Generator Excitation Loss Detection on Various Excitation Systems and Excitation System Failures

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Abstract. Generating steadiness of synchronous generator is highly dependent on their exciter as the direct current from excitation system sustains stator and rotor windings magnetically coupled. But generator loss of excitation weakens stator and rotor coupling which result in mechanical and electrical power imbalance and rotor speed rise beyond synchronous speed. And this phenomenon is able to damage both the generator and the grid if an early protection is not issued through excitation loss relay. This paper presents performance evaluation of excitation loss relay for DC, AC and static (ST) type exciters and various causes of excitation loss. Comparatively the relay shows a good performance in all causes of full loss of excitation than in partial field voltage loss in any type of excitation systems. But the relay detection time in static type exciter is short compare to DC and AC type exciters.

Keywords: Excitation loss protection · Excitation system failures · Generator excitation loss

1 Introduction

The efficacy of electrical energy transmission in all part of power system is highly dependent on the reliability of synchronous generating machines as these machines are the main source of energy for the whole system. Generally synchronous generator has two inputs; mechanical input from turbine and field voltage from excitation system [1]. And at normal condition generator is able to produce and deliver active power due to the mechanical input and reactive power due to the field voltage. Excitation system is part of generating unit which produces flux by passing current in the field winding to supply its output through either brushes or slip rings to run synchronous machines [1, 2]. Generally excitation system consists of two relatively independent components, excitation regulator (AVR) and the exciter itself [3]. Excitation system regulation should include these three main characteristics: speed of system operation which identifies the reliability of stability in power system in terms of over voltage limitation in under load condition or de-excitation in internal failure condition, autonomy of excitation system that insure reliability of exciter at any condition and maximal drive security that ensures reliability function of integrated components [4, 5].

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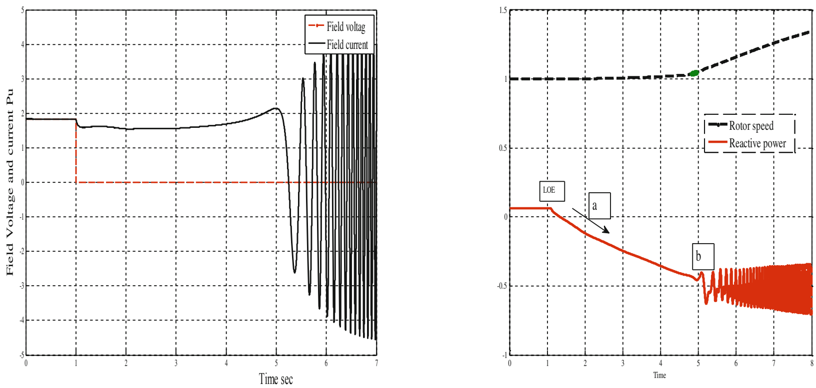
Thus, excitation system is able to control voltage and reactive power flow by ensuring if the machine does not exceed the capability limits. Excitation systems can be classified in terms of their construction as static or rotating and according to excitation energy source as separate or self-excited systems [1]. In static exciters energy is brought through slip rings and carbon brushes to the generator field winding. To perceived use of brushes in large synchronous machines, use of brushes in static excitation systems have been eliminated in rotating excitation systems [1]. Generally excitation system can be classified as (DC), AC or static (ST) type.

DC type exciters uses direct current generators as sources of excitation power and provide current to the rotor of the synchronous generator through slip rings. This type of exciter mainly have replaced by the other two types except a few synchronous machines are equipped with DC exciters. This group consists of four models as described in [6]. In AC type of exciters Alternating Current machines are used as source of the main generator excitation power and rectification of AC voltage is carried out through controlled or non-controlled rectifiers to provide DC to the generator field winding. However, except AC4A model, DC exciters did not allow negative field current flow which does not allow them de-excitation in case of internal failures in the generator. This is the main disadvantage of this type of systems because it does not allow de-excitation of generator. In static exciters however, energy is brought through slip rings and carbon brushes to the generator field winding. In such systems generator itself is power source or the generator is self-excited. This type of excitation system consist of seven models and the possibility to produce negative excitation current is their significant advantage. Thus, it provides quick de-excitation which may be needed in case of generator internal fault. In this paper, DC1A, AC1A and ST1A exciters will be used to study performance of excitation loss relay detection for various excitation fault type scenarios.



