The Comparison and Analysis for Loss of Excitation Protection Schemes in Generator Protection

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Keywords: Generator Protection, Loss of excitation protection schemes, comparison and solutions.

Abstract

Loss-Of-Excitation (LOE) condition of a generator may cause severe damages on both generator and the interconnected systems. This paper analