

A Setting-Free Approach to Detecting Loss of Excitation in Synchronous Generators

Behnam Mahamedi, Jian Guo Zhu, *Senior Member, IEEE*, and Sayyed Mohammad Hashemi

Abstract—Synchronous generators of any size require to be protected against loss of excitation because it can cause harmful effects to both the generator and power grid. This paper proposes a new setting-free approach to detecting loss of excitation in synchronous generators. Unlike the conventional method which requires a demanding work to set the relays, the proposed method does not require any threshold to act. It will be shown that after loss of excitation, the rate of change of resistance measured by relay 40 (ANSI Code for protection against loss of excitation) will become negative and remain negative for a while. On the other hand, it will be shown that during the slowest power swings, the rate of change of resistance cannot remain negative for more than 1.7 seconds. This, therefore, can be used as a criterion for detecting the loss of excitation of a synchronous generator. The main advantages of the proposed method are that it is setting-free and meanwhile acts faster than the most famous method introduced in 1949.

Index Terms—Generator protection, impedance locus, loss of excitation, measured resistance, power swing.

I. INTRODUCTION

SECURE and reliable operation of power systems is mainly guaranteed by protection relays, the worthy devices which prevent electrical equipment from being damaged by system faults, and preserve system stability following large disturbances. To provide a reliable protection system, all system components including power lines, transformers, generators, and capacitor banks, etc., should be protected by appropriate protective functions. Among these components, generators are the sources of power systems and should be protected with the highest accuracy and reliability. There are different protective functions associated with generation units which protect the units against internal and external faults. It can be claimed that the most challenging abnormal/fault conditions in a generator to deal with are those interacting with transmission systems, and one of them is the loss of excitation (LOE) [1]. The NERC implies that in order “to reduce the number of unnecessary trips of generators during system disturbances”, it is necessary to provide a “proper protection and control coordination between power plants and the transmission system” [2].

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LOE protection, with the ANSI code 40, is one of the necessary protective functions for generators of any size that trips the generator when its excitation system is completely or partially lost. An LOE occurs when the DC source of the generator field is interrupted due to incidents such as open circuit in the field, a short circuit in the field, accidental tripping of the field circuit breaker, a regulator control system failure, loss of field in the main exciter, or a loss of AC supply to the excitation system [3]. Following the LOE, the synchronous generator still produces active power and starts consuming reactive power from the grid. The extension of this condition will impose serious effects on both the generator and transmission network to which it is connected and finally result in loss of synchronism and generator instability. A fully loaded steam turbine generator, for instance, will lose its synchronism within a few seconds after an LOE [4] and protective actions, e.g. tripping the LOE-exposed generator, should be taken within this short time interval. LOE protection plays an important role in power plant stability and prevents the generators from inadvertent tripping. Various examples of LOE-related events in power plants are presented in [5] and [6], showing the importance of LOE protection from the practical viewpoint.

Relays 40 are traditionally mho-type impedance relays (sometimes known as R-X relays). The earlier version of these relays comprise one off-set zone lying in the lower side of R-X plane introduced by Mason [7], while the later versions contain two characteristic zones [8], aiming to improve the relay robustness during transient swings and low frequency disturbances. There are also some other types of LOE protection schemes, though not being widely used, such as the R-X with directional element scheme, G-B scheme, P-Q scheme and U-I scheme [9], [10]. A comparison of these schemes is presented in [9], in terms of the operation speed, accuracy and reliability in different operating modes of generators.

The conventional settings for relay 40 introduced in [7], which is the most common approach because of its excellent performance, are the offset equal to the half the generator transient direct axis reactance ($X_d'/2$) and the diameter of generator direct axis reactance (X_d). Considering a time delay to provide a secure operation of the relay is the most demanding part of the setting process. Moreover, the relay settings should be coordinated with the generator controls such as under-excitation limit, steady state limit and AVR response [2]. It is shown in [11] that the impedance loci in open-circuit LOE faults enter to the relay 40 zones faster than those of short-circuit faults, and the adaptive relaying is proposed for in-

creasing the operation time of relay 40. Some guidelines are provided in [12] to improve the performance of relays 40 in isolated systems. Moreover, a real time digital simulator (RTDS) framework is introduced in [13] in order to coordinate between LOE protection and generator under-excitation controls considering power system dynamics.

Efforts to develop the LOE protection include artificial neural network based fault classification [14], protection by using the rate of change of reactance [15], LOE relay based on fuzzy interface mechanisms [16], enhanced LOE protection using phasor measurements [17], combined criteria using voltage magnitude, voltage angle, and reactive power [18], LOE detection using decision tree technique [19], and protection using LOE index which is calculated by the generator's terminal voltage and output reactive power [20].

LOE relays may experience some adverse effects when the transmission lines connected to the generator are compensated with FACTS controllers, especially with the midpoint STATCOM [21]-[23]. Artificial Neural Network (ANN) and Support Vector Machine (SVM) are suggested as useful techniques for LOE protection in this case [21]. Meanwhile, a new LOE relay based on the flux versus negative sequence current (FVNCS) is proposed in [22] to remove STATCOM effects, and it has been claimed that the FVNCS relay is faster than R-X relay and does not require coordination with other relays. The method presented in [23] uses the same characteristics of conventional R-X LOE relay, but employs PMU measurements to correct the impedance seen by the relay.

In this paper, a new setting-free approach to LOE detection is proposed. It will be shown that after a few seconds from LOE occurrence, the rate of change of resistance measured at the generator terminal (the location of relay 40) will become and remain negative. To secure the proposed method against false detection, a time delay is predicted since during other disturbances, particularly power swings, the rate of change of resistance will become and remain negative. It will then be shown that during the slowest swings, the rate of change of measured resistance will not be negative for more than 1.7 seconds, while in an LOE, it will remain negative for more than this time.

II. PROPOSED METHOD

A. Developing the Idea

LOE occurs in synchronous generators when the field current is lost either due to short-circuit or open-circuit in the field winding. To demonstrate an LOE condition, assume a synchronous generator connected through a transformer to the main grid. Fig. 1 shows the single-line diagram of the connection. When an LOE is observed by relay 40, because the LOE has a symmetrical nature, the equivalent circuit of system after the LOE occurrence can be modeled per phase as shown in Fig. 2. When the LOE occurs, the magnitude of generator internal voltage (E_G) will decrease. This causes variations in voltages and currents at the generator terminal resulting in changes in impedance measured by the relay.

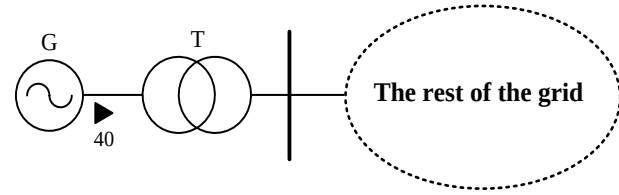


Fig. 1. Connection of a synchronous generator to the grid through a power transformer.

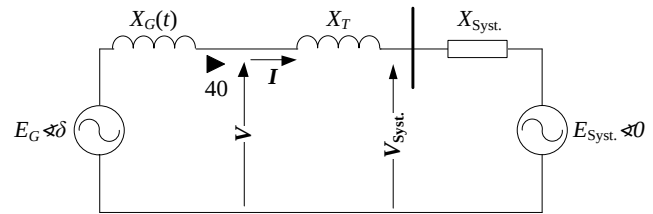


Fig. 2. Equivalent circuit illustrating the connection of the generator to the main grid after LOE occurrence.

In Fig. 2, $X_G(t)$ is the reactance of generator during LOE, X_T is the leakage reactance of transformer, and $X_{Syst.}$ and $E_{Syst.}$ are the equivalent reactance and equivalent voltage of transmission grid, respectively. From the LOE occurrence, X_G varies until it settles to a value between the average of the direct-axis and quadrature-axis sub-transient reactances $(X_d'' + X_q'')/2$ and the average of the direct-axis and quadrature-axis synchronous reactances $(X_d + X_q)/2$ [7]. Hence, it is reasonable to consider it as a function of time starting from the LOE occurrence. From Fig. 2, it can be derived as

$$V = E_G \angle \delta - jX_G(t) \cdot I \quad (1)$$

$$I = \frac{E_G \angle \delta - E_{Syst.} \angle 0}{j(X_G(t) + X_T + X_{Syst.})} \quad (2)$$

Dividing (1) by I results in

$$Z = \frac{V}{I} = \frac{E_G \angle \delta - jX_G(t) \cdot I}{I} = \frac{E_G \angle \delta}{I} - jX_G(t) \quad (3)$$

Substituting I from (2) into (3), one can find the impedance measured at the generator terminal as

$$Z = j \cdot \frac{E_G \angle \delta}{E_G \angle \delta - E_{Syst.} \angle 0} \cdot (X_G(t) + X_T + X_{Syst.}) - jX_G(t) \quad (4)$$

Assuming $k = E_{Syst.}/E_G$, the impedance can be ultimately expressed as

$$Z = \frac{k \cdot \sin \delta}{1 + k^2 - 2k \cdot \cos \delta} \cdot X_{Tot.}(t) + j \cdot \left(\frac{1 - k \cdot \cos \delta}{1 + k^2 - 2k \cdot \cos \delta} \cdot X_{Tot.}(t) - X_G(t) \right) \quad (5)$$

where

$$X_{\text{Tot.}}(t) = X_G(t) + X_T + X_{\text{Syst.}} \quad (6)$$

By splitting the real and imaginary parts of (5), the resistance and reactance measured by relay 40 are

$$R(t) = \frac{k(t) \cdot \sin \delta}{1 + k(t)^2 - 2k(t) \cdot \cos \delta} \cdot X_{\text{Tot.}}(t) \quad (7)$$

$$X(t) = \frac{1 - k(t) \cdot \cos \delta}{1 + k(t)^2 - 2k(t) \cdot \cos \delta} \cdot X_{\text{Tot.}}(t) - X_G(t) \quad (8)$$

Here, the real part, $R(t)$, of impedance measured by relay 40 will be utilized to develop a method for LOE detection. When the LOE occurs, k starts increasing while δ can be safely assumed as a constant since the generator still keeps its synchronism. Taking derivative of (7) in terms of time will then result in

$$\begin{aligned} \frac{dR}{dt} = & \underbrace{\frac{(1 - k(t)^2) \cdot \sin \delta}{(1 + k(t)^2 - 2k(t) \cdot \cos \delta)^2} \cdot \frac{dk}{dt} \cdot X_{\text{Tot.}}(t)}_{\text{first term}} \\ & + \underbrace{\frac{k(t) \cdot \sin \delta}{1 + k(t)^2 - 2k(t) \cdot \cos \delta} \cdot \frac{dX_{\text{Tot.}}(t)}{dt}}_{\text{second term}} \end{aligned} \quad (9)$$

Since k increases, dk/dt is positive. Therefore, as long as k is less than 1, that is $E_{\text{Syst.}} < E_G$, the first term of (9) will be positive. This condition is not threatening the generator itself and the power system to which it is connected since it has not yet turned to a “sink” of reactive power. During this period it is not possible to judge the sign of the second term since the variation of $X_{\text{Tot.}}(t)$ is non-monotonic and $dX_{\text{Tot.}}(t)/dt$ can be either positive or negative. However, after a few seconds when $X_G(t)$ settles to its final value, the second term will become zero. At this time, k has increased far more than 1, that is $(1 - k^2)$ becomes negative while dk/dt still remains positive. Therefore, after a period of time, the first term will become and remain negative and so will dR/dt . As a result, the relay will observe the rate of change of $R(t)$ and if dR/dt becomes and remains negative for a while, LOE can be detected.

During a power swing, similar condition can occur which means that dR/dt becomes and remains negative for a while. To distinguish the LOE from the power swing, it is then necessary to determine for how long dR/dt will remain negative during power swing at the worst case.

Under the power swing conditions, on the contrary, δ will change and k can be safely assumed constant. Moreover, X_G is very close to X_d' and can be considered as a constant and so $X_{\text{Tot.}}$. Therefore, dR/dt during the power swing will be

$$\frac{dR}{dt} = \frac{dR}{d\delta} \cdot \frac{d\delta}{dt} = \frac{(1 + k^2) \cdot k \cdot \cos \delta(t) - 2k^2}{(1 + k^2 - 2k \cdot \cos \delta(t))^2} \cdot \frac{d\delta}{dt} \cdot X_{\text{Tot.}} \quad (10)$$

Without losing generality, assume $k=1$ during the power swing, and one obtains

$$\frac{dR}{dt} = \frac{2 \cdot \cos \delta(t) - 2}{(1 + k^2 - 2k \cdot \cos \delta(t))^2} \cdot \frac{d\delta}{dt} \cdot X_{\text{Tot.}} \quad (11)$$

Since $(2\cos\delta - 2)$ is always negative, the sign of dR/dt is opposite that of $d\delta/dt$. According to [24]–[27] and many records in different utilities worldwide, $d\delta/dt$ oscillates with the frequency between 0.3 and 7 Hz. Thus, the longest period of $d\delta/dt$ that can be expected during a power swing is $1/0.3=3.33$ seconds, as illustrated in Fig. 3. As shown, in half of this period, $d\delta/dt$ remains positive. Therefore, during the slowest power swing dR/dt will not remain negative for more than 1.67 seconds. To distinguish an LOE from the power swings, relay 40 should then wait for 1.67 seconds and if dR/dt still remains negative, an LOE can be detected. Considering a safety margin, one can set the time delay to 1.7 seconds.

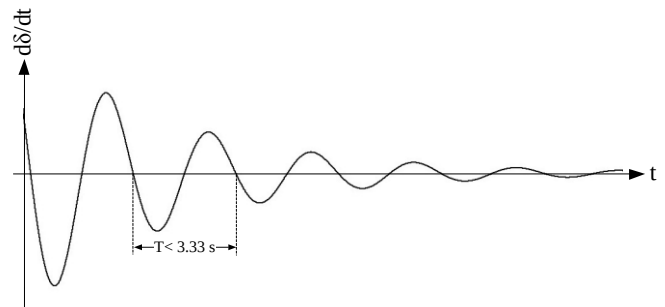


Fig. 3. Oscillations of $d\delta/dt$ during the slowest power swing.

B. Logic of the Proposed Method

Fig. 4 shows the proposed method in a logical pattern. At first, the relay calculates dR/dt . Once dR/dt is non-zero, it will check the sign of dR/dt . If dR/dt becomes and remains negative for more than 1.7 seconds, an LOE can be detected and a trip signal is sent to the generator circuit breaker (GCB). If dR/dt remains negative for less than 1.7 seconds and changes to positive, a power swing or an out-of-step condition can be identified.

It can be inferred that the proposed method acts as a setting-free method since there is no need to set any threshold for the rate of change of R and only its sign is required. Moreover, the generator and system parameters are not required to be known.

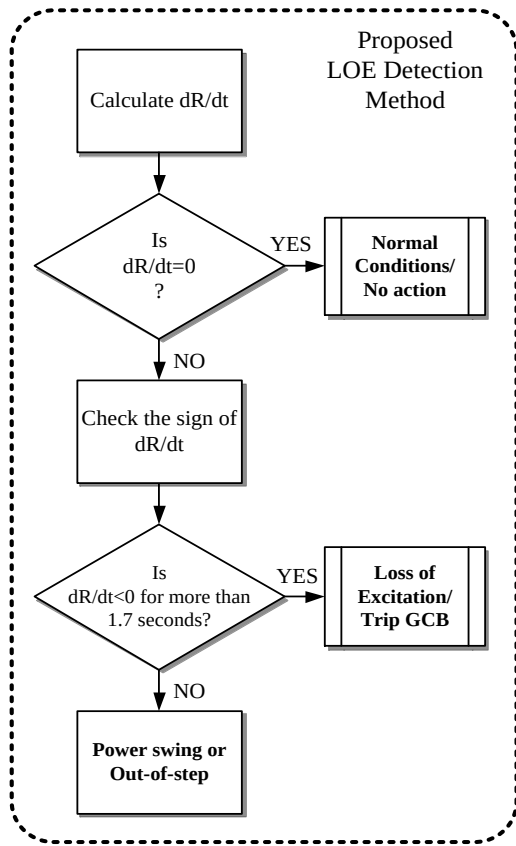


Fig. 4. Proposed method in a logical pattern.

III. SIMULATION EXPERIMENTS

In this section, the performance of the proposed method will be evaluated. To demonstrate the superiority of the proposed method over the conventional ones, its performance will be compared to one of the most famous conventional method introduced by Mason [7]. This conventional method detects an LOE based on the impedance measured at the generator terminal in the RX plane. Fig. 5 shows the operating area of Mason's method. After an LOE, the impedance locus will become closer to the circular characteristic and when it enters into the characteristic, the relay will trip after a time delay which should be set. Moreover, the offset and the diameter of the circle should also be set. As previously mentioned, Mason suggested $X'_d/2$ (half the transient reactance of the generator) for the offset and X_d (synchronous reactance) for the diameter. Therefore, these parameters of the generator are required which are sometimes not provided accurately. We will compare the performance of the proposed method with this conventional one.

To do this, a power plant with all lines connected to it were simulated. Fig. 6 shows the single line diagram of the power plant. In the simulated system, there are two types of generators including gas and steam turbine generators. G_1 to G_4 are steam turbine generators and G_5 to G_{12} are gas turbine generators. Moreover, the steam units are connected to 400-kV voltage level while the gas units are connected to 230-kV voltage level. The proposed method will be evaluated for the LOE in

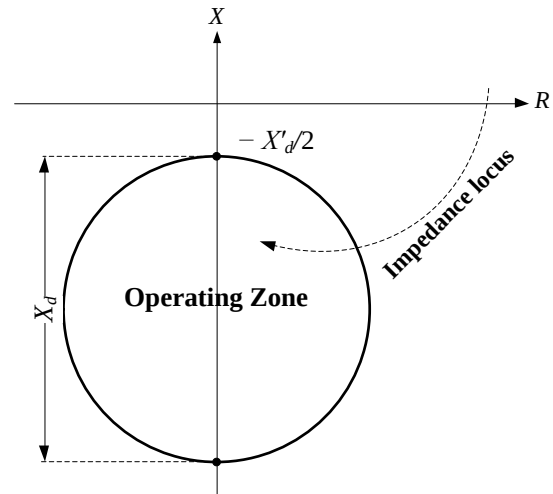


Fig. 5. Operating characteristic of the conventional method proposed in [7].

both types of generators.

A. Evaluating the Performance of Proposed Method for Complete LOE Scenarios

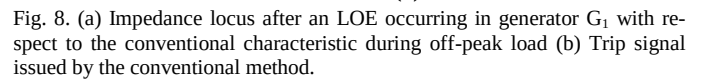
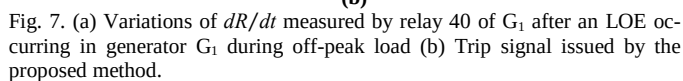
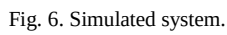
The performance of the proposed method will be scrutinized for two load conditions, off-peak and peak loads because there is a measurable difference between LOEs occurring in off-peak and peak loads.

1) Evaluating for off-peak load

In the first scenario, we assume steam turbine generator G_1 loses its excitation at $t=0.2$ seconds in the simulated system. Fig. 7(a) shows dR/dt measured by relay 40 of the generator after an LOE. As shown, following some oscillations, dR/dt becomes and remains negative. After the last positive cycle, the relay starts counting and **if dR/dt remains negative for more than 1.7 seconds**, a trip signal will be sent to the generator circuit breaker. Fig. 7(b) shows a trip signal beginning at $t=2.69$ seconds.

Fig. 8(a) shows the impedance locus with respect to the conventional LOE characteristic. In this method, it is a common practice to present all values including impedance locus and setting parameters in per-unit (pu) with the base impedance of the generator. The impedance locus enters into the characteristic at $t=3.56$ seconds and after a time delay which is usually set to 0.5 seconds, it will issue the trip signal at $t=4.06$ seconds as shown in Fig. 8(b).

In the second scenario, gas turbine generator G_5 loses its excitation at $t=0.2$ seconds. Fig. 9(a) shows dR/dt measured by relay 40 of the generator after an LOE. Similar to the first scenario, following some oscillations, dR/dt becomes and remains negative. Therefore, after the last positive cycle, the relay counts a timers and if dR/dt remains negative for more than 1.7 seconds, the trip signal will be sent to the generator circuit breaker. Fig. 9(b) shows the trip signal beginning at $t=2.89$ seconds.



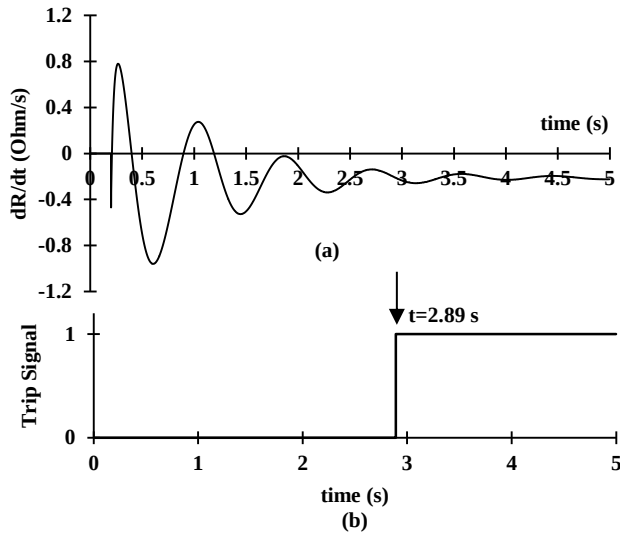


Fig. 9. (a) Variations of dR/dt measured by relay 40 of G_5 after an LOE occurring in generator G_5 during off-peak load (b) Trip signal issued by the proposed method.

