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A High Speed Method for Loss of Excitation Detection

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***Abstract*—In case of generator protection, accurate detection of loss of excitation (LOE) of generator is a major concern for power system operation. The conventional approach based on impedance trajectory is prone to mal-operate during stable power swing (SPS) and any large disturbance near the generator bus. Any mal-operation of generator relays threatens both the generator and power system stability. This paper presents a new approach only by investigating the armature current and active power at the generator terminal. This method doesn't consider any intentional time delay. Robustness of method is assured considering different types of loadings. In this work, both the total loss of excitation (TLOE) and partial loss of excitation (PLOE) have been considered. The proposed method is independent of the generator size. The verification of the proposed method and all the required simulations have been done in PSCAD platform.**

Keywords—loss of excitation (LOE) detection, partial loss of excitation (PLOE), stable power swing (SPS), total loss of excitation (TLOE)

I. Introduction

With the advancement of power system components in a power system network, protection scheme should also be adjusted and needs to be revised. In this connection, generator protection scheme plays a vital role. Among all the relays used for generator protection, loss of excitation (LOE) relay is very essential. In a generator, loss of excitation can occur due to several reasons like mal-operation of rotor field circuit breaker, flashover at slip rings, open circuit or short circuit in the rotor winding and excitation system. After loss of excitation, the armature current suddenly reduces for a time interval as the source of reactive power that is excitation starts reducing**.** During this time, speed of alternator slightly increases and runs at super-synchronous speed. Due to this slip, eddy current induces on the rotor surface which may cause damage of the rotor. Simultaneously, the armature starts absorbing the reactive power demanded by the generator from the infinite bus. Hence, stator current becomes very high and stator winding gets heated up and it may get damaged. So, it is very essential to stop the generator before thermal limit is exceeded.

In 1949, the first approach is introduced by Mason to detect LOE using single-phase negative-offset mho relay [1]. Improvement of previous method has been done by Berdy which introduces two negative offset zones in R-X plane [2]. For zone1, time delay of 3 to 5 cycles and 30 to 40 cycles for zone 2 are proposed [8]. But it is mentioned that in case of heavily lagging loaded condition of generator and during 3-phase fault condition near to generator bus or during power swing, the locus of curve in R-X plane directly doesn't enter in the mho relay characteristics and it passes through very closely to the mho relay characteristics [2]. So, there is a high chance of mal-operation of mho relay in a heavily loaded generator.

In [3], authors have proposed LOE detection based on generator terminal voltage and field voltage. This method needs to be changed for different system configuration. ANN based algorithm [4] has been used to classify the LOE and loss of transient stability and here the method requires large number of data. Rate of change of reactance has been used in [5] and set points are decided by the system and machine configuration. An admittance based LOE detection scheme has been proposed by Harman and Smit [9]. Usta et al. [11] have presented a LOE relay on the basis of three phase reactive power out of alternator. Fuzzy logic based LOE detection technique [13] improves the operation time as well as security of system. Terminal voltage and apparent impedance are considered as input in fuzzy inference mechanism. However, when generator starts absorbing huge amount of reactive power this method is unable to discriminate LOE from SPS [21]. Measuring resistance variation at relay terminal, which in turn a setting free approach, is presented in [17]. This method is used for out of step protection but it is unable to detect LOE separately from out of step condition. In 2015, Elsamahy et al. have discussed [18] how midpoint STATCOM affects LOE detection methods and intentional time delay worsen the previous methods. Presence of FACTS devices also causes under reach of relay [20]. In presence of FACTS controllers, a new method [20] based on PMU, has been proposed. Multiplication of variations of reactive power and terminal voltage of generator has been used as an index to detect LOE [21]. This method performs better, however, selection of threshold is dependent on system configuration. An AI technique based on decision tree [22] concept for LOE detection takes a lot of time. Variation of magnetic flux in the air-gap of generator has been used differently for LOE detection and these flux based methods [23-26] are very reliable and eliminates the problem of mal-operation during other system disturbances. However, for the measurement of air-gap flux some sensors are required and hence the whole detection process depends upon the reliability of the magnetic sensors. Discrimination between SPS and LOE has been shown using derivative of output reactive power and terminal voltage. An analytical based technique considering the variation of armature current has been proposed in [28]. The most recent method [29] is the use of slip frequency measured at terminal of alternator. This method can detect LOE accurately but it takes large time. Fuzzy logic based method is also utilized to detect loss of excitation in some research [30]. A few of the authors have used conventional techniques to detect faults in the power network [31-32]. Dynamic state estimation based LOE detection has been done in [33]. Authors in [34] have proposed a setting free scheme to detect LOE.

