Synchronous Generator Excitation Loss Detection Based on Reactive Power Flow Limit

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Abstract. The direct current from the excitation system sustains the stator and rotor magnetically coupled with spawning reactive power in the generator. Though, any excitation system failure grades to generator loss of excitation and suspend power transmission from the generating unit to the grid. This paper presents a new excitation loss protection scheme based on the study of field voltage, quadrature axis voltage, and reactive power under specified system voltage. The proposed algorithm limits the reactive power consumption of the faulted generator to the ability of the system to feed the faulted generator without system loss of stability. In this paper, the IEEE-9 bus system is used to study the proposed approach to various excitation loss events. And the results showed that the new algorithm not only overwhelmed the mal-operation of the excitation loss relay but also detects all possible excitation failures without system collapse in a short time.

Keywords: Excitation loss protection · Reactive power limit · Synchronous generator

1 Introduction

Ever since discovered, electrical energy has gradually transformed life activities into easy and labor-intensive systems. On the other hand, the unprotected and unsecured transmission of electrical energy can cause serious damage to living things and their properties. So, a modern power system concern must be consistency and security on all parts of the power system (generation unit, transmission unit, and distribution unit) [1]. First and foremost, the efficacy of energy transmission mainly depends on synchronous generating machines as they are the source of energy. In a normal state, generators can produce and deliver active power due to the mechanical input and reactive power due to the field voltage from the excitation system [1]. However, any failure in the excitation system grades excitation loss in the generator and suddenly the machine will start to consume reactive power from the grid-connected with it to stay excited [2]. This results in voltage and current instability, generator over speed, and if it continues to a blackout of the whole system [3, 4]. This instability after excitation failure may lead to complete or partial excitation loss of the synchronous generator. Complete loss of excitation occurs when field winding open circuit, short circuit or sudden opening of the field supply breaker happen whereas partial loss of excitation can occur when suddenly

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field voltage drop or short-circuiting in a section of the field winding happens [2]. No matter how it is caused, loss of excitation represents huge damage to the generator and the whole system if early protection is apprehended. In 1949, Mason [5] suggested an impedance protection method using generator terminal voltage and current to protect Loss of Excitation (LOE). This method uses a negative off-set mho-type distance relay to sense the generator impedance variation in excitation loss condition. If the impedance of the generator falls under a predefined protective zone in the R-X plane, the relay detects loss of excitation and sends a trip signal to the field breaker. In 1975, Berdy [6] presented a method based on the addition of another mho unit to Mason's protection scheme aimed to protect lightly loaded generators. This type of protection is the most common method of LOE protection which detects the generator terminal parameter variation at any cause of excitation failures and it is the actual technique used in most power system industries until now. Later on, the impedance protection scheme was modified using modern computational methods such as neural networks [7, 8], decision tree [9], and fuzzy [10] algorithms which comparatively present good results. However, these methods require a considerable amount of training and their protection scheme mainly consists of a complex simulation scenario. With the help of digital relays, quadrangular lay which uses the rate of change of the reactance seen in the terminals of the machine was proposed in 2005, by S. R. Tambay and Y. G. Paithankar [11]. Similarly, another method based on the Space Vector Machine (SVM) technique to discriminate between Loss of Field (LOF) and stable power swing (SPS) is presented in [12]. However, both of the above-mentioned schemes need a significant amount of data for training. In 2016, Behnam M. and Jian Guo Zhu, [13] presented a setting free approach using resistance variation at the generator terminal as an excitation loss detector where the derivation of the resistance will become and remain negative a short period after the LOE event occurred. Though, the algorithm may reset for loss of excitation events with high slip frequency due to an oscillatory nature of resistance in variable speed associated with slip frequency.

M. Abedini et al. [14] proposed an analytical method using the rate of decay of the generator internal voltage with the field flux linkage variation. An adaptive and threshold loss of excitation index is introduced depend on terminal voltage to discriminate system disturbance from excitation failure such if the generator achieves a greater excitation loss index for a given sample, the loss of excitation will be detected. This method has accurate sensing results since it uses the capability curve of the generator, however, the setpoints identification is a difficult task and may involve extensive simulation processes that make it unpractical. Those authors modify the mentioned criterion in 2017 [15], which uses the Fast Fourier Transform (FFT) coefficient of three-phase active power to prevent the mentioned algorithm from mal-operation in the face of Stable Power Swig (SPS). Excitation loss detection through generator internal parameters can be evaluated also using flux interaction of the stator and rotor windings, internal voltage, or internal current measurements. A flux-based method is presented in [16], which uses the installed search coils in stator slots to measure the air-gap flux. This scheme, however, should normally be implemented by the generator manufacturer. In this paper, a new excitation loss protection scheme is proposed based on the variation of reactive power, quadrature axis voltage, and field voltage which are the parameters noticeably reduce in the excitation loss event. After calculating the minimum possible value of quadrature axis voltage using the generator measurable signals, the total amount of reactive power that the system can afford to feed faulted generator without system instability will be evaluated with low computational complications.

1.1 Generator Characteristics in Excitation Loss Event

Any synchronous generator has two inputs, torque input from a turbine coupled to its rotor and an excitation current coupled to the field winding of a rotor [1, 17]. Thus, the mathematical model of a synchronous machine is given by a set of differential equations representing the dynamics of the machine, exciters, and other controls and algebraic equations representing the network relation [18]. In this paper, a fourth-order (two-axis) generator model which neglects sub-transient effects is used as presented in [17] in the following equations.

$$T_e = E_d^{'} i_d + E_q^{'} i_q + (X_d^{'} - X_q^{'}) i_q i_d \tag{1}$$

$$\dot{\omega_m} = \frac{1}{2H}[P_m - P_e - D(\omega - \omega_s)] \tag{2}$$

Where ωs is the synchronous speed, $\Delta\omega$ speed deviation, ω generator speed, Pm is mechanical power and Pe is electrical power. The d-axis and q-axis voltages and field voltage of the synchronous generator are also given as the following equations.

$$\frac{d}{dt}E_q^{'} = \frac{1}{T_{d0}^{'}}[(-E_q^{'} + (X_d - X_d^{'})i_d) + E_{fd}] \tag{3}$$

$$\frac{d}{dt}E_d^{'} = \frac{1}{T_{q0}^{'}}[(-E_d^{'} - (X_q - X_q^{'})i_q)] \tag{4}$$

Also the generator terminal parameters are given as the following equations.

$$V_t = V_d + jV_q \tag{5}$$

$$I_t = i_d + ji_q \tag{6}$$

Where the d-axis and q-axis currents are given as:

$$i_d = \frac{E_q^{'} - V_q}{X_d^{'}} \text{ And } i_q = \frac{V_d - E_d^{'}}{X_q^{'}}$$

$$P_t = V_d i_d + V_q i_q \tag{7}$$

$$Q_t = V_q i_d - V_d i_q \tag{8}$$

The main electrical and mechanical quantities of the generator including voltage, current, and rotation speed will deviate from the related steady-state values during the

LOE event. In the loss of excitation, the apparent power of a synchronous generator falls off to zero within a short time [1, 2] which causes a mismatch between the mechanical power input and the electrical power output. Generator speed rises exponentially and eventually reaches asynchronous conditions. At this point, the mechanical power produced by the turbine equates with the asynchronously developed electrical power [9].

To study the excitation loss event on a synchronous generator, the IEEE 9-bus test system has been modeled on MATLAB/SIMULINK as shown in the following figure. Also, the parameters of the generator under study are given in Table 1.