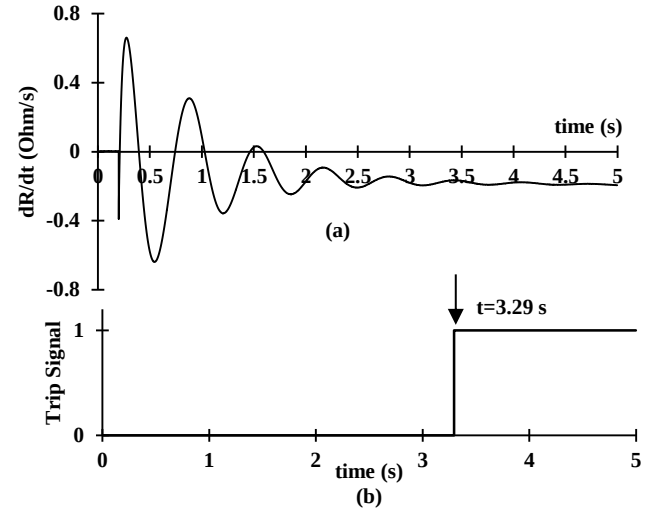


Fig. 11. (a) Variations of dR/dt measured by relay 40 of G_5 after an LOE occurring in generator G_5 during peak load (b) Trip signal issued by the proposed method.

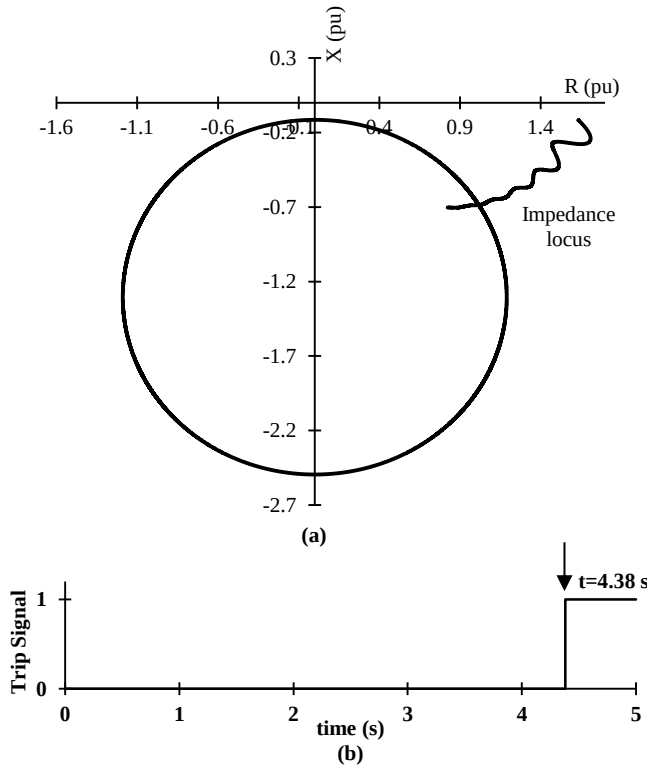


Fig. 10. (a) Impedance locus after an LOE occurring in generator G_5 with respect to the conventional characteristic during off-peak load (b) Trip signal issued by the conventional method.

Fig. 10(a) shows the impedance locus with respect to the conventional LOE characteristic set by the aforementioned values. The impedance locus enters into the characteristic at $t=3.88$ seconds and after a time delay of 0.5 seconds, it will issue the trip signal at $t=4.38$ seconds as shown in Fig. 10(b).

2) Evaluating for peak load

The similar scenarios are studied for peak load. At $t=0.2$ seconds, generator G_1 loses its excitation. Fig. 11(a) shows the

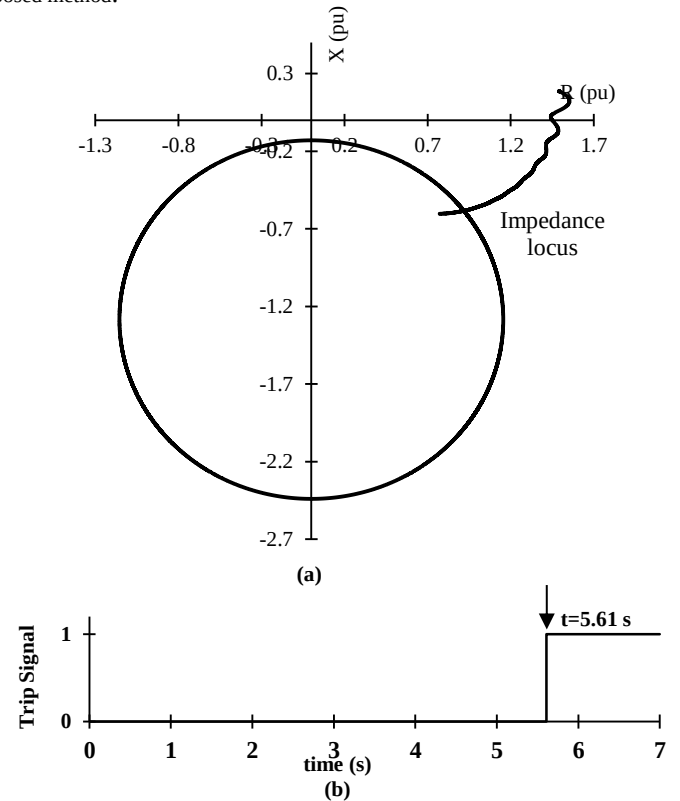


Fig. 12. (a) Impedance locus after an LOE occurring in generator G_1 with respect to the conventional characteristic during peak load (b) Trip signal issued by the conventional method.

variations of dR/dt showing that after a few seconds it becomes and remains negative. Fig. 11(b) shows the trip signal issued by the proposed method at $t=3.29$ seconds.