From the above discussion it is found that some AI based methods work accurately but large number of data is required for training process. Some flux based methods need magnetic sensor which is costly as well as reliability depends on the performance of the sensor. The conventional impedance based approaches need more time for LOE detection because of addition of intentional time delay. So, in this paper a new algorithm is proposed using machine's external parameters i.e. armature current and active power at generator terminal. The algorithm is very simple and doesn't take large time. The threshold values are selected on pu basis and hence the method is independent of system configuration. The proposed algorithm is tested for both TLOE and PLOE and robustness of the method is also achieved.

II. Proposed Scheme

Two important parameters (rms armature current and active power) at the relay location are chosen to develop the algorithm for the detection of LOE event. This section explains why theses parameters are considered for LOE detection and how the algorithm works. Whenever there is a modification or change in power system network configuration, generator terminal parameters also change. In case of generator, terminal voltage is controlled by excitation system and active power output is controlled by the governor. So, when excitation fails in rotor, there is sudden decrease in armature current for a very short interval of time. After that interval, when the field current starts decaying following its time constant, the generator starts absorbing reactive power to magnetize its air-gap and hence the armature current also starts increasing. The time interval when the armature current decreases, is considered to be as LOE detection period. During that time, the change in real power at the generator terminal is negligible due to large inertia of rotor and turbine. On the other hand, when any disturbance occurs near the generator terminal, there is a drastic change in the waveform of armature rms current as well as real power. So, these two parameters are enough to distinguish LOE and the disturbances like SPS, load rejection.

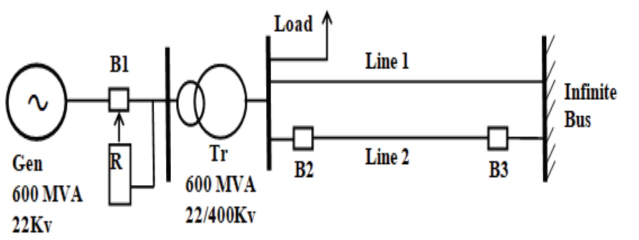


Fig. 1. *Single machine infinite bus system (SMIB) with the proposed scheme*

A SMIB model in Fig. 1 is created in PSCAD and all the case studies have been done in the model. LOE condition has been created by controlling a switch in the exciter model. In this paper, both TLOE and PLOE are considered. To generate a power swing in the generator, a three phase fault is created in the middle of line 2 at 50 km from the generator terminal. A PQ load is connected to generator bus and by opening the circuit breaker, large load rejection is created near generator terminal to check the reliability of proposed method.

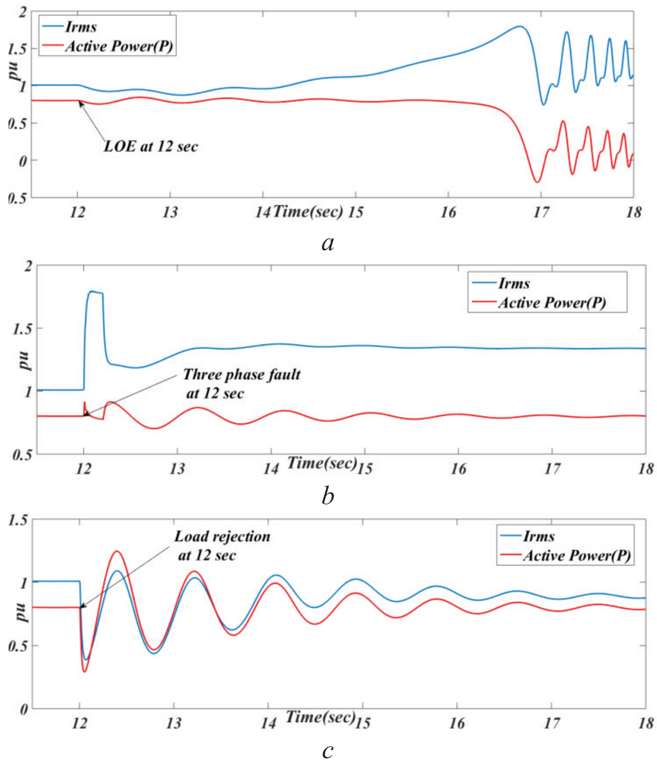


Fig. 2. *Output variables of generator after (a) LOE in generator, (b) three phase fault near to generator bus, (c) load rejection near generator bus*

From Fig. 2(a), there is a decrease in armature current for 2.2 sec then it starts increasing whereas the variation of real power at the relay location is small. The machine goes out of synchronism at 16.8 sec. But in case of 3-phase fault, there is a large fluctuation of real power and armature current increases instantaneously to a high value as shown in Fig. 2(b). In case of large load rejection at generator bus terminal, current decreases abruptly and real power variation is also large as shown in Fig. 2(c).

On the basis of different nature of rms current and active power during different type of disturbances at generator terminal, a new algorithm is developed which is very simple and robust to detect the loss of excitation condition. The proposed algorithm is shown as flow chart to detect loss of excitation event illustrated in Fig. 4. During LOE condition for both open circuit and short circuit in rotor, the nature of rms current and active power signal is same.

All the signals are sampled at 1 kHz and hence we get 1 sample per ms. Here the threshold values are in pu and hence this method is independent system configuration. At first rms armature current is measured at the generator terminals and 100 current sample value is taken. Now, algebraic difference '$\triangle I_r$' between initial value of current and instantaneous value for each sample is calculated using (1) and then $(\triangle I_r)_{sum}$ of all the $\triangle I_r$ of 100 samples are calculated using (2).

$$\triangle I_r = I_{initial} - I_{instantaneous} \quad (1)$$

$$(\triangle I_r)_{sum} = \sum_{n=1}^{100} \triangle I_r \quad (2)$$

Simultaneously, $(\Delta P)_{sum}$ is calculated as follows, active power at each instant is calculated using (3) and then algebraic difference ΔP between initial value of active power and instantaneous value for each sample is calculated using (4). The sum $(\Delta P)_{sum}$ of all the ΔP of 100 samples are calculated using (5).

$$P = real(V_1^* I_1^* + V_2^* I_2^* + V_3^* I_3^*) \quad (3)$$

$$\Delta P = P_{initial} - P_{instantaneous} \quad (4)$$

$$(\Delta P)_{sum} = \sum_{n=1}^{100} \Delta P \quad (5)$$

If this $(\Delta I_r)_{sum}$ is more than -0.01 pu then it's not a LOE condition and if it is less than -0.01 pu then there is chance of occurrence of LOE as well as sudden large load rejection but surely it will not be a 3-phase fault because during 3-phase fault current increases.

