Comparison study among the different existing loss of excitation protection schemes in synchronous generator

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Abstract: Synchronous generator is the most important element of a power system and its fast and reliable protection is crucial. One of the most abnormal conditions in a generator is loss of excitation (LOE) which is harmful to both the generator and the power system. This condition should be detected and the generator isolated from the system to avoid generator damage as well as power system instability.

This work presents an experimental study and comparison of the two conventional LOE protection schemes, negative-offset and positive-offset mho element under different conditions. The results show that the two schemes can detect LOE fault under total or partial LOE conditions, however in terms of speed (fault detection time) the positive offset scheme is faster than the negative offset scheme under all loading conditions. Besides, the two LOE protection schemes are reliable and do not operate under power swing disturbances caused by any type of external faults.

Keywords: Loss Of Excitation (LOE), positive-offset mho element, negative-offset mho element, loading conditions.

1. INTRODUCTION

The earliest Loss Of Excitation (LOE) protection scheme employs an over-current and under-voltage relays based on the measurement of machine field current. However, this scheme may not operate during all system conditions [1]. An approach for LOE detection based on a single-phase negative-offset mho element is introduced first by Mason [2]. A later approach contains two characteristic zones introduced by Berdy [3], designed to improve the relay robustness during transient swings and low frequency disturbances. This approach has been improved by combining a positive-offset element and a directional unit, which provides security for close in external faults [4]. There are also some other types of LOE protection schemes, such as G-B scheme, P-Q scheme and U-I scheme, but they are not widely used [5] [6].

To enhance the performance of LOE detection algorithm, in term of speed (fault detection time), reliability, security and selectivity, especially to discriminate the LOE event from power swings, some other techniques have been proposed:

- Free settings approach based on the rate of change of resistance [5],

- Dynamic simulations introduced by Ref. [7] aiming to improve the generator LOE protection.
- LOE detection algorithm based on a digital-phase comparator [8],
- In order to coordinate between LOE protection and generator under-excitation controls considering power system dynamics, a real time digital simulator (RTDS) framework is introduced in [9],
- Artificial neural network based fault classification algorithms [10]
- Support vector machine (SVM)-based technique for identifying loss-of excitation condition from power-swing disturbances [11],
- Protection by using the rate of change of reactance [12]
- LOE relay based on fuzzy interface mechanisms [13],
- Adaptive loss of field protection using an approach for on-line identifying system equivalent impedance based on PMU measurements [14],
- Combined scheme based on the derivative of the terminal voltage and the output reactive power of the generator [15],

- Combined criteria using voltage magnitude, voltage angle, and reactive power [16],
- LOE detection based on decision tree technique [17],
- Analytical technique based on the generator armature current variation [18],
- New approach for LOE faults detection in hydro-generators using adaptive neuro fuzzy inference system is presented in [19],
- Analytical approach based on internal voltage calculation [20],
- New approach for dependable and secure LOE detection relay based on rotor signals estimation [21],
- Secure and setting-free technique based on different electrical quantities of the generator [22],

This work presents a comparative study of the two conventional LOE protection schemes, negative-offset and positive-offset mho elements under different conditions. In terms of speed, the two schemes are compared under total and partial loss of excitation. Then, in terms of security against power swings, the two schemes are compared under different external faults.

2. GENERATOR LOSS OF EXCITATION CAUSES

When a generator loses excitation, the magnetic coupling between rotor and stator magnetic fields gradually decreases until the machine loses synchronization. Besides, the generator will overspeed and operate as an induction generator obtaining its excitation from the system by absorbing reactive power [7]. Therefore, the generator may be completely or partially loss its excitation through such incidents as:

- Field breaker accidental tripping,
- Field open circuit,
- Field short circuit (flashover of the slip rings),
- Voltage regulation system failure.
- Loss of supply to the excitation system.