(a) (b)

Fig. 1. Generator (a) field current and voltage (b) rotor speed and reactive power

Any failure in excitation system directly interrupts the generating capability of the synchronous generator and transmission of power to the system. The phenomenon where the generators lose its excitation is called excitation loss. In excitation loss event, the excitation system fails to deliver DC current and the generator seek a way to stay excited which causes the faulty generator to absorb a large amount of reactive power from the system connected with it. And consequently reduces reactive power delivery from generator to system and lead to power system voltage and current instability and if it continues to blackout of the whole system [6, 7]. Generator excitation loss can be summarized as two stages as shown in Fig. 1b as point (a) and (b). Region-(a) is the first stage of excitation loss event and the generator starts to consume reactive power from the system. In this stage, the system is capable of feeding reactive power to the generator and the generator remains in synchronism. The reactive power amplitude consumed by the generator could be as large as 1.56 times rated power of the generator which indicates the machine is trying to run the faulted generator and to keep the system stable. On the second stage shown point (b), the system reaches the maximum limit of reactive power delivering and the generator speed rises rapidly beyond synchronous speed due to power imbalance. In this stage, the relation between the stator and rotor is already very week due to under-excitation limit is achieved. And over speed of the generator consequences the generator to loss synchronism and bring a huge damage to the system [3, 8]. In this condition the generator must be isolated from the remaining system.

Generator terminal voltage and terminal current measurement is used to protect against excitation loss event. In 1949, Mason [9] suggests a negative off-set mho-type distance relay to sense the impedance variation of generator terminal point due to excitation loss. When the impedance trajectory falls under predefined protective zone in R-X plane for a reasonable pre-set time delay, excitation loss will be detected. Shortly afterwards, in 1975, Berdy [10] presents a two off-set mho circle protection zones by addition of another mho unit to this protection scheme proposed in [6] to reduce detection duration of lightly loaded generators. These two methods are the base of excitation loss detection algorithms proposed ever since but mal-operating in stable power swing is the main threat for the algorithms. Some years later, the above methods have been modified using modern computational methods, such as neural networks [11], decision tree [12] and fuzzy algorithms [13] in protection against loss of excitation. These methods may present good results, however require a considerable amount of training and vast simulation scenarios. With the advent of digital relays, a Space Vector Machine (SVM) technique is proposed to differentiate system and excitation failures [14] but the algorithm needs a significant amount of data for training. In 2016, Mahamedi and Zhu [15] present a setting free approach using generator terminal resistance variations where if the derivative values of the resistance remains negative for predefined time delay, excitation loss will be detected. However, the oscillatory nature of terminal resistance is speed variation the algorithm may reset in excitation loss events with high slip frequencies. On the same year, Abedini et al. [16], proposes a method using the rate decay of the generator internal voltage with the field flux linkage variation. An adaptive and threshold loss of excitation index is introduced such if the generator achieve greater excitation loss index for a given samples, then loss of excitation will be detected. A combined index based on generator terminal voltage, reactive power and power angle variations is presented in [6]. Although this technique can be implemented by considering a special case of the network operation, regarding the network combination is inevitable. A flux based method is presented in [17], which it 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.

Still the actual excitation loss protection in power system industries is so called impedance type protection proposed almost four decades ago. Since the protective relays should be designed with requirements of sensitivity to sense all possible failures of excitation systems for all types of excitation systems and accuracy and reliability as should be easy and less complex to set the threshold of the protective devices after a possible failure. In this paper, the actual excitation loss relay in power system industries will be studied on various type of excitation loss and excitation system.

Excitation Loss Relay

The main indicator in capturing the probability of excitation failure is the significant flow of reactive power into the generator. The most common excitation loss protection is based on the calculation of the impedance at generator terminal. In modern power system industries, Berdy method [10] is the most popular which has two protection circle zones plotted on the R-X plane of the terminal impedance as can be observed in Fig. 2 [6, 10]. The protection zones are positioned in the negative reactance coordinate of the R-X plane with offset value X′d/2 and with circle zone diameter of 1 pu and Xd for zone-1 and zone-2 respectively. As can be seen from Eq. (1) in normal operating condition, both generator resistance (R) and reactance (X) are positive and the terminal impedance is located in the first quadrant in R-X plane. However, when the generator loses excitation the generator starts to draw reactive power from the system and reactance becomes negative from the relay point of view. As a result, the terminal impedance trajectory in R-X plane moves to the forth quadrant and the relay is able to detect excitation loss event when the impedance trajectory enter in the protection zones. A reasonable time delay is proposed to distinguish between a recoverable swings and loss of excitation. For zone-2, 0.5 s and 1 s time delay is suggested to send alarm and trip signals consequently. But for zone-1no delay is suggested.

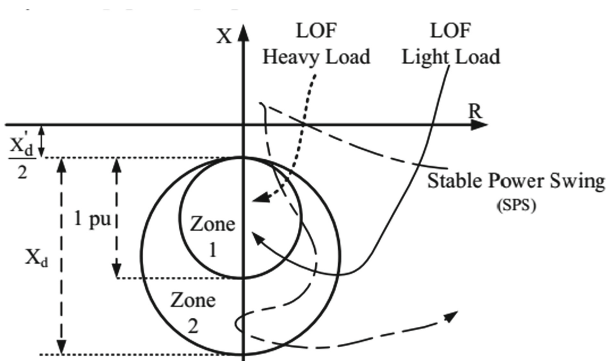


Fig. 2. Excitation loss relay

$$Z = \frac{V}{I} = R + jX = \frac{V^2 P_t}{P_t^2 + Q_t^2} + j\frac{V^2 Q_t}{P_t^2 + Q_t^2} \quad (1)$$

Where $R = \frac{V^2 P_t}{P_t^2 + Q_t^2}$ *and* $X = \frac{V^2 Q_t}{P_t^2 + Q_t^2}$

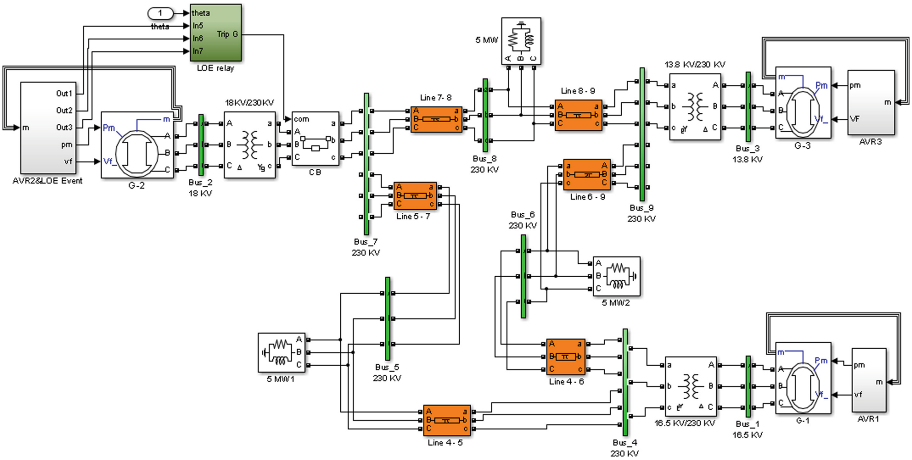


Fig. 3. Simulink model of IEEE 9-bus system

2 Excitation Loss Types

Generator loses its excitation completely when the field voltage or field current supplied to the generator is totally lost and the exciter fails to run the synchronous generator completely. In this condition the synchronous generator is able to produce active power due to the mechanical input but it starts consuming reactive power from the system. Full loss of excitation is initiated either due to field winding failure, poor brush contact, AVR control failure, slip ring flash over, main circuit breaker failure or sudden AC voltage loss to exciter [2, 7]. Despite the cause of excitation loss, either the field voltage or field current reduce in value or to zero depend on the type of excitation loss cause or sever of the failure. To study excitation loss event, IEEE nine bus system shown in Fig. 3 has modeled in MATLAB/SIMULINK and excitation loss is created on G-2 of the system as its parameter values has given in Table 1.

Table 1. Parameter values of generator under study (G-2)

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

2.1 Field Winding Short Circuit

A short circuit on field winding is the most common type of excitation system fault. In field winding short circuit the field voltage literally decline to zero as shown in Fig. 1a. But the field current remains high and it is able to swing when the generator lose synchronism due to self-exciting excitation system is used and field current is dependent on parameters of generator.

Figure 4 shows the impedance trajectory of G-2 for field winding short circuit in different loading effects; heavy load, medium load and light load conditions. In heavy load condition excitation loss relay detect field winding short circuit at 4.16 s for DC1A, 4.33 s for AC1A and 4.037 s for ST1A exciters through zone-1 since the first zone of impedance protection is modelled to protect heavy loaded generators. On the other hand, when the loading effect starts to decrease, zone-2 is capable of detecting excitation loss event with a reasonable time delay. In medium load the event is detected after 5.804 s through zone-2 for DC1A exciter. On the same manner, in light load condition, the generator delivers 30% of the rating power, and field winding short circuit is detected after 6.286 s. But, the impedance trajectory enters zone-1 after 13.43 s which is much slower than in heavy load case.

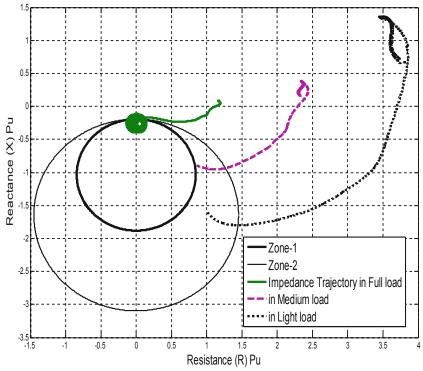


Fig. 4. G-2 impedance trajectory in field winding short circuit

2.2 Sudden Failure of Main Circuit Breaker

When the main circuit breaker between the exciter and generator opened due to sudden failure, the exciter and the generator totally isolated and the generator loses its field voltage totally. Due to this the generator field voltage reduce to zero and results in complete loss of excitation but the exciter remains at normal state. Also AVR failure reduces field voltage of the generator to null. These causes of excitation loss have similar characteristics to field winding short circuit due the field voltage generator is terminated to null. And excitation loss relay detect sudden failure of main circuit breaker and AVR failure scenarios with in similar length of time as their impedance trajectory given in Fig. 5. For both cases, heavy load condition is detected through zone-1 after 4.16 s for DC1A exciter similar to field winding short circuit.

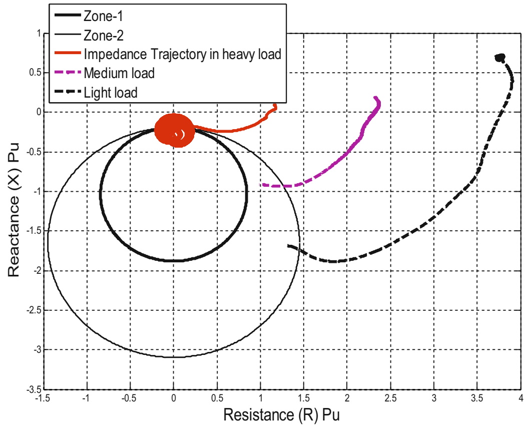
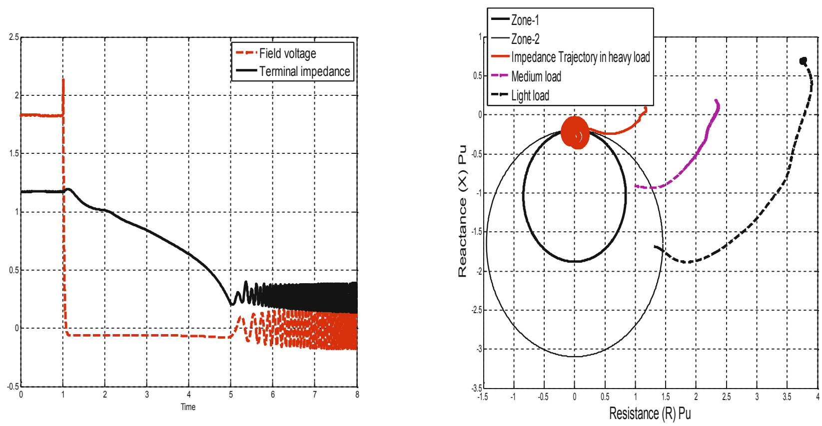