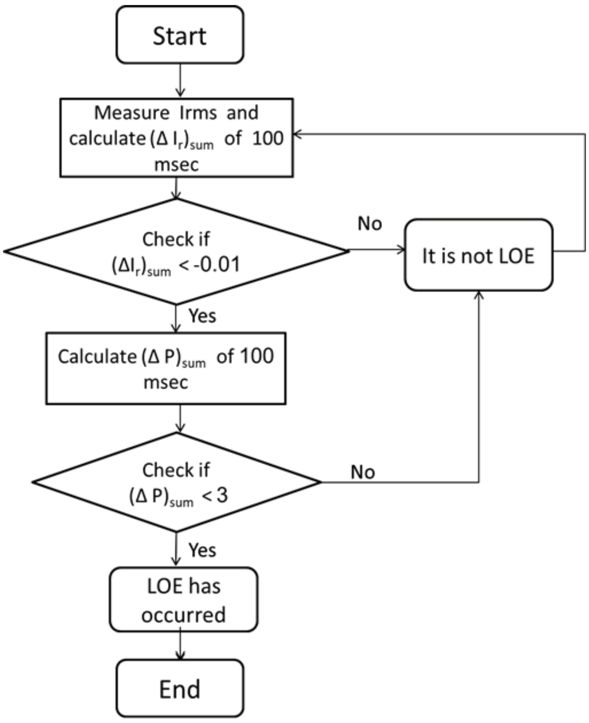


Fig. 3. *Flow chart for the proposed method*

Now if $(\Delta P)_{sum}$ is less than 3 pu then it is a LOE condition due to less fluctuation of active power during LOE, otherwise it is a load rejection condition. The threshold value of $(\Delta I_r)_{sum}$ is set as -0.01 pu and threshold value of $(\Delta P)_{sum}$ is as 3 pu after solving large no of loading conditions in Table 1.

III. Case Studies and Responses

This section consists of results found using the proposed methodology and its performance against LOE condition and other disturbances at the generator terminals like 3phase fault, load rejection. As it is told earlier, heavily loaded generator operating at lagging pf is more prone to mal-operate and at leading power factor, LOE detection is difficult. So, the case studies have been done in SMIB model based on different lagging and leading load conditions. In the Table 1, various loadings are considered to test the proposed method. Out of 15 cases, four important loading conditions are selected and analysed in this paper. Two lagging loads (L1, L4) and two leading loads (L9, L15) are chosen and L1 and L9 are heavy loadings whereas L4 and L15 are light loadings.

TABLE I. Loadings of Generator

Loading	P+jQ pu	Loading	P+jQ pu	Loading	P+jQ pu
L1	0.8+j0.6	L6	0.1+j0.5	L11	0.6-j0.2
L2	0.7+j0.4	L7	0.1+j0.2	L12	0.5-j0.6
L3	0.5+j0.4	L8	0.8-j0.6	L13	0.4-j0.2
L4	0.4+j0.2	L9	0.8-j0.2	L14	0.3-j0.6
L5	0.3+j0.5	L10	0.7-j0.2	L15	0.3-j0.1

A. Generator LOE

The rating of generator is 600 MVA, 22 kV. During loss of excitation, variation of current signal changes with the loading condition of generator.

Comprehensive studies: A sudden fault occurs in the excitation circuit at t=12 sec and the DC field voltage becomes zero. Since the generator loses its excitation voltage, the output reactive power reduces while the active power at the generator terminal is still constant at its initial value. The most usual operation condition is 0.8+j0.6pu loading and corresponding waveforms during LOE is shown in Fig. 4 (a) and (b).

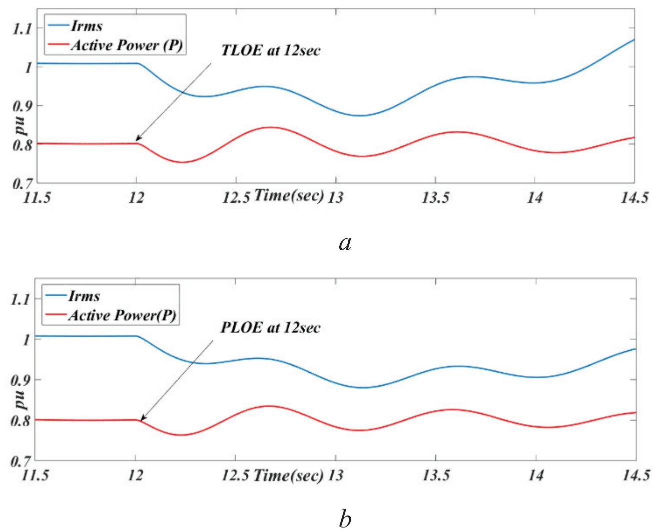
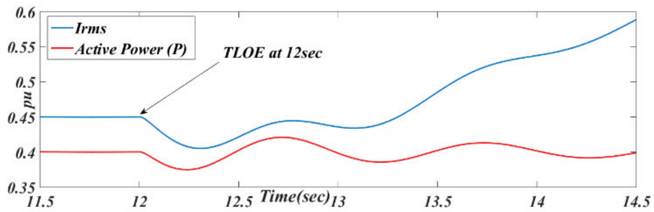