Furthermore, when a generator loses excitation, both the machine and the power system are at risk. The generator may suffer rotor over-heating, stator winding overload, stator end-core damage and mechanical failure. The power system may have voltage collapse, unnecessary relays tripping and

loss of synchronism of some normal operating generators [4] [23].

The disturbance severity during generator loss of excitation depends primarily on the generator initial loading as clearly shown in Fig.3.1. Curve (a) shows the impedance trajectory with initial full load at point C and terminates at point D above the average of the direct and quadrature-axis sub-transient generator impedances (X_d , X_q). Curve (b) shows a generator that initially operates at 30 percent load and underexcited. In this case, the impedance trajectory follows the path from E to F to G and oscillates in the region between F and G. Usually, under any generator loading the impedance trajectory will end at the area inside the dashed curve from D to L. [4]

Fig.1. Generator loss-of-excitation characteristic[4].

Moreover, the induction generator slip depends on the generator initial load; the higher initial load produces a higher slip value and a lower generator impedance, which means higher reactive-power consumption, higher stator and rotor currents, and lower terminal voltage. Hence, the worst case is when the generator loses excitation at full load, where slip is typically in the 2 to 5% range [7].

3. IMPEDANCE-BASED LOSS OF EXCITATION PROTECTION SCHEMES

There exist two basics LOE protection schemes, negative-offset and positive-offset mho elements [4]. The two schemes based on impedance calculation at the generator terminals, using the measured currents and voltages as shown in Fig.2.

Fig. 2 Generator loss-of-excitation protection.

In order to construct the R-X diagrams for a balanced three phase conditions, the R and X should be determined as follow:

$$R = \frac{P \times V^2}{P^2 + Q^2} \quad (1)$$

$$X = \frac{Q \times V^2}{P^2 + Q^2} \quad (2)$$

in which, P, Q and V are the active power, the reactive power and the voltage of the relay location, respectively.

Negative-offset mho element

This protection scheme uses two zones mho impedance-based units as shown in Fig.3. Both zones have the same offset that is equal to half of the direct-axis transient reactance [24]:

$$Offset = \frac{X'_d}{2} \quad (3)$$

The first zone (Z1) is set with a diameter equal to 1.0 pu (generator base); this element detects LOE during high loading conditions down to about 30% load. A short time delay of 0.1 s is allowed to prevent misoperations during switching transients.

The second zone (Z2) is set with a diameter equal to the direct axis synchronous reactance (X_d). This element detects LOE during light loading conditions. A time delay of 0.5 to 0.6 s is allowed to prevent misoperations during power swings.

Positive-offset mho element

This protection scheme uses a combination of two mho impedance-based units and a directional unit as shown in Fig.4. The first Zone (Z1) has a negative offset mho characteristic, and it is set using the following equations [24]:

$$Diameter = 1.1X_d - \frac{X'_d}{2} \quad (4)$$

Fig.3. Negative-offset mho element, LOE protection scheme.

Fig.4. Positive-offset mho element, LOE protection scheme.

$$Offset = \frac{X'_d}{2} \quad (5)$$

A time delay of 0.1 to 0.3 second is recommended to prevent mal-operation under transient swings.

The second zone (Z2) has a positive-offset mho characteristic, and it is set using the following equations:

$$Diameter = 1.1X_d + X_s \quad (6)$$

$$Offset = X_s \quad (7)$$

Where X_s is the sum of all the impedances away from the generator terminals (up to relay location) in per unit. A time delay may be considered between 0.25 to 1 second [24].

Moreover, this positive offset element is controlled by a directional element to prevent mal-operation when close external

faults occur. The directional element is set at an angle between 10 and 20 degrees. Therefore, a failure on the minimum excitation limiter might occur. Hence, both the directional and the mho element operate and initiate an alarm. A one minute time delay may be introduced in many cases to trip the unit if the situation cannot be restored before the damage proposed [4] [10].