Fig. 5. G-2 impedance trajectory in sudden main circuit breaker failure

2.3 Sudden Loss of AC Voltage to Excitation System

Despite the variety of excitation system, any exciter has its own starting means either separate source or direct from the machine connected with it (self-exciting) depend on the type of excitation system. However, if the AC voltage that run the exciter interrupted by any means, excitation system and also the generator connected with the exciter will be faulted. In this work self-excited exciter is used, so sudden loss of AC voltage to the exciter is studied when the generator terminal voltage run the exciter is suddenly interrupted. Thus, AC voltage loss to the exciter also results in full loss of excitation in generator as can be shown in Fig. 6a below. Complementary to other causes of excitation loss, excitation system got support from the other components of the exciter in sudden



(a) (b)

Fig. 6. G-2 (a) field voltage and terminal impedance (b) impedance trajectory in sudden AC voltage loss to exciter

AC voltage loss to exciter since the field voltage is dependent on the initial value of field voltage and the terminal voltage of the generator.

For simulation, let the excitation system of G-2 suddenly loss AC voltage at 1 s. The relay detects the event at 4.223, 4.418 and 4.109 s for DC1A, AC1A and ST1A exciters consequently through zone-1 in heavy load condition which is about 0.63 s longer than the above causes.

2.4 Field Winding Open Circuit

In field winding open circuit, field current is terminated to null. It is associated with inserting of an infinite discharge resistance which tends to reduce the field current to almost null. This is the worst cause of excitation loss event that generator lose synchronism in fraction of microseconds in any loading conditions. As can be observed from Fig. 7a, comparing the courses of generator values during loss of excitation in field winding open circuit, system reactive power feeding limit is reached at 0.06 s after fault which is almost 4 s before in other causes of excitation loss. And it can be noticed that the peak value reactive power is smallest in open-circuit case comparing to other causes of excitation loss as can observed from Figs. 1b and 7a.

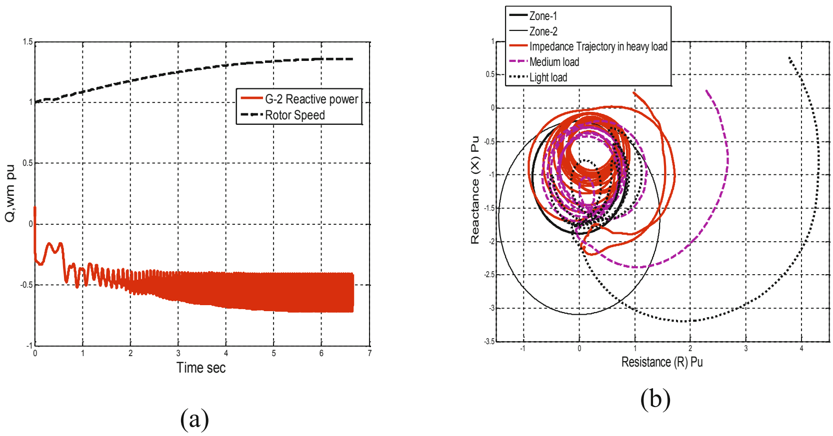


Fig. 7. G-2 (a) field current and reactive power (b) impedance trajectory in field winding open circuit

From Fig. 7b, after the fault is initiated the seen impedance by the relay moves from quadrant-one toward the fourth-quadrant of the R-X plane and then moves back to the third-quadrant. For DC1A excitation type, LOE relay detect field winding open circuit in 0.0835 s for heavy load, 0.0467 s for medium and 1.131 s for light initial load conditions which is faster than the other causes of excitation loss.

Table 2 summarizes excitation loss relay performance on various causes of full excitation loss on the three types of excitation systems. Generally, excitation loss relay detect field winding open circuit in very short period of time than the other causes in any generator initial loading condition. On the other hand in AC excitation system the relay has longer detection time than the other two exciter. And it can also observe that, impedance protection of excitation loss is highly dependent on initial generation ability of the generator. But, the relay was able to detect full loss of excitation in less than 6.5 s in all loading conditions.

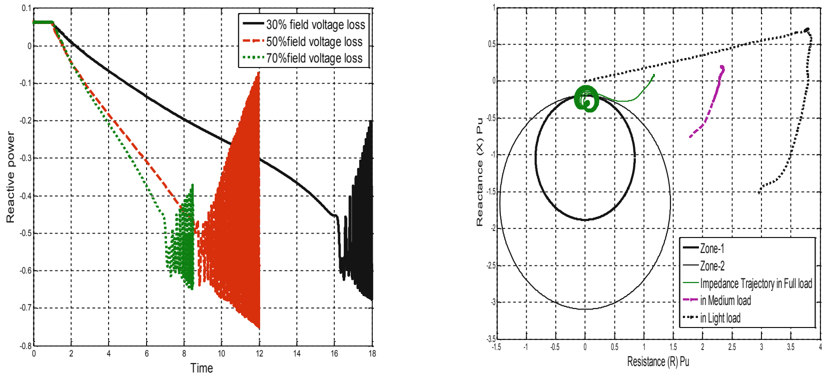
Table 2. Excitation loss relay detection ability in main causes of full excitation loss

Initial loading (in pu)	Types of excitation	Type of LOE and Generator tripping time (second)			
		FW short circuit	AC voltage loss	Main CB failed	FW open circuit
0.8485 + j0.06307	DC1A	4.160	4.223	4.160	0.0835
	AC1A	4.281	4.450	4.160	0.2638
	ST1A	4.037	4.223	4.160	0.0687
0.7604 + j0.04781	DC1A	4.961	5.027	4.160	0.06485
	AC1A	5.03	5.236	4.160	0.0783
	ST1A	4.850	5.109	4.160	0.0783
0.6792 + j0.03679	DC1A	5.165	5.236	4.160	0.05115
	AC1A	5.482	5.703	4.160	0.0618
	ST1A	5.095	5.296	4.160	0.0584
0.2547 + j0.3	DC1A	6.286	6.348	4.160	1.131
	AC1A	6.400	6.634	4.160	1.237
	ST1A	6.163	6.267	4.160	0.994
0.3396 + j0.03424	DC1A	5.773	5.853	4.160	0.0341
	AC1A	5.903	6.004	4.160	0.0508
	ST1A	5.560	5.752	4.160	0.0327

2.5 Partial Loss of Excitation

Partial loss of excitation is happen when field winding voltage of the generator decrease in value by any reason. In this case, 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 reactive power from the system even if that is slower than full loss of excitation The detection ability of excitation loss relay will be studied for different percentage losses of field voltage starting from the worst partial loss which is decrease Efd by 1.6497 pu till the least loss 0.1833 pu field voltage reduction as can be scrutinized in Table 3.

When the field voltage reduced to 30% of its normal value, the system is able to feed reactive power to the synchronous generator for about 15 s after fault happen. On the other hand, when the generator lost 50% and 70% of the field voltage, the synchronous generator was able to consume reactive power from the system for about 9 s and 7 s respectively without loss of synchronism as shown in Fig. 8a. Thus, the field voltage reduction only affects the reactive power consumption duration and variable changing rate of the machine and the initial condition determines the generator output during loss of excitation.



(a) (b)

Fig. 8. G-2 (a) reactive power reduction (b) impedance trajectory in 30% field voltage loss

Figure 8b shows the impedance trajectory of G-2 in 30% field voltage loss. Excitation loss relay successfully detects 30% diminishing of field voltage only for heavy loaded generator after 15.210 s for DC1A exciter. Similarly, reduction of half field voltage remains un-detected for 24.15 s in medium load and not detected at all in light condition. This threat system stability and may lead to blackout of the whole system. But in heavy load the field voltage reduction is detected after 8.563 s.

