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A Setting-Free Loss of Excitation Detection of Synchronous Generator in the Presence of FACTs Device

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ABSTRACT

This paper analyzes the loss of excitation (LOE) fault, as one of the most common faults in synchronous generators, and investigates the methods of its detection. Then, the performance of a power system equipped with STATCOM is simulated using Matlab/Simulink software, and the effects of the generator performance on the resistor and its derivatives in the generator terminal are analyzed. A novel LOE detection method based on a derivative of resistance is proposed. To demonstrate the efficiency of this method, various generator load sizes and conditions are considered. The simulation results show that the amount of resistance time derivative in all cases, whether with or without STATCOM, serves as a reliable new criterion for LOE detection. This method proves to be faster and more accurate than conventional methods. The simulation results at different load amounts and types confirm the validity of the proposed method.

NOMENCLATURE

		$X_{Tot}(t)$	Total Reactance
E_G	Inner Voltage of The Generator	$FACTS$	Flexible AC Transmission Systems
$X_G(t)$	Reactance of The Generator	SPS	Stable Power Swing
X_T	Leakage Reactance of The Transformer	LOE_{th}	Threshold Value
X_{syst}	Reactance of The Transmission Network	R	Resistance
E_{syst}	Voltage of The Transmission Network	Q	Reactive power
LOE	Loss of Excitation	S	Apparent Power
δ	Power Angle	P	Active Power

I. Introduction

The blackouts of August 14, 2003, in North America highlighted many aspects of system protection [1,2]. Considering that power outages in industrial centers may inflict irreparable losses when a fault occurs, the relay must detect faults, track them, measure them, and prepare the alarming devices or, if necessary, automatically take action to interrupt the electric circuit. If the fault is dangerous, only the

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faulty device should be disconnected from the circuit, and the other faultless parts of the network should continue to operate without power interruption until the fault does not threaten them. The good and reliable performance of power systems is mainly protected by protective relays. If we aim to establish a highly reliable system, all components must be protected [3]; especially, generators require robust protection as they are the main sources of energy. Therefore, any faults in these generators must be detected quickly, so they need relays that offer high and reliable protective capabilities.

Loss of Excitation (LOE) is an important fault in synchronous machines that adversely affects both the network and the generator. LOE occurs when DC sources fail due to events such as field open circuits, accidental interruptions, regulator failures, or loss of field in the exciter [5, 6]. The primary method of LOE protection involves using voltage and current transfers, which are associated with the field circuit and may glitch in some cases. Masson [11] introduced a single-phase mho component with a negative offset. Berdy [12] proposed a distance relay with two zones for LOE detection, which is now regarded as a trustworthy procedure for LOE detection. Figure 1 shows the performance waveform of this relay. This procedure may not distinguish between stable power swing (SPS) and LOE, so a time delay is used to interrupt relay maloperation. However, this solution is not a rational way because this deliberateness time delay can have additional impacts on the device and network, as the defective generator continues to draw reactive power for an extended period. Other strategies, such as those based on neural networks, require substantial training data under various circumstances and can take a considerable amount of time. Since these strategies depend on framework characteristics, they may not work well when utilizing wholly different frameworks [7, 8].

Among other strategies for LOE detection are methodologies based on fuzzy logic, which are utilized to move forward the execution of common strategies for LOE discovery by utilizing the impedance tracking and terminal voltage of the generator [9,10]. These strategies are faster and more secure than traditional impedance procedures. Researchers have also examined the influence of transmission line midpoint STATCOM on generator protection behavior [11, 12]. This research investigates a power plant with two generators under two potential LOE scenarios: complete LOE and partial LOE, based on field short circuits and sudden drops in excitation voltage at various generator loads. The findings indicate that midpoint STATCOM adversely affects the performance of LOE relays, particularly in terms of time delay. Unlike the impedance-based approach, another strategy represents the event (LOE) by utilizing the rate of change of terminal voltage and output reactive power [13]. This strategy employs the voltage derivative and reactive power derivative to introduce an index known as the Loss of Excitation Index (LOEI). If this index exceeds a threshold value (LOE_{th}), the LOE has occurred. This strategy can also distinguish between LOE and SPS and performs much faster than existing methods. Yaghubi [14] provided a quick and accurate distinction between SPS and LOE of synchronous generators. Since there is an imbalance in the SPS condition, the detection of this phenomenon remains a challenge. This study proposed a rapid diagnostic method for addressing this issue. The proposed hybrid approach was based on the derivatives of reactive output power and terminal voltage, as well as the rapid change of the Fourier transform coefficients of the three-phase active power at the relay location [14]. At the moment of an LOE fault, the proposed index exceeds the threshold value, and the active power FFT remains relatively stable. However, during the occurrence of SPS, the active power FFT exhibits significant changes. In recent years, to enhance power transmission and optimize the utilization of power system capabilities, the adoption of flexible AC transmission systems (FACTS) such as static synchronous compensators (STATCOM) has become increasingly popular. Nevertheless, STATCOM alters the voltage and current within the power system, potentially disrupting relay operation (LOE). As a result, Yaghobi [15] introduced a novel method for flux-based LOE protection in the presence of STATCOM, which relies on changes in the generator linkage flux at the relay's position. This relay operates independently of coordination with other generator protection relays.

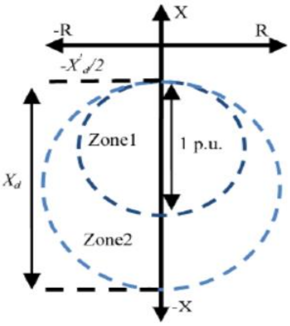


Figure (1): Two protection zones of Berdy Relay

Another paper on the protection of synchronous generator excitation loss during and after various external faults is presented by Yaghobi [16]. This method relies on changes in the magnetic flux in the air gap and the negative sequence current. In [17], the author introduced a new LOE detection method and proposed a modern approach for LOE detection that uses a combined conspire based on the derivative of the terminal voltage and power angle of the generator. Niaz Azari [18] presented a setting-free method to detect this malfunction. To address this issue, a flux derivative method was proposed for fault detection. Since the time derivative of the flux or the rate of change in the flux at the moment of LOE has a negative value, it serves as a reliable indicator for identifying this fault.

Among the methods discussed, the LOE detection method that uses distance relays is the most prevalent due to its simplicity. However, it cannot distinguish between LOE and SPS, which is the main problem with these types of relays. To address this issue, a deliberate time delay was implemented to prevent LOE from malfunctioning. However, this approach proved ineffective, as the time delay increased tension within the device and the power network. To resolve this problem, methods such as fuzzy logic, neural networks, and magnetic flux were employed. These techniques are faster and more accurate than the distance relay method, though each has its own challenges.

Section II describes a new method of LOE detection in the presence of FACTS devices, specifically STATCOM. This method is simpler than existing methods, offers appropriate accuracy, and does not require setting.

II. The Proposed LOE Detection Method

A. Without STATCOM

LOE in synchronous generators occurs when the field current is interrupted due to an open circuit in the field winding. To illustrate an LOE situation, assume that a generator is connected to the electrical network via a transformer. Figure 2 depicts the single-line connection diagram. When LOE is distinguished by relay 40, the equivalent circuit of the system after the LOE event can appear at each stage as in Figure 3, since LOE is symmetrical in nature.

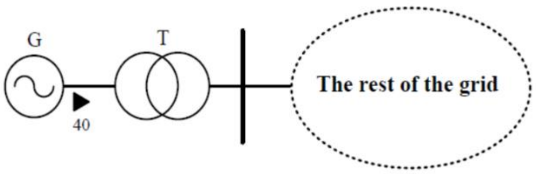


Fig. 2. The single-line diagram of the system

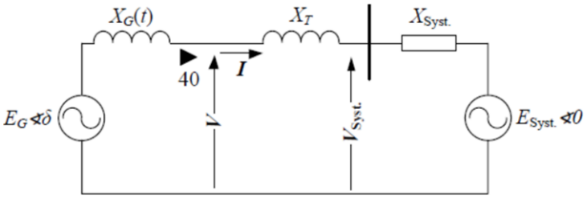


Fig. 3. The system equivalent circuit

When LOE occurs, the inner voltage of the generator (E_G) diminishes, inducing changes in the terminal voltage and current, which can result in variations in the impedance detected by the relay. During the LOE occasion, $X_G(t)$ changes, so it is sensible to think of it as a function of time from the minute of the start of the LOE. Assuming K=Esyst/EG, the time derivative of the equivalent resistance can be expressed as [3]

$$\frac{dR}{dt}=\frac{(1-K(t)^2)\cdot \sin\delta}{(1+K^2-2K\cos\delta)^2}\cdot\frac{dK}{dt}\cdot X_{Tot}(t) + \frac{K(t)\cdot\sin\delta}{1+K^2-2K\cos\delta}\cdot\frac{dX_{Tot}(t)}{dt} \tag{1}$$

It should be stated that the total reactance can be as follows:

$$X_{Tot}(t)=X_G(t)+X_T+X_{syst} \tag{2}$$

Since k is expanding, $\frac{dK}{dt}$ is positive and because ($E_{syst}<E_G$), the primary portion of (1) is positive. Based on [3], after a few seconds, the second part of Eq. (1) will be zero. At this time, E_{syst} will be more than E_G, so after a certain duration, $\frac{dR}{dt}$ will continue to be positive and LOE can be identified. In power swing conditions, $\frac{dR}{dt}$ is again negative for some time. But, the negative time is different from the LOE. When it happens, K can be assumed 1 and the value of the proposed index can be written as follows:

$$\frac{dR}{dt}=\frac{2\cos\delta(t)-2}{(1+K^2-2K\cos\delta(t))^2}\cdot\frac{d\delta}{dt}\cdot X_{Tot} \tag{3}$$

As proven in [3], the sign of $\frac{dR}{dt}$ is the opposite of $\frac{d\delta}{dt}$. The $\frac{d\delta}{dt}$ swings have a frequency of 3.0 to 7 Hz, so the longest period of $\frac{d\delta}{dt}$ that occurs during the oscillation is expected to be 3.33 seconds. As is evident in Figure 4, $\frac{d\delta}{dt}$ is positive in the primary half of periodicity, and hence $\frac{d\delta}{dt}$ will not be negative for more than 1.67 seconds during power swings. To discriminate LOE from power swings, the proposed relay must wait 1.67 seconds. If $\frac{d\delta}{dt}$ is negative, LOE will be distinguished[3].

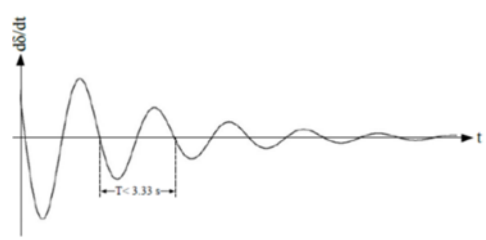


Fig. 4. $\frac{d\delta}{dt}$ diagram during power swings[3]

B. In the Presence of STATCOM

It can be assumed that in the presence of STATCOM devices, Esyst will be equal to 1pu with the compensation done. So, K will be 1/EG. Therefore, in the event of LOE, K will exceed 1. As a result, according to Eq. (3), the R time derivative will be negative when the fault occurs. It must be emphasized that if the STATCOM compensation is extreme, Esyst will be more than 1pu and again K will be more than 1 and there will be no problem in fault detection with the proposed method.

Accordingly, Figure 5 displays the proposed method in the form of a flowchart in the presence and absence of STATCOM. First, the relay calculates $\frac{dR}{dt}$. When it is not zero, it will check its sign. If it is negative for more than 1.67 seconds, LOE can be detected and a trip signal is sent to the generator circuit breakers. If it is negative for less than this time, a power swing can be reported.

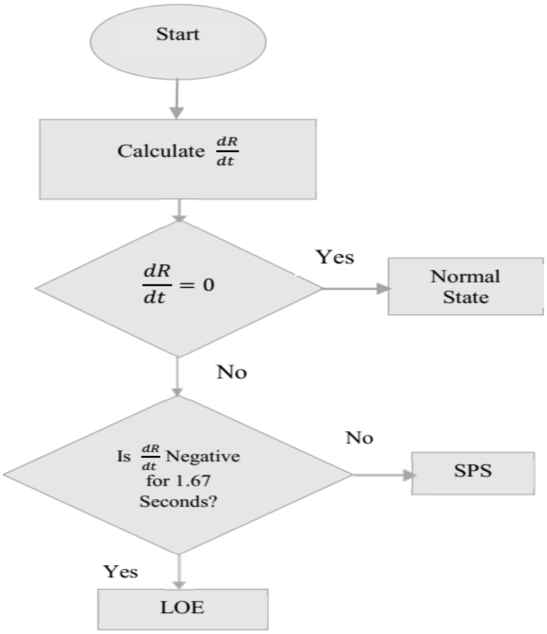


Fig .5. The algorithm of the proposed method in the presence and absence of STATCOM

III. Simulation and analysis of the results

This section analyzes the performance of the proposed method. Figure 6 shows a schematic of a power system with infinite bus. The performance of the proposed method will be compared with this method's performance in the absence of STATCOM. In this configuration, a 200 MW, 8.13 kV salient pole synchronous generator is connected to a 500 kV, 20,000 MW power grid through a transformer.

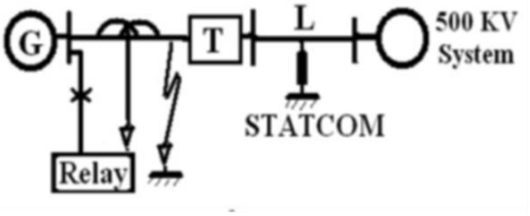


Fig. 6. The general scheme of the simulated power system

In addition, the different loads in each generator unit based on the capability curve are shown in Table 1. STATCOM is connected to the middle of the transmission line for voltage regulation, transmission, and optimal use of power. STATCOM mitigates reactive power by monitoring the terminal voltage and comparing it with the set value.

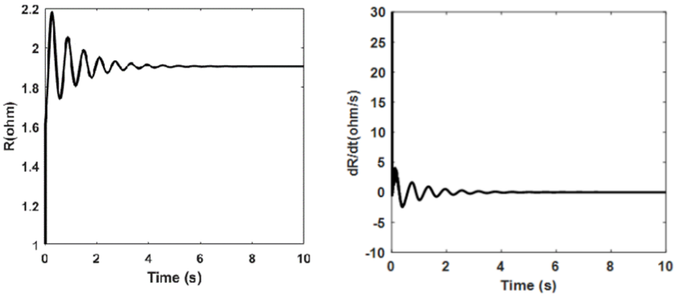
TABLE 1 Different generator loads

Load No.	S=P +jQ	Load No.	S=P +jQ
1	0.1+j0.5	11	0.9-j0.2
2	0.1+J0.2	12	0.7-J0.2
3	0.3+J0.2	13	0.7-J0.5
4	0.3+J0.5	14	0.5-J0.2
5	0.5+J0.2	15	0.5-J0.4
6	0.5+j0.4	16	0.5-j0.6
7	0.7+J0.2	17	0.3-J0.6
8	0.7+J0.4	18	0.3-J0.4
9	0.9+J0.3	19	0.3-J0.2
10	0.9+J0.1	20	0.1-J0.6

A. *Simulation in the Absence of STATCOM*

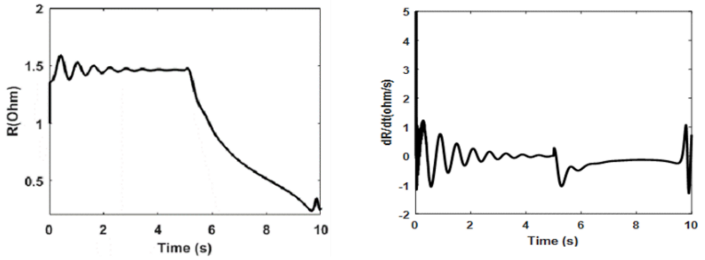
In this part, different loading conditions are examined to observe the behavior of the proposed LOE relay in the absence of STATCOM. First, the normal conditions are examined in the simulation and then the output waveforms for the resistance and the derivative of the resistance are displayed. Figures 7(a) and 7(b) show the output diagram of R and $\frac{dR}{dt}$ under normal conditions, respectively. Next, to show that the proposed method is reliable and efficient for all loading situations, some inductive and capacitive, heavy and light loads are tested. Since the LOE occurs in the fifth second, Figure 8 shows the diagram of R and $\frac{dR}{dt}$ in low load of L=0.1+J0.5.

The diagram illustrating the resistance indicates that in the moments preceding the fault, the resistance value follows a sinusoidal pattern with a positive value. However, when the fault occurs, the resistance value, which is dependent on the voltage, begins to decrease. The derivative of the resistance becomes negative after the LOE event that occurs in the fifth second, remaining negative until the ninth second, after which it starts to increase again. In the following, the capacitive load is examined. Figure 9 displays the value of the resistance and the derivative of the resistance in the load L=0.3-J0.2 and it can be seen that in this load and in inductive loads, the resistance value starts to decrease at the beginning of the fault but will remain positive. Furthermore, according to the diagram, the resistance derivative stays negative for longer than 1.67 seconds, so it is concluded that the proposed method can be used as a valid indicator for LOE fault identification.



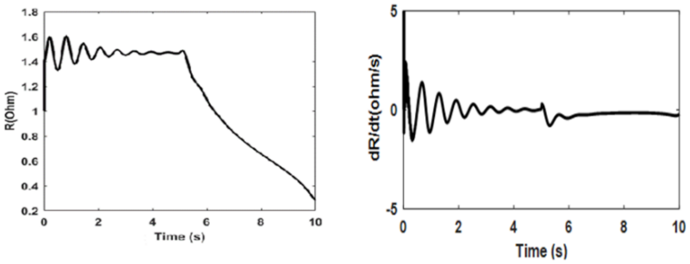
(a)-R (b)- $\frac{dR}{dt}$

Fig. 7. Diagrams derived from the simulation under normal conditions



(a)-R (b)- $\frac{dR}{dt}$

Fig. 8. Diagrams derived from the LOE simulation for the load of L=0.1+J0.5

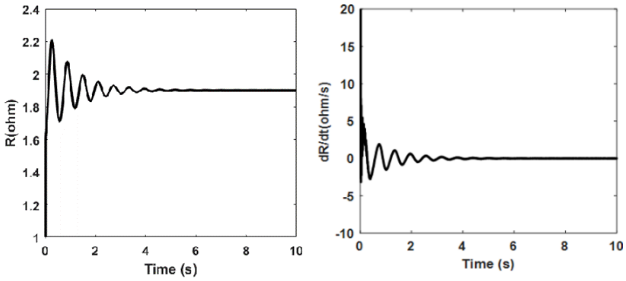


(a)-R (b)- $\frac{dR}{dt}$

Fig. 9. Diagrams derived from the LOE simulation for the load of L=0.3 J0.2

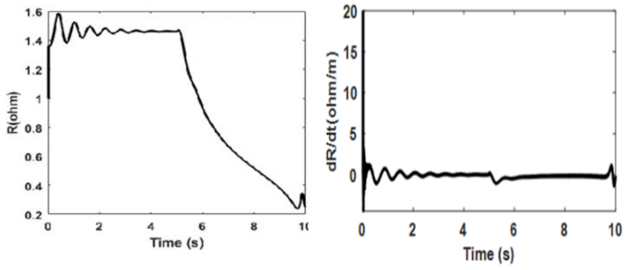
B. Simulation in the Presence of the STATCOM

This section addresses the behavior of the proposed method in the presence of STATCOM. First, Figure 10 displays the output diagram of the resistance and the derivative of the resistance in the normal state. According to this diagram, the resistance value seen in the generator terminal is sinusoidal with a positive value and is the same as in the absence of STATCOM, and the derivative diagram of resistance starts to decrease after a few oscillations and finally approaches the zero point. Now, the condition of the fault detection in different loads is examined. First, the output waveform for inductive load L=0.1+J0.5 is shown in Figure 11. According to this figure and the fact that the fault occurs in the 5th second, it can be concluded that like the case of the absence of STATCOM, the proposed method gives the correct answer to detect the LOE fault in such a way that the value of R is positive, and its derivative remains negative for a long time. Figure 12 shows the output diagram of resistance and its derivative in the case of capacitive load L=0.3-J0.2 in the presence of STATCOM. According to these diagrams and in comparison to the other situations, it can be seen that the new method can distinguish the LOE in this situation too.



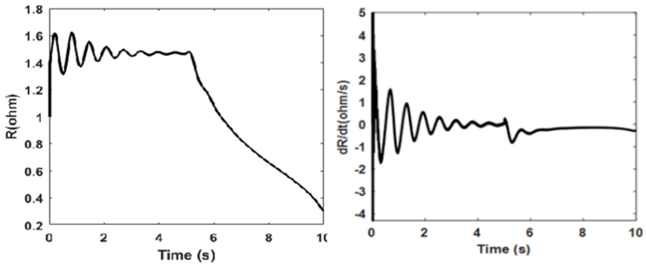
(a)-R (b)- $\frac{dR}{dt}$

Fig. 10. Diagrams derived from the simulation at Normal state in the presence of STATCOM



(a)-R (b)- $\frac{dR}{dt}$

Fig. 11. Diagrams derived from the simulation for the load of L=0.1+J0.5 in the presence of STATCOM

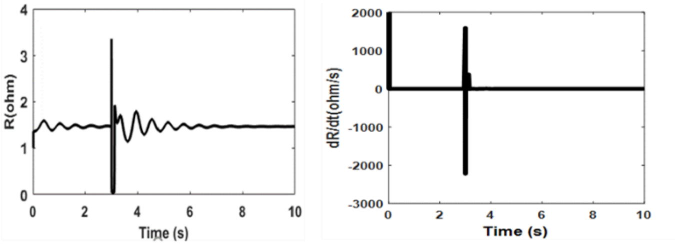


(a)-R (b)- $\frac{dR}{dt}$

Fig.12. Diagrams derived from the simulation for the load of L= 0.3-J0.2 in the presence of STATCOM

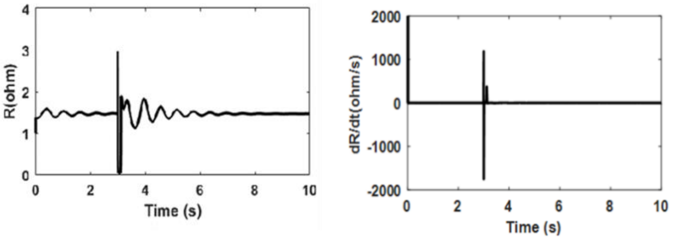
C. SPS conditions Simulation

This section discusses the conditions for detecting SPS and distinguishing it from LOE. SPS is caused by a short circuit fault. In SPS conditions, unlike LOE conditions, the dR/dt output graph fluctuates positively and negatively and returns to normal after a few seconds. Figure 13 shows the behavior of resistance and its derivative in SPS mode at load L=0.1+J0.5 in the absence of STATCOM. SPS starts at the 3rd second and disappears at 1.3. According to the above figure, which shows that the resistance value is positive and according to its derivative becoming positive and negative and finally returning to its initial state, it can be stated that in accordance with the proposed procedure, unlike the LOE detection mode, the derivative value remains negative for a relatively long period of time. The negative time of the resistance derivative is less than 1.67 seconds, so it can distinguish SPS. Figure 14 displays the diagrams of resistance and its derivative in the event of SPS at load L=0.1+J0.5 in the presence of STATCOM. According to these diagrams, it can be expressed that the proposed procedure can detect SPS and distinguish it from LOE fault in this condition.



(a)-R (b)- $\frac{dR}{dt}$

Fig. 13. Diagrams for SPS condition for the load of L=0.1+J0.3 in the absence of STATCOM



(a)-R (b)- $\frac{dR}{dt}$

Fig. 14. Diagrams for SPS condition for the load of L=0.1+J0.3 in the absence of STATCOM

IV. Comparison of Methods

Table 2 shows the operating time of different relays, both in the presence and absence of STATCOM. Based on this performance timetable, the proposed method is much faster than the common methods. Of course, the flux method and flux derivative are the fastest in operation, but as it is known, it is sophisticated to implement these methods.

In terms of computational complexity and implementation difficulty, the proposed method outperforms the other ones such as fuzzy logic [9], neural network [19], and state estimation [20] methods since they need training data and complex mathematical equations and relationships for LOE fault detection.

TABLE 2 COMPARISON OF METHODS

Relay type	**Operating Time**	**Without STATCOM**	**With STATCOM**	**Setting Free**
Positive Offset	11.2	Yes	No	**No**
Berdy	10.4s	Yes	No	**No**
Fuzzy Logic	9.1s	Yes	No	**No**
Flux	3.1s	Yes	Yes	**Yes**
Flux Derivative	1.7s	Yes	Yes	**Yes**
Proposed Method	5.35s	Yes	Yes	**Yes**

V. Conclusions

Considering that most methods of LOE fault detection and their distinguishing from SPS are based on impedance paths, these methods cannot often differentiate between the two options. Consequently, an intentional time delay is employed to prevent the improper operation of the impedance relay. However, this time delay is not an ideal solution, as it increases the stress on both the generator and the system. This paper proposed an algorithm based on the resistance derivative method that can effectively detect LOE and SPS and distinguish between them in the presence of STATCOM in different capacitive and inductive loads. Specifically, if the derivative of the resistance remains negative for longer than 1.67 seconds, it indicates an LOE fault. If it is shorter, it indicates an SPS. A key advantage of this proposed method, unlike impedance-based methods that require setting, is that it does not necessitate any adjustments.

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