4. EXPERIMENTAL STUDY

Experimental setup

In this experimental study, a real single machine infinite bus (SMIB) is used. The model as shown in Fig.5, consists of a 10 KVA synchronous generator, connected via 110/440 v step-up transformer to a large system (Belgium Grid) through a transmission line. Fig.6 presents the block diagram of the

experimental setup that has been done at the BEAMS Laboratory, ULB, Brussels. The system data are given in appendix A.

Fig. 5 Experimental power system model.

Fig. 6 Block diagram of the experimental setup.

LOE protection schemes settings:

Negative-offset mho element setting:

Zone 1: Circle diameter: 1 pu.

Offset = 0.06 pu

Time delay: 0.1 s

Zone 2: Circle diameter = 1.13 pu.

Fig. 7 Negative-offset mho element settings.

Positive-offset mho element setting:

Zone 1: Circle diameter 1.095 pu.

Offset = 0.06 pu

Time delay: 0.1 s

Zone 2: Circle diameter = 1.443 pu.

Offset = 0.2

Time delay: 1 s

Directional element: set with angle -18°

Fig. 8 Positive-offset mho element settings.

Experimental Results

Experimental tests have been done under different conditions; total LOE, partial LOE and under external faults. Simulation studies in order to analyze the constructed data from the numerical relay (SIPROTEC 7SA87) have been conducted using

Simulink/MATLAB software, where the two conventional LOE protection schemes, negative-offset and positive-offset mho elements are compared.

a) Experimental comparison under TLOE

Total (complete) loss of excitation is considered on the generator after 19 s of starting the recording time with 100 % initial load. Fig. 9 shows the generator real and reactive power transient time responses during LOE with 100 % initial load. It can be seen from this figure that due to the LOE at around 20 s, the generator real power decreased sharply before loss of synchronism. Moreover, the reactive power

output decreases sharply to negative single, which means that the generator starts to absorb the reactive power from the system until it losses the synchronism.

Fig. 9 Generator active and reactive power during

TLOE.

Fig. 10 Generator terminal voltage during TLOE.

Figure 10 shows the generator terminal voltage before and after TLOE. Therefore, due to the large amount of the absorbed reactive power after the LOE, the phase current increased sharply before loss of synchronism. However, the terminal voltage

Fig. 11 Impedance trajectory measured by: a) positive-offset mho element. b) negative-offset mho element.

decreases until it reaches almost 0.8 p.u. and starts to oscillate.

Figure 11 depicts the impedance trajectories measured by the two different LOE protection schemes. The impedance trajectory starts at 19.9s after TLOE occurred, and penetrates

- (a) zone 2 of the positive-offset mho element (Fig. 11a) at 20.2 s, then penetrates zone 1 at 20.28 s. this protection scheme trips by zone 1 (after its timer of 0.1 s is timed out) at $t = 20.38$ s, this means that the clearing time is $t = 0.48$ s. However, the impedance trajectory penetrates zone 2 of the negative-offset mho element (Fig. 11b) at 20.26 s, then penetrates zone 1 at 20.3 s this protection scheme trips by zone 1 (after its timer of 0.1 s is timed out) at $t = 20.4$ s, the clearing time is $t = 0.5$ s.

Comparing the two clearing times shows that, the clearing time of the positive-offset mho element is less than the clearing time of the

negative-offset mho element by 0.02 s under

		Initial load $S = P + jQ$ (pu)			
		100%	60%	40%	10%
Clearing time (s)	Positive-offset mho element	0.48 Zone1	0.5 Zone1	0.64 Zone1	1.6 Zone1
	Negative-offset mho element	0.5 Zone1	0.52 Zone1	0.68 Zone1	1.84 Zone2

the same initial load.

The same experimental study under different initial loading have been repeated and presented in Table 1. The results show that when a total loss of excitation occur, the positive-offset mho element protection scheme is faster than the negative-offset mho element under all loading conditions.