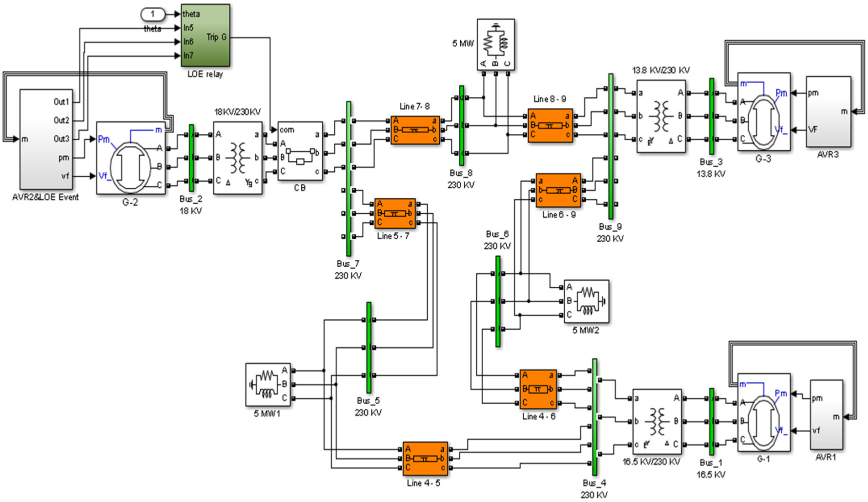


Fig. 1. SIMULINK model of IEEE 9-bus system

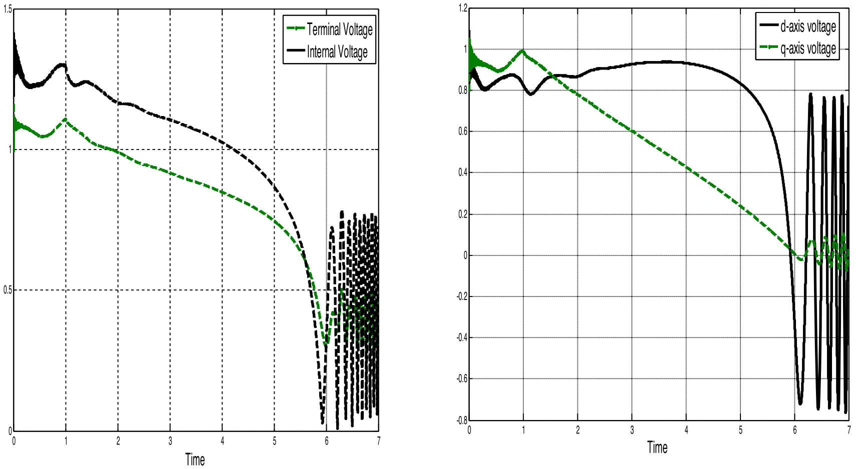
Table 1. Parameters of generators under study

Generator	MVA	kV	X$_d$	X'$_d$	T'$_{do}$
G-2	192	18	1.72	0.23	8

$$V_t = V_d + jV_q = \frac{X_d^{'} - X_q}{1+sT_{q0}^{'}} i_q - R_a i_d - X_d^{'} i_q + j\left(\frac{X_d^{'} - X_d}{1+sT_{d0}^{'}} i_d + \frac{E_{fd}}{1+sT_{d0}^{'}} - R_a i_q + X_d^{'} i_d\right) \tag{9}$$

$$e_i = E_d^{'} + jE_q^{'} = \frac{X_d^{'} - X_q}{1+sT_{q0}^{'}} i_q + j\left(\frac{X_d^{'} - X_d}{1+sT_{d0}^{'}} i_d + \frac{E_{fd}}{1+sT_{d0}^{'}}\right) \tag{10}$$

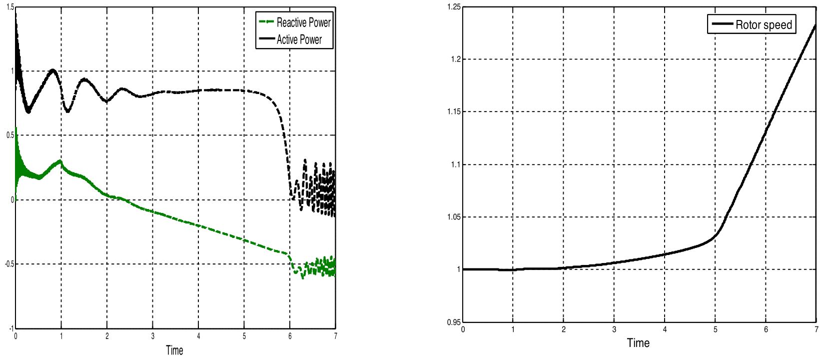
As can be seen from Eqs. (9 and 10) and Fig. 2a, the terminal and internal voltage of the synchronous generator varies with generator field voltage reduction. Comparatively, the q-axis voltage diminishes faster than the other parameters as shown in Fig. 1b and



(a) (b)

Fig. 2. Generator (a) Terminal and internal voltage (b) q-axis and d-axis voltage in LOE event created at 1 s

Eq. (3). This indicates that the terminal parameters of the generator are composted by the condition of the gird. The reactive power will indeed reduce to negative as shown in Fig. 3a. So does the reality, in the LOE event the generator consumes reactive power from the system. And the active power almost remains constant till loss of synchronism.



(a) (b)

Fig. 3. Generator (a) active and reactive power (b) rotor speed in LOE event

If the system can feed the excitation system a reactive power, the generator parameters remains in synchronism. However, the moment the system stops reactive power feeding to a generator, the whole system loses synchronism. In this simulation, as can be shown in Fig. 3, LOE event is created in 1s and the generator loses synchronism after 4.23 s.

$$\omega = \frac{R_a i_d + V_d}{\Psi_q} = \frac{R_a i_d + V_d}{-E_d^{'} - X_q^{'} i_q} \tag{11}$$

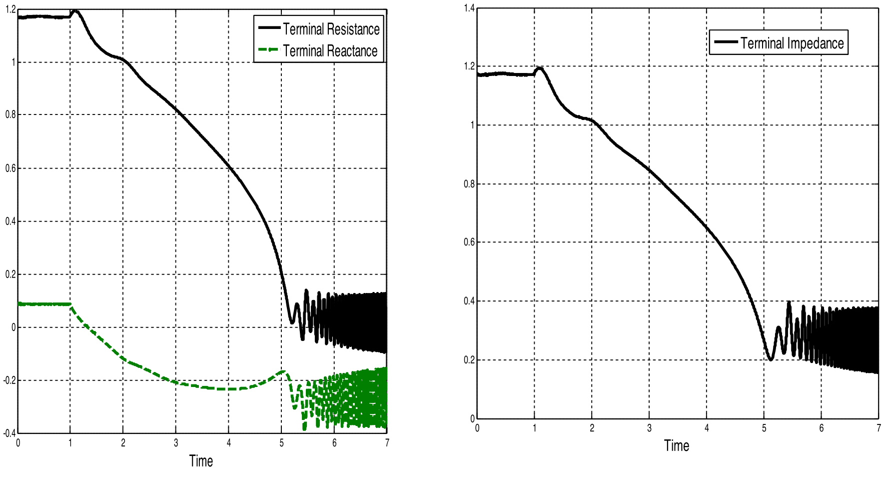
Where the d-axis and q-axis induced stator flux linkages are given as:

$$\Psi_q = -E_d^{'} - X_q^{'} i_q \text{ And } \Psi_d = E_q^{'} - X_d^{'} i_d$$

The speed of the generator rises under the loss of excitation event as shown in Fig. 3b. When the speed of the generator increases above the synchronous speed, the machine will act like an induction generator which induces rotor surface slip currents. This is because the speed of a rotating magnetic field is proportional to the frequency of excitation current. Voltage in excitation loss depresses to such extent under-voltage relays may sense it. This reduces the terminal impedance of a generator which can be expressed in terms of terminal voltage and current as of the following equation.

$$Z = \frac{V}{I} = R + jX = \frac{V^2 P_t}{P_t^2 + Q_t^2} + j\frac{V^2 Q_t}{P_t^2 + Q_t^2} \tag{12}$$

In excitation loss event, the resistance of the generator declines to zero gradually proportional to terminal voltage decay, and terminal reactance decreases to a negative value proportional to reactive power decline as can be shown in Fig. 4a. This results in terminal impedance reduction in the excitation loss event.



(a) (b)

Fig. 4. Generator terminal (a) resistance and reactance (b) impedance in LOE event

2 Proposed Excitation Loss Detection Scheme

The main factors that affect the operation range of synchronous generator are armature current, terminal voltage, the limit of stability, field current, initial loading capacity, and minimum possible excitation. Thus, any variations of these parameters jeopardize the stability of the machine and the system as a whole.

In any LOE event, the field voltage noticeably decreases from the initial value and so the reactive power. Here, the reactive power keeps reducing to negative value until the generator loses synchronism if any action is not taken. In some conditions of system disturbances, the reactive power also reduces to negative but the field voltage raise in value to pay off the terminal voltage reduction. In this section, the stability of the system in loss of excitation will be studied to calculate the reactive power margin of a generator at a specified field voltage using the q-axis voltage decay in the excitation loss event. The general scheme of the proposed algorithm can be sum up as Fig. 5 flow chart. The q-axis voltage is highly dependent on field components and it is reasonable that its response really fasts for field failures than other parameters of the generator.

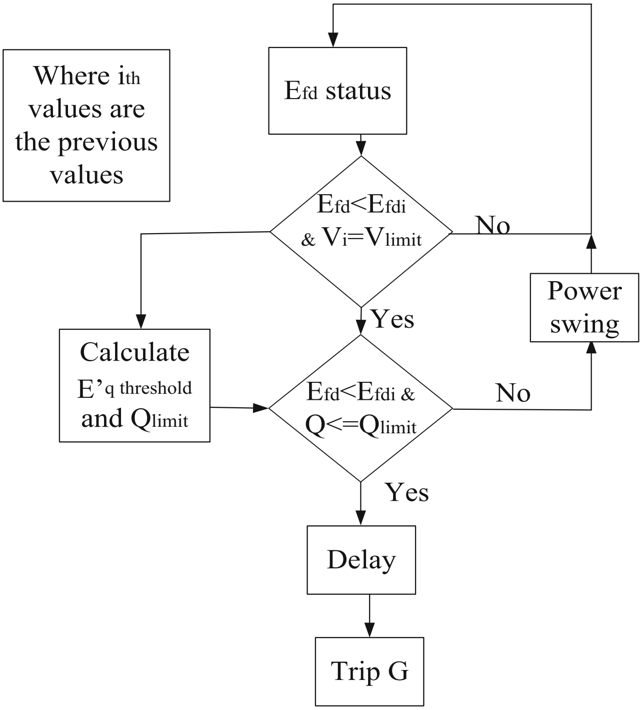


Fig. 5. Flow chart of proposed excitation loss protection

The minimum quadrature axis voltage reduction that leads to voltage collapse of the system will be calculated from the terminal voltage and field voltage of the generator. And this will be the threshold and minimum q-axis voltage that keep the system instability at any moment.

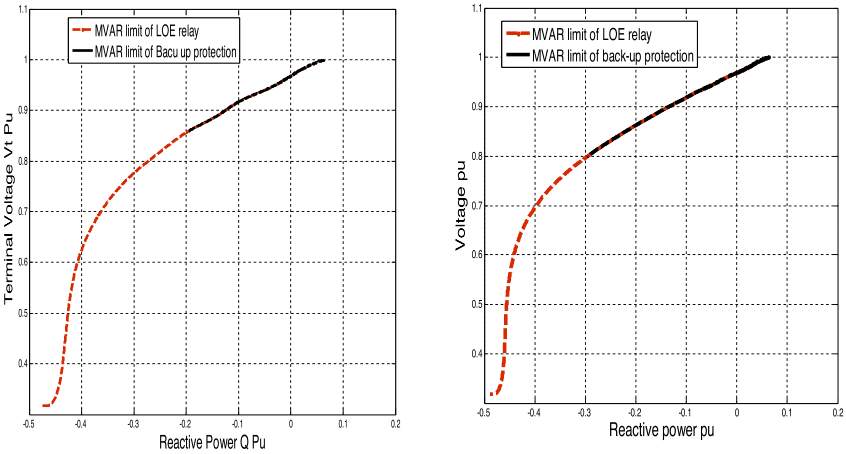
$$E_q^{'} = i_d X_d^{'} + v_q = \frac{X_d^{'}}{\frac{X_d^{'} - X_d}{1 + sT_{d0}^{'}} + X_d^{'}} (V_q + R_a i_q - \frac{E_{fd}}{1 + sT_{d0}^{'}}) + V_t \sin(\delta) \tag{13}$$

At the specified margin of terminal voltage, the q-axis voltage can be calculated from Eq. (13) above. The threshold q-axis voltage is also used to identify the minimum possible value of reactive power the system can feed the faulted generator without system collapse. Limiting the reactive power consumption of the generator will be the main concern of this proposed algorithm since the actual excitation loss relay mal-operation is due to the algorithm fails to limit the possible capability reactive power to the generator in excitation loss condition. In some kinds of literature, this concept has been used to detect excitation loss [19] but the unpredictable behavior of power systems in light load conditions, partial loss of field, and system outages have been threatening them. So, in this algorithm limiting the reactive power consumption with the internal field component will increase the sensitivity of the method for excitation loss event than system disturbances. Synchronous generator reactive power consumption ability in a given field voltage is highly dependent on the initial MW output of the machine. To understand the algorithm in different loading conditions, active power status is also one factor to identify the reactive power consumed by the generator. Thus, the reactive power of the synchronous generator in Eq. (8) can be re-formulated in terms of q-axis voltage and active power as the following equation.

$$Q_t = E_{qthre}^{'} i_d - X_d^{'} i_d^2 - (\frac{P_t - V_q i_q}{i_d}) i_q \tag{14}$$

Where e’qthre is the threshold q-axis voltage and Pt the output active power of the synchronous generator. This reactive power identifies the ability of the system to recover the reactive power loss due to the excitation loss generator at the same time it is the amount of reactive power consumed by the faulted generator without voltage collapse. If the synchronous generator model considers sub-transient components, the generator parameters swing in the normal state should be counted through a reasonable time delay for tripping the generator. In this work, the two-axis generator model has been used so the transient characteristics of the generator have been considered with a time delay of 0.81 s.

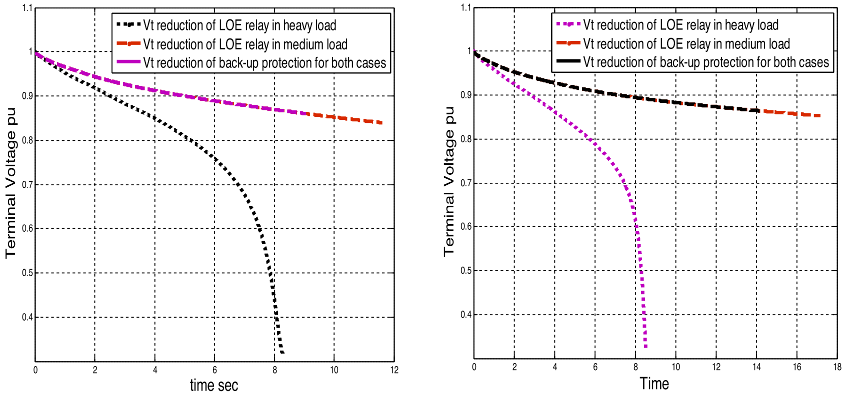
The conventional method of excitation loss protection is based on the calculation of the impedance at the generator terminal. It has two circle zones plotted in the negative reactance coordinate of the R-X plane with offset value X’d/2 and with circle zones of 1pu and Xd for zone-1 and zone-2 respectively [6]. If the R-X value of the generator entered the protection zones of the relay, a trip signal will be sent after a pre-determined time delay. The relay has good performance in the full loss of excitation but it mal-operates in some partial loss excitation and power system disturbances. Figure 6 expresses the reactive power-voltage (Q-V) curve of LOE relay and the proposed algorithm in full and partial loss of excitation. In full loss of excitation, the generator consumes reactive power until the terminal voltage of the generator diminish to 0.289 pu before excitation loss relay detect the event. However, in the proposed scheme the generator was able to consume reactive power until the terminal voltage reduce to 0.86pu. Similarly in partial loss of excitation, the back-up protection have response faster than LOE relay as given in Fig. 6b. At the same loading condition, generator reactive power consumption is the same despite the type of excitation loss.



(full excitation loss)

(50% of field voltage reduction)

Fig. 6. Q-V curve of LOE relay and proposed excitation loss protection



Full loss of excitation

50% Efd loss

Fig. 7. Terminal voltage reduction in LOE relay and back-up protection

On the other hand on the same type of excitation loss type, power consumption differs for various initial loading conditions. Thus, for 50% field voltage loss, the generator was able to consume reactive power until 0.289 pu terminal voltage reduction before detected through the LOE relay in heavy load condition which is similar to a full loss of excitation. As shown in Fig. 7, limiting reactive power consumption of faulted generator have maintained the system from voltage collapse and system loss of stability. In the proposed algorithm, the terminal voltage of the generator is kept at 0.86 pu for both full and partial loss of excitation. However, in the conventional relay, the terminal voltage reduced 0.28 pu before the relay detects the failure which may further jeopardize system stability in addition to generator excitation loss.

2.1 Results and Discussions

Full Loss of Excitation

The generator loses its excitation completely when the field voltage or field current supplied to the synchronous generator from the excitation system is lost and the excitation system fails to excite the synchronous generator completely. In this condition, the synchronous generator can produce active power due to the mechanical input but it completely stops producing reactive power. Full loss of excitation is initiated either due to field winding failure, main circuit breaker between the excitation system and generator failure, or sudden AC voltage loss to the exciter. Table 2 shows the comparison of excitation loss relay and the proposed back-up protection in the full loss of excitation. The back-up protection has improved the time elapsed to detect excitation loss and reactive power consumption limit of the generator. In field winding short circuit case, the proposed algorithm detects full loss of excitation 1.857 s after fault happen which is 2.303 s before the LOE relay. Similarly, for medium and light loaded generators the detection length has improved to about 16% of excitation loss relay. The excitation loss relay (impedance protection) have also detected full loss of excitation in less than 6.5 s in all loading conditions.

