated complex system

TABLE VI

OBTAINED *LOEI* VALUES FOR DIFFERENT LOSS OF EXCITATION EVENTS

System configuration	**Generator initial loading**		***LOEI* first peak value**
	***P* [MW]**	***Q* [MVAR]**	
G_1, G_2 and G_3 in service L_1 and L_2 in service	140	52	74
	100	47	62
	45	43	59
G_2 out of service L_1 and L_2 in service	140	73	99
	45	69	82
G_1, G_2 and G_3 in service L_2 out of service	140	52	70
	45	41	58
G_1 and G_2 in service L_1 and L_2 in service Replacing G_3 with infinite bus	140	42	49
	45	39	45

TABLE VII

LOEI AND ASSOCIATED VALUES FOR DIFFERENT SGS EVENTS

System configuration	**Fault clearing time (ms)**	**Generator initial loading**		***LOEI* peak value**	**LOEI duration above threshold [s]**
		***P* [MW]**	***Q* [MVAR]**		
G_1, G_2 and G_3 in service	50	140	52	5.8	0
	100	140	52	29	0.25
	150	140	52	54	0.4
	100	140	52	29	0.25
	100	100	47	2.5	0
	100	45	43	0.6	0
	100	140	52	29	0.25
	100	140	-54	55	0.4
G_2 out of service G_1 and G_3 in service	100	140	52	2	0
	100	45	43	0.5	0
G_1 and G_2 in service, Replace G_3 with a weak power grid	100	140	52	4.8	0
	100	45	43	2.3	0
G_1 and G_2 in service, Replace G_3 with infinite bus	100	140	52	7	0
	100	45	43	4.5	0

Table VII shows the obtained results for the studied system of Fig. 11. As illustrated in this table, the time delay should be adjusted based on the following conditions, as the worst case:

- Maximum probable fault clearing time.
- Maximum feasible output active power of the generator while absorbing/injecting the maximum probable reactive power.
- Minimum short circuit level for the busbar connected to the line end.
- Connecting a generator at the line end (it should be noted that variations of the generator voltage and the reactive power increase when a generator is connected to the line

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end. Thus, an equivalent generator should be considered at the line end instead of Thevenin impedance and its associated voltage source.)

As a result, the proposed relay can be systematically adjusted, performing simulations only for two worst cases as described above.

V. Conclusion

In this paper a new strategy is proposed to detect loss of excitation event in the synchronous generator. The strategy can detect LOE using a different approach compared with the most common methods which are impedance-based. The concept of the strategy stems from the fact that the derivative of filtered both the generator terminal rms voltage and the output reactive power variables have the same sign for LOE events. Whereas, they have different signs at the instant of system disturbance occurrences including SGS, short circuit fault, and system or load variations. Thus, an index is introduced based on this theory to discriminate LOE events from system disturbances which should be calculated after a disturbance. The LOE detection strategy is studied based on comprehensive simulation studies for various system and generator conditions to evaluate its performance as compared with the two existing approaches. Performed studies demonstrate that the proposed strategy operates more quickly. Furthermore, this algorithm remains stable against generator swings, even for a heavily loaded generator which absorbs a large reactive power, whereas both existing approaches may maloperate for such a case. Accordingly, the proposed strategy enhances both LOE detection security and operation time.

Appendix

TABLE VIII
Exciter and AVR Parameters

Tr	Ka	Ta	Tc	Tb	Te	Kf	Tf1
0.02	175	0.005	3.1	40	0.05	0.01	0.3
Ke	E1	Se1	E2	Se2	Vrmin	Vrmax	
0.96	1	0	2.044	0	0	2.83	

TABLE IX
Transformers Parameters

Sn (MVA)	Short Circuit Impedance (%)	Copper Loss (kW)
176	12	106
210	12.5	410

TABLE X
Transmission Line Parameters

R (Ohm/km)	X (Ohm/km)	B (µS/km)	Length (km)
0.0609	0.277	3.99	60

TABLE XI
Load Parameters

P (MW)	Q (MVAR)
50	40

TABLE XII
Generator Parameters

S [MVA]	125	154	187.5	210
V [kV]	11.5	11.5	11.5	11.5
X_d *[p.u]*	2.046	2.046	1.71	2.64
X_q *[p.u.]*	1.944	1.944	1.71	2.346
H [s]	4	4.31	7.36	14.688
R_{st} *[p.u.]*	0.000967	0.0014	0.000843	0.000843
T'_d *[s]*	0.937	0.943	0.77	0.635
T'_q *[s]*	0.468	0.475	0.415	0.423
T''_d *[s]*	0.031	0.042	0.011	0.015
T''_q *[s]*	0.07	0.07	0.05	0.012
X'_d *[p.u.]*	0.225	0.225	0.24	0.337
X'_q *[p.u.]*	0.459	0.3	0.24	0.557
X''_d *[p.u.]*	0.164	0.164	0.16	0.21
X''_q *[p.u.]*	0.181	0.181	0.2	0.18
Sat. 1.0	0.12	0.12	0.12	0.067
Sat. 1.2	0.6	0.6	0.6	0.2

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