Fig. 4. *Waveform of rms armature current and active power at generator terminals during (a) TLOE, (b) PLOE condition at L1 loading*

From Fig. 4 and 5, it is to be noted that as initial loading decreases, variation in rms armature current and active power also reduces. But for both heavy and light loading, the proposed method can detect LOE very accurately.



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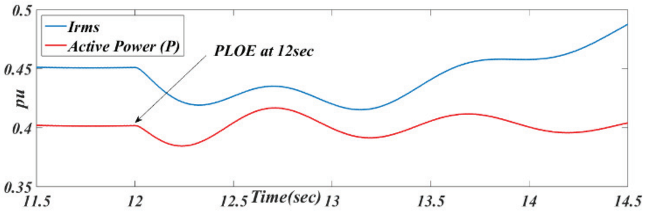

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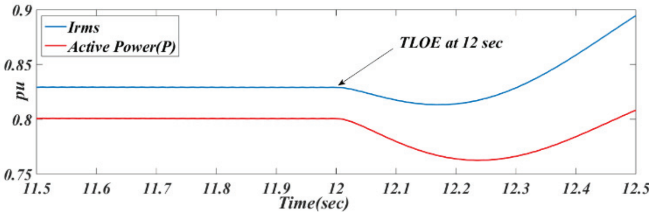
Fig. 5. *Waveform of rms armature current and active power at generator terminals during (a) TLOE, (b) PLOE condition at L4 loading*



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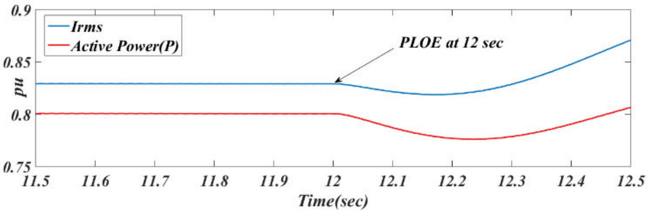

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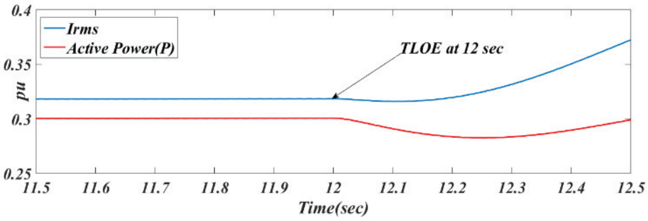
Fig. 6. *Waveform of rms armature current and active power at generator terminals during (a) TLOE, (b) PLOE condition at L9 loading*



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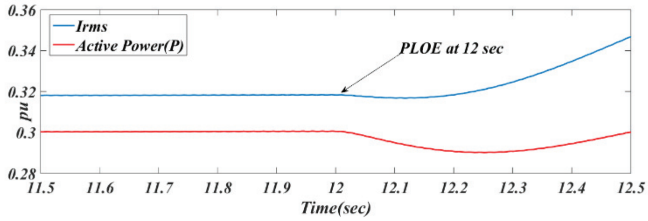

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Fig. 7. *Waveform of rms armature current and active power at generator terminals during (a) TLOE, (b) PLOE condition at L15 loading*

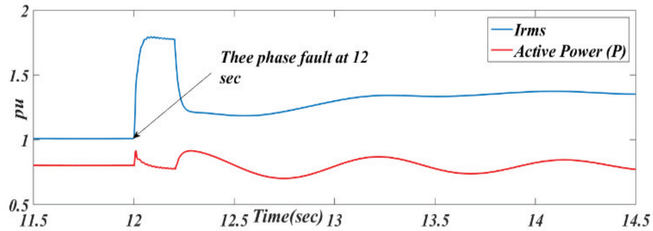
From Fig. 6 and 7, it is found that the variation of rms armature current gradually decreases in the leading pf region with decrement in initial loading of generator. Below L15 loading, the proposed method fails to detect both TLOE and PLOE.