Table 3. Excitation loss relay detection ability in partial loss of excitation

Initial loading (in pu)	Types of excitation	Field voltage percentage loss (% Efd loss) and G-tripping duration [Y(sec)/N]				
		30%	40%	50%	70%	90%
0.8485 + j0.06307	DC1A	15.210	10.940	8.563	5.913	4.592
	AC1A	16.021	4.450	8.932	6.209	4.927
	ST1A	15.082	4.016	8.202	5.731	4.320
0.7604 + j0.04781	DC1A	18.210	12.51	9.563	6.816	5.493
	AC1A	18.864	13.042	10.06	7.023	5.780
	ST1A	18.109	12.302	9.392	6.590	5.285
0.6792 + j0.03679	DC1A	22.29	14.100	10.48	7.161	5.659
	AC1A	22.940	14.905	10.960	7.823	5.828
	ST1A	21.102	13.89	10.362	7.008	5.406
0.2547 + j0.3	DC1A	N	N	N	13.41	7.37
	AC1A	N	N	N	13.894	7.893
	ST1A	N	N	N	13.058	7.031
0.3396 + j0.03424	DC1A	N	N	24.15	10.04	6.644
	AC1A	N	N	24.602	10.592	6.942
	ST1A	N	N	23.883	9.704	6.172

Excitation loss relay have a good performance in detecting field voltage loss greater than half of the rated field voltage as have been shown in Table 3. On the other hand, for partial excitation loss less than half of the rated field voltage of the synchronous generator, it fails detecting field voltage diminishing except for heavily loaded generators for each type of excitation types.

2.6 Power Swings

Power swing is the oscillation of 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. Table 4 summarizes excitation loss relay performance on various system disturbances. In order to ensure the reliable operation of LOE relay there is a short time delay between entering time to the operating zone and the initiation of a tripping signal. Comparing to critical transmission line outage, main load rejection worsens the impedance trajectory closeness to the relay characteristics (Fig. 9).

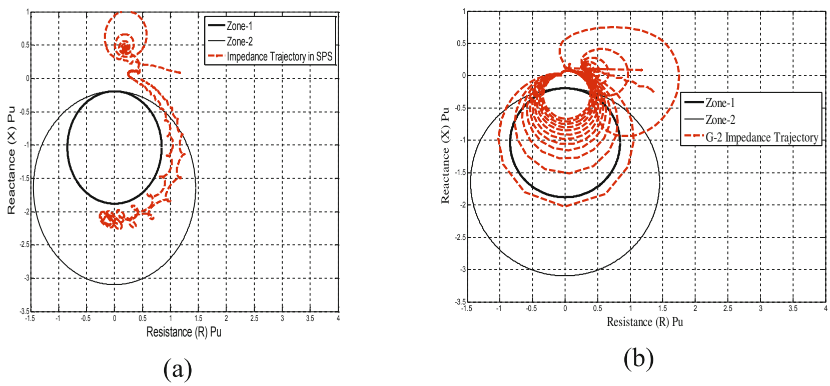


Fig. 9. G-2 impedance trajectory in (a) SPS (B) Unstable swing

Table 4 shows LOE relay performance on various system disturbances including SPS and OOS on heavy, medium and lightly load generators. As can be observed from the results, LOE relay had actually detected a loss of synchronism which was caused by prolonged fault clearing times even in short period of time than LOE event for all type of exciters.

Table 4. Performance of excitation loss relay on system disturbances

Initial loading (in pu)	Types of excitation	System disturbances			
		SPS	OOS	Line outage	G-outage
Heavy load	DC1A	1.105	0.856	N	N
	AC1A	0.902	0.508	N	N
	ST1A	1.05	0.884	N	N
Medium load	DC1A	1.25	0.601	N	N
	AC1A	1.3	0.573	N	N
	ST1A	1.008	0.693	N	N
Light load	DC1A	1.053	0.638	N	N
	AC1A	1.058	0.601	N	N
	ST1A	1.118	0.750	N	N

3 Conclusion

The performance of excitation loss relay was assessed for various type of excitation system by simulating the test system with different excitation loss type. From the results, it has shown that field current reduction detected faster than field voltage reduction and comparatively excitation loss in static type exciter detects in less time than the remaining exciters. Based on the simulation and results obtained for the above test cases, the time available to trip loss of excitation depends on various conditions such initial loading of the generator, type of excitation loss, reactive power support from interconnected systems and type of excitation system. More generator active power output and full excitation loss implies that there is less time before the excitation loss protection detected and vice versa for weak MVAR support from the system and partial excitation loss.

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