Table 2. Comparison of actual and proposed excitation loss detection in field winding short circuit

Initial loading (pu)	Tripping duration (sec)		Possible MVAR consumed by G-2 before fault detected (pu)	
	LOE relay	Proposed	LOE relay	Proposed
Heavy load	4.16	1.857	−0.431	−0.194
Medium load	5.804	4.537	−0.321	−0.2688
Light load	6.286	4.104	−0.231	−0.2055

Partial Loss of Excitation

Partial loss of excitation happens when the field winding voltage of the generator decrease in value for any reason. In heavily loaded generators it may cause severe damages as much as a full loss of excitation.

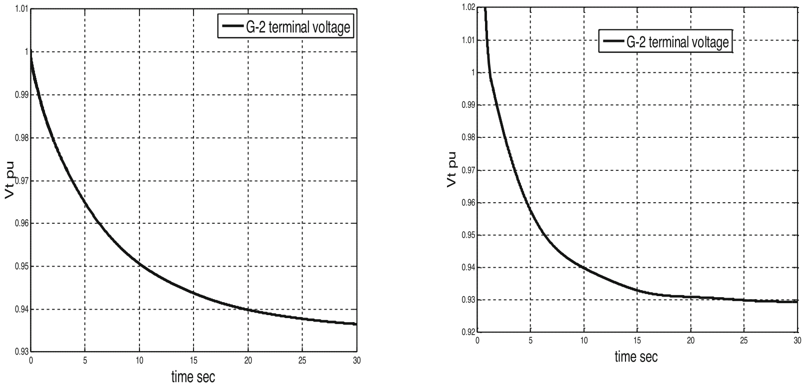
In PLOE, the filed voltage does not subject to null, so there will be some reactive power generation but not enough to feed the system so the generator still consumes

Table 3. Comparison of actual and proposed excitation loss detection in partial field voltage loss

%Efd loss	Initial loading (in pu)	Tripping status Y (sec)/N		Possible MVAR consumed by G-2 before fault detected (pu)	
		LOE relay	Proposed	LOE relay	Proposed
20%	H	26.46	12.86	−0.4897	−0.204
	M	N	N	−0.2720 (in 30 s)	−0.116 (in 30 s)
	L	N	N	−0.1906 (in 30 s)	−0.05 (in 30 s)
30%	H	15.21	7.24	−0.4882	−0.2021
	M	N	29.017	−0.2735 (in 30 s)	−0.19
	L	N	N	−0.1909 (in 30 s)	−0.101 (in 30 s)
40%	H	10.94	5.075	−0.4883	−0.198
	M	N	28.72	−0.2805 (in 30 s)	−0.264
	L	N	29.803	−0.1909 (in 30 s)	−0.1802
50%	H	8.563	3.935	−0.4887	−0.1957
	M	17.19	14.33	−0.2837	−0.2645
	L	N	15.37	−0.191	−0.1907
60%	H	6.99	3.22	−0.4858	−0.1945
	M	11.96	9.948	−0.2885	−0.266
	L	9.673	9.402	−0.198	−0.1965
70%	H	5.913	2.724	−0.482	−0.1938
	M	9.242	7.648	−0.2919	−0.2669
	L	7.332	7.11	−0.2076	−0.2045
80%	H	5.153	2.359	−0.4792	−0.1929
	M	7.632	6.216	−0.296	−0.265
	L	6.143	5.697	−0.216	−0.206
90%	H	4.592	2.079	−0.4768	−0.1939
	M	6.569	5.241	−0.3669	−0.268
	L	5.383	4.773	−0.2236	−0.2056

reactive power from the system even if that is slower than a full loss of excitation. To verify the reliability of the protection schemes in different LOE events, the method has been tested in all possible partial loss of field voltage in three different loading conditions as shown in Table 3. Similarly to a full loss of excitation, the proposed algorithm detects partial loss of excitation in heavily loaded generators twice less time than LOE relay in all possible field voltage reduction. LOE relay is not able to detect field voltage reduction until half of the rated value in medium and light loaded generators, and the proposed method has improved this.

LOE relay and also the proposed back-up protection have found not detecting 20% field voltage for medium and light load conditions and 30%Efd loss for light load condition. However, from the parameter variation of the generator and the whole system as shown in Fig. 8, the terminal voltage of the generator remains above 0.93pu. And this voltage value is a stable voltage range. So, the generator should not be tripped for the stable case since the un-necessary eliminating of synchronous generators will further jeopardize system stability despite its economic issue.



(a)

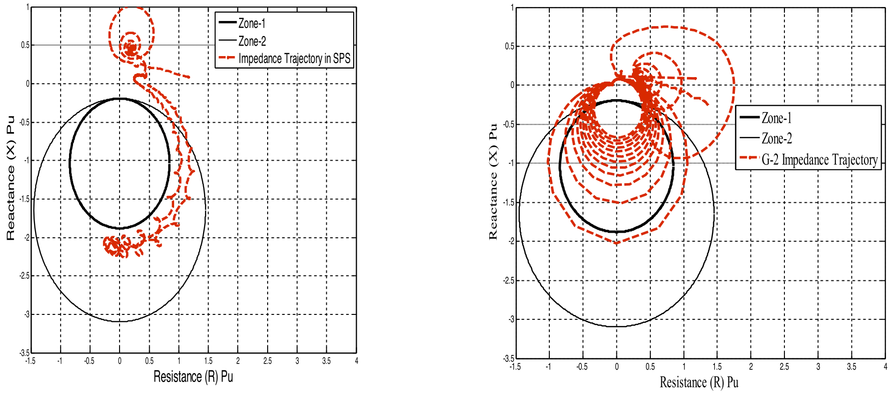
(b)

Fig. 8. Generator terminal voltage in partial loss of excitation (a) medium load 20%Efd loss (b) light load 30%Efd loss

Power Swing

Power swing is the oscillation of the machine rotor angle due to power system disturbances like a fault, generator, or line outages and load propagation that alters the mechanical equilibrium of one or more machines. LOE relay has mal-operate for severe power swings as having shown in Table 3. SPS and out of step conditions are simulated by three-phase to ground fault at G-2 terminal with pre-fault initial condition of 0.8485 + j0.06307 pu. In Out of Step (OOS) condition the generator becomes unstable and should be isolated from the remaining system but LOE protection should not give any response for this condition. LOE relay had actually detected a loss of synchronism which was caused by prolonged fault clearing times even in a short period of time than LOE event as shown in Fig. 9.

From the simulation results summarized in Table 4, all the mal-operation of LOE relay in system disturbance have overcome through the proposed excitation loss protection. In LOE and SPS event created at 1s, the LOE relay send a trip signal after 0.15 s SPS happened which is before the LOE event detected through the relay but the proposed algorithm sends a trip signal after 1.857 s which is the duration LOE event should be detected.



(a)

(b)

Fig. 9. Generator impedance trajectory in (a) SPS condition (b) Out of step condition

From the simulation results, the proposed algorithm has differentiated any excitation loss event from any system disturbance such no trip signal is issued for any power swings. And while detecting the excitation failure, system stability is held by limiting the reactive power consumption of the generator to the ability of the system to feed the faulted machine without system collapse.

Table 4. Comparison of actual and proposed excitation loss detection in system disturbances

System disturbances	Fault clearing time (ms)	Tripping status Y (sec)/N	
		LOE relay	Proposed
SPS	100	N	N
	150	N	N
	200	Y (1.15 s)	N
OOS	250	Y (0.856)	N
	350	Y (0.420)	N

(*continued*)

Table 4. (*continued*)

System disturbances	Fault clearing time (ms)	Tripping status Y (sec)/N	
		LOE relay	Proposed
G3 outage and 100MW load addition in bus-2	–	N	N
G2-outage	–	N	N
G2&G3 outage	–	N	N
L5–7 outage	–	N	N
Load rejection at bus-6	–	N	N
Load rejection at bus-5 and short circuit fault at L8–9	100	N	N
SPS and LOE at 1s	200	Y (1.15 s)	Y (1.857)

3 Conclusion

Excitation loss not only imperils the faulted generator but also the whole system's stability due to electrical and mechanical power imbalance on the generator. Strictly limiting reactive power flow from the system to the generator using quadrature axis voltage has kept the system in stable condition even in the excitation loss event. Thus, the proposed algorithm has improved the detection time elapse to twice less for heavily loaded generators and almost 16% less for lightly loaded generators than LOE relay, detects the failure before system collapse, differentiates all system failures and excitation loss events, and have detected all the possible partial loss of excitation that can lead to system instabilities.

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