B. *Power Swing Event and System Disturbances*

LOE detection methods mainly mal-operate during a major disturbance that is 3-phase fault [23] near generator bus which causes huge power swing in the generator.

Comprehensive studies: In the SMIB model, three phase fault is created at 12 sec in line 2 at 50 km from the generator terminal. The distance is taken so high because if the proposed method can discriminate three phase fault from LOE condition then the proposed method can also detect three phase fault.

From the Fig. 8, fluctuation of active power is large compared to the condition of LOE. It is found that as the loading increases the initial fluctuation in power also increases. During this, armature current starts increasing after 3 phase-fault whereas armature current decays for a period of time in both the case LOEs and load rejection. Values of



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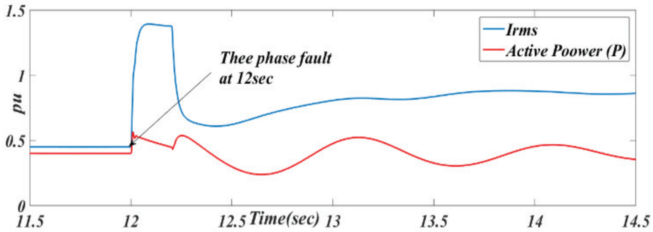

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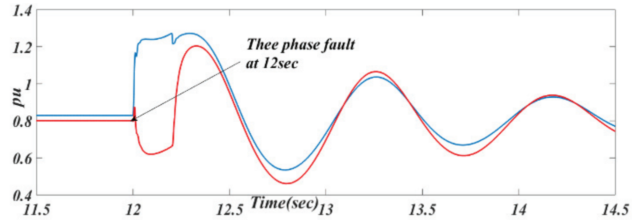

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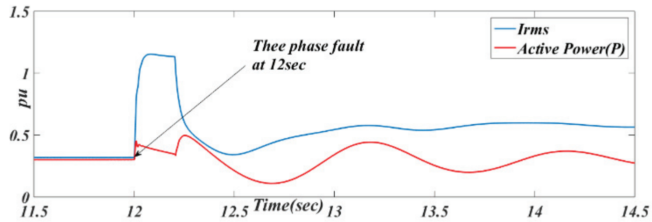

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Fig. 8. *Waveforms of rms armature current and active power at generator terminals during three phase fault near generator terminals (a) L1, (b) L4, (c) L9, (d) L15 loading*

$(\Delta I_r)_{sum}$ and $(\Delta P)_{sum}$ becomes very high than the threshold value. Hence, the proposed algorithm never mal-operates during power swing condition.

C. *Case Studies on Load Rejection*

At any time, generator may be required to trip for maintenance purpose or to protect it from the fault. Any generator tripping causes sudden large load rejection to the other generators running in parallel. During large rejection of load near the generator bus may cause mal-operation of LOE relay.

TABLE II. COMPARISONS DURING DIFFERENT LOE SCENARIOS AND INITIAL LOADINGS

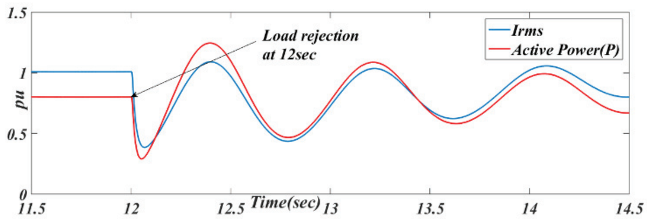
Initial loading (pu)	Mode of LOE	Impedance-based method (s)	Flux-based method (s)	Armature current based (s)	MCLOE=40 MCSPS=1000 (s)	Proposed Method (s)
0.8+j0.6	E_f=0	4.16	2.15	1.7	0.125	0.1
	E_f=0.4pu	6.3	3.65	1.7	0.151	0.1
0.4+j0.2	E_f =0	5.6	2.2	1.7	0.137	0.1
	E_f=0.4pu	7.46	3.72	1.7	0.176	0.1
0.8-j0.6	E_f =0	10.8	2.42	1.7	0.214	0.1
	E_f=0.4pu	17.1	4.12	1.7	0.340	0.1

TABLE III. COMPARISONS DURING VARIOUS INITIAL LOADINGS AND SPS CONDITIONS

Initial loading (pu)	Fault clearing time (ms)	Impedance-based method	Flux-based method	Armature current based	MCLOE=40 MCSPS=1000	Proposed Method
0.8+j0.6	100	no trip	no trip	no trip	no trip	no trip
	200	no trip	no trip	no trip	no trip	no trip
0.4+j0.2	100	no trip	no trip	no trip	no trip	no trip
	200	no trip	no trip	no trip	no trip	no trip
0.8-j0.6	100	trip after 0.74 s	no trip	no trip	no trip	no trip
	200	trip after 0.78 s	no trip	no trip	no trip	no trip

Comprehensive studies: In SMIB model, a PQ load is connected at generator bus and load is rejected by opening a circuit breaker. This load rejection condition is also considered to investigate the robustness and reliability.

From the Fig. 9, after load rejection the nature of armature current and active power is same for different initial loading conditions. The value of ΔI_r becomes very high during LOE and fluctuation of active power is large compared to the condition of LOE. Hence, the proposed algorithm never mal-operates during load rejection conditions..



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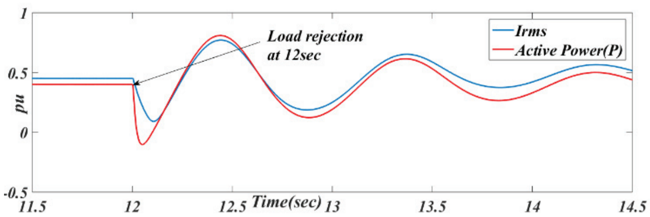

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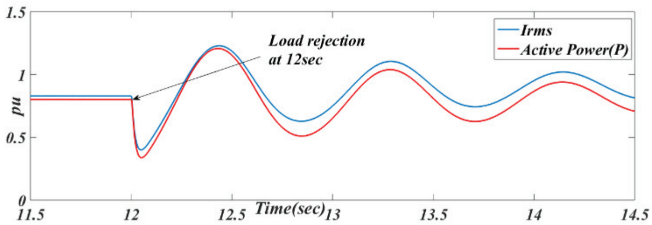

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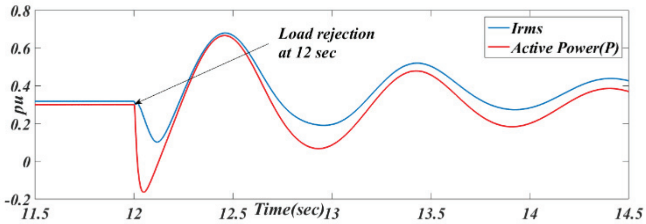

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Fig. 9. *Waveforms of rms armature current and active power at generator terminals during large load rejection near generator terminals (a) L1, (b) L4, (c) L9, (d) L15 loading*

IV. CONCLUSION

In this paper, loss of excitation of generator is detected using a new algorithm based on monitoring two parameters (rms armature current and real power) at the generator terminals. This method avoids intentional time delay and hence make the LOE detection faster. The algorithm is verified with all kind of loading (heavily loaded and lightly loaded at both lagging and leading pf) considering TLOE, PLOE and other different system disturbances near the generator bus. Compared to the other methods, this method is faster and the algorithm can be modified if FACTS devices are considered which can be further work in this field. Moreover, advanced machine learning techniques can be incorporated to get better LOE detections for broader perspective.

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