Fig. 12(a) shows the impedance locus with respect to the conventional LOE characteristic for this scenario. The impedance locus enters into the characteristic at $t=5.11$ seconds and after a time delay of 0.5 seconds, it will issue the trip signal at $t=5.61$ seconds as shown in Fig. 12(b).

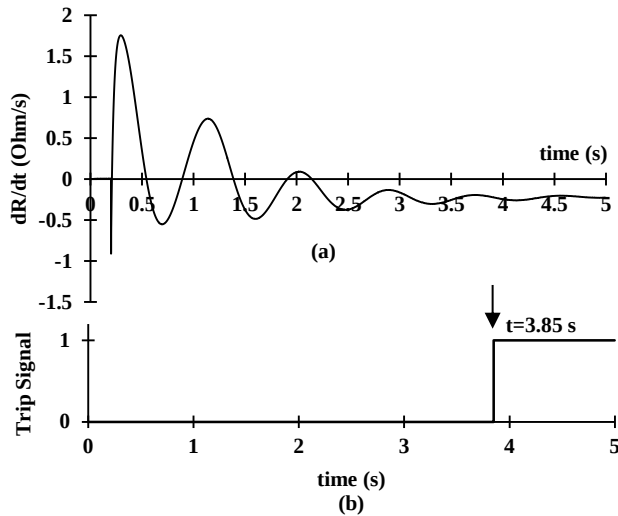


Fig. 13. (a) Variations of dR/dt measured by relay 40 of G_5 after an LOE occurring in generator G_5 during peak load (b) Trip signal issued by the proposed method.

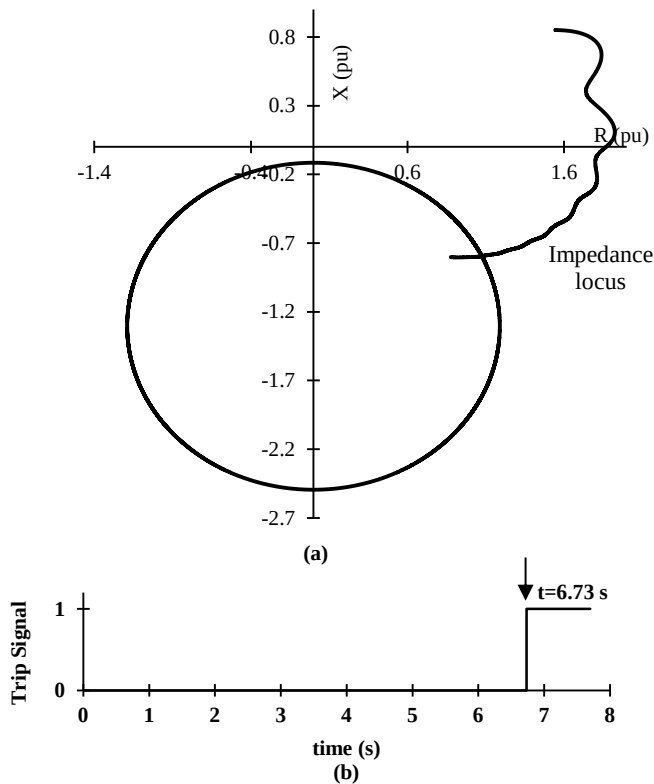


Fig. 14. (a) Impedance locus after an LOE occurring in generator G_5 with respect to the conventional characteristic during peak load (b) Trip signal issued by the conventional method.

In the second scenario, G_5 loses its excitation at $t=0.2$ seconds. Figs. 13(a) and 13(b) show the variations of dR/dt and the trip signal beginning at $t=3.85$ seconds, respectively.

Figs. 14(a) and 14(b) show the performance of the conventional method for this scenario and the trip signal starting at $t=6.73$ seconds, respectively.

B. Evaluating the Reliability of Proposed Method

It is necessary to scrutinize how the proposed method re-

spond to other disturbances threatening the reliability of LOE relays. One of the most possible disturbances is the power swing which has caused mal-operation to the conventional method in some cases. In this section, the performance of the proposed method will be investigated under power swing conditions. Numerous power swing scenarios have been studied, but only two of them are presented here to avoid lengthening the paper as follows.

In the first scenario of power swing, a three-phase fault occurs on one of the circuits of line L7 at $t=0.2$ seconds. The fault will be cleared by the action of the line relays and opening the corresponding circuit breakers at $t=0.6$ seconds. It is assumed that the relays have detected the fault after 0.4 seconds from occurrence. In the second scenario, a three-phase fault occurs on line L9 at $t=0.2$ seconds and will be cleared by the action of the line relays and opening the corresponding circuit breakers at $t=0.3$ seconds.

Fig. 15 shows the variations of dR/dt measured by relay 40 of generator G_1 during the first power swing scenario. As can be seen, during the power swing, there is no time interval more than 1.7 seconds in which dR/dt remains negative. Therefore, no trip signal will be issued by the proposed technique.

Fig 16 shows the variations of dR/dt measure by relay 40 of generator G_5 for the first power swing scenario. Similar to G_1 , there is no time interval more than 1.7 seconds in which dR/dt remains negative. Therefore, proposed relay 40 of G_5 will also not act to this scenario.

The results for the second power swing scenario from the viewpoint of G_1 and G_5 relays have been depicted in Figs. 17 and 18, respectively. Similar to the first scenario, dR/dt will not remain negative for more than 1.7 seconds during the second scenario from viewpoint of both relays.

These results clearly indicate the reliability of the proposed method during other disturbances.

C. Evaluating for a Partial LOE and an LOE Occurring During Power Swings

It is of interest to investigate how the proposed method respond to a partial LOE and to an LOE occurring during power swings. A partial LOE in generator G_1 in which G_1 loses half of its excitation voltage was then simulated at $t=0.2$ seconds.

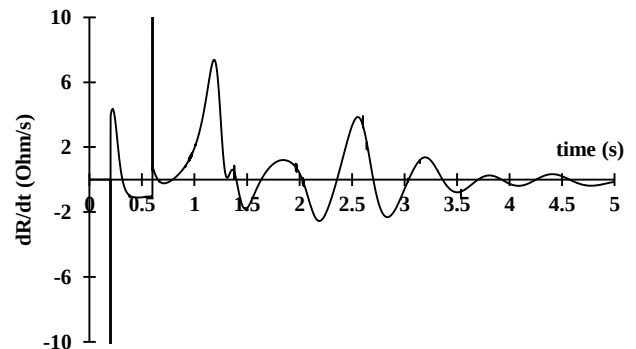


Fig. 15. Variations of dR/dt measured by the proposed relay 40 of generator G_1 during the first power swing scenario.

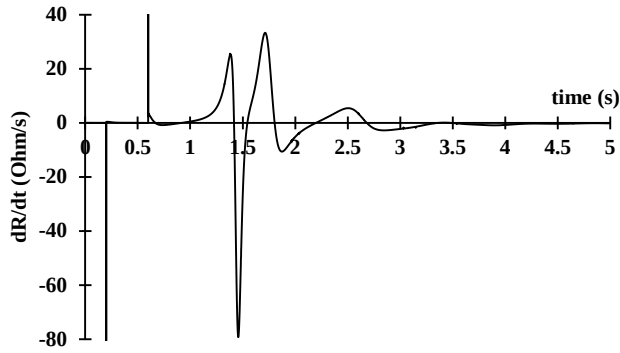


Fig. 16. Variations of dR/dt measured by the proposed relay 40 of generator G_5 during the first power swing scenario.

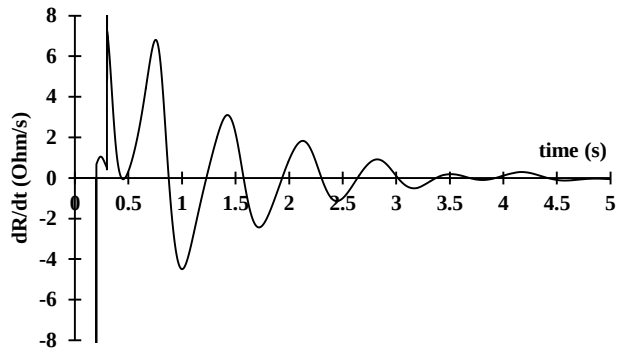


Fig. 17. Variations of dR/dt measured by the proposed relay 40 of generator G_1 during the second power swing scenario.

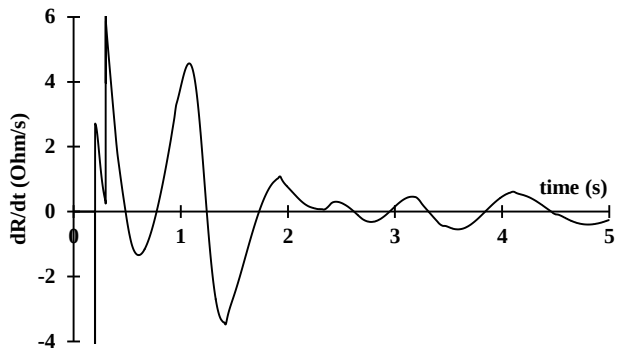


Fig. 18. Variations of dR/dt measured by the proposed relay 40 of generator G_5 during the second power swing scenario.

Fig. 19 shows variations of dR/dt for this scenario. Trip signal is issued at $t=2.69$ seconds, 2.49 seconds from LOE occurrence. Fig. 20 shows the response of the conventional method to the partial LOE for which it trips the generators at $t=7.10$ seconds. It can be obviously seen that the proposed method acts much faster than the conventional method.

As seen, the proposed method still works for this case, which means dR/dt becomes and remains negative. The only difference is the steady-state negative value (about -0.1 Ohm/s) which is more than the case obtained in case of complete LOE (about -0.2 Ohm/s). However, it does not matter

since the proposed method works with the sign of dR/dt not with its steady-state value.

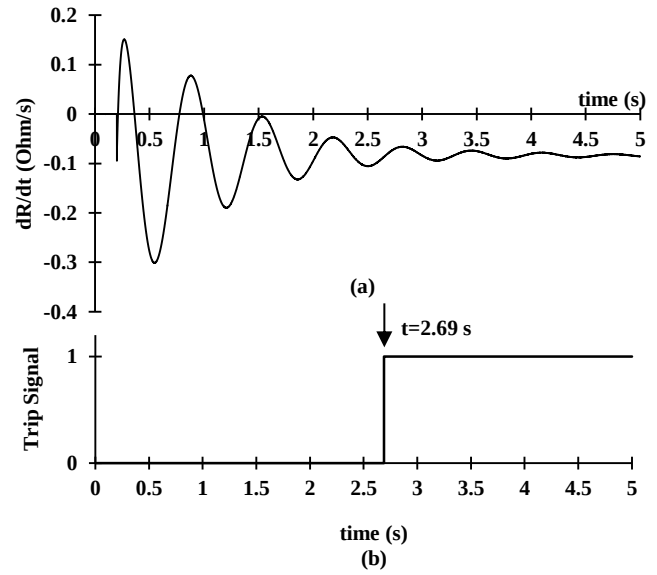


Fig. 19 (a) Variations of dR/dt measured by relay 40 of G_1 after a partial LOE occurring in generator G_1 (b) Trip signal issued by the proposed method.

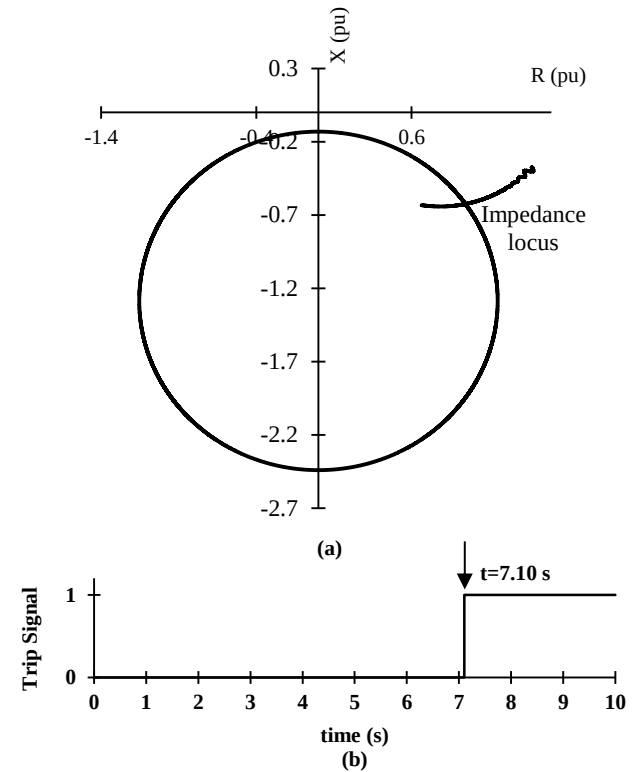


Fig. 20. (a) Impedance locus after a partial LOE occurring in generator G_1 with respect to the conventional characteristic (b) Trip signal issued by the conventional method.

Fig. 21 shows dR/dt during a power swing when an LOE occurs at $t=2.5$ seconds. During the power swing dR/dt does not remain negative for more than 1.7 seconds while after

LOE occurs, dR/dt becomes and remains negative for more than 1.7 seconds. Trip signal is issued at $t=4.44$ seconds, 1.94 seconds after LOE occurrence.

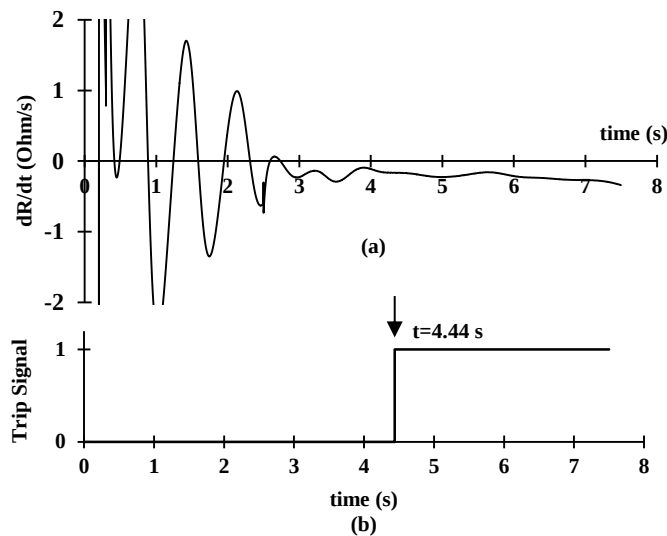


Fig. 21 (a) Variations of dR/dt during power swing and when an LOE occurs at $t=2.5$ seconds (b) Trip signal issued by the proposed method.

IV. CONCLUSION

This paper describes a setting-free method for detecting loss of excitation in synchronous generators. It was shown that after a short period from loss of excitation, the rate of change of resistance measured at the generator terminals will become and remain negative. In order to secure the proposed technique to other disturbances such as power swings and out-of-step, a time interval of 1.7 seconds was considered and the proposed method should issue the trip signal after this time delay. The superiority of the proposed method over other existing ones can be summarized as follows:

- The main advantage of the proposed method is that it is setting-free which means that there is no need to know about generator and system parameters.
- It acts faster than the conventional methods and thus can isolate the generator suffering from an LOE with less time delay.
- The proposed technique is reliable and does not respond to the power swings and out-of-step conditions, which are threatening the operation of the conventional methods.

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