Table 1 Clearing time of the two LOE protection schemes under TLOE

b) Experimental comparison under PLOE

Comparison studies of the two LOE protection schemes under different initial loading and with two different partial loss of excitation conditions ($E_f = 0.4$ pu / $E_f = 0.2$ pu) are presented in Tables 2 and 3. The results show that when a partial loss of

		Initial load $S = P + jQ$ (pu)			
		100 %	60 %	40 %	10 %
Clearing time (s)	Positive-offset mho element	1.98 Zone 1	3.48 Zone 1	UR	UR
	Negative-offset mho element	2.02 Zone 1	3.76 Zone 1	UR	UR

excitation occur, the fault clearing time of the positive-offset mho element protection scheme is faster than the negative-offset mho element protection scheme. However, when a partial loss of excitation occur under light loading, the fault will not cleared (under reach).

Partial pu) is

Figure the

loss of excitation ($E_f = 0.4$ considered on the generator after 6.2 s of starting the recording time. 12 depicts the impedance trajectories measured by two different LOE protection schemes under PLOE.

Table 2 Clearing time of the two LOE protection schemes under PLOE.
UR: under reach

Fig. 12 Impedance trajectory measured by: a) positive-offset mho element. b) negative-offset mho element. Under PLOE.

Table 3 Clearing time of the two LOE protection schemes under PLOE.

Fig.13 Impedance trajectory under three-phase external fault measured by: a) positive-offset mho element. b) negative-offset mho element.

		Initial load $S = P + jQ$ (pu)			
		100%	60%	40%	10%
Clearing time (s)	Positive-offset mho element	NO	NO	NO	NO
	Negative-offset mho element	NO	NO	NO	NO

c) Experimental comparison under external faults

In order to investigate the behavior of the two LOE protection schemes in external fault situation, a three-phase fault is applied

(200 ms fault duration), with 100% initial load; Fig. 13 depicts the impedance trajectories measured by the two different LOE protection schemes. The impedance trajectory penetrates the two zones of the two schemes. Because the maximum duration time does not exceed the time delay of the two zones, the two protection schemes will not operate.

The same simulation study under different initial loading and with two different fault durations have been repeated, the results are presented in Table 3. The results show that the two LOE protection schemes will not operate under power swing disturbances caused by any type of external fault for 200 ms fault duration.

Table 4 The effect of three phase to ground external fault on LOE protection schemes.

		Initial load $S = P + jQ$ (pu)			
		100%	60%	40%	10%
Clearing time (s)	Positive-offset mho element	1.58 Zone 1	UR	UR	UR
	Negative-offset mho element	1.68 Zone 1	UR	UR	UR

NO: No Operation

5. CONCLUSION

This work presents the study on one of the most abnormal condition in synchronous generator, which is the loss of excitation (LOE). Experimental studies have been conducted using the single machine infinite bus (SMIB) and the two conventional LOE protection schemes, negative-offset and positive-offset mho elements are modeled.

Consequently, a comparative experimental study of the two traditional LOE protection schemes is investigated. The obtained results show that the two LOE protection schemes detects the fault under total or partial LOE; however, in terms of speed the positive-offset mho element is faster than the negative-offset mho element. Furthermore, the two LOE protection schemes are reliable and will not operate under power swing disturbances caused by any type of external faults. Therefore, the positive-offset mho element protection scheme has been selected

because it gives the best performance in terms of speed (fault detection time).

Appendix A

Parameters of the experimental setup elements in BEAMS Lab, University ULB,Brusselles, Belgium.

1) Generator parameters: 10 KVA, 110 V, $X_d = 1.13$ pu, $X_q = 1.03$ pu, $X'_d = 0.12$ pu, $X''_d = 0.1$ pu.

2) Transformer parameters: Δ/Y , $S_{max}=15$ KVA, 110V / 440 kV

3) Transmission line: 440 kV, $Z = 2.1 + j2.7$ %

4) Equivalent system: 440 kV, $Z = 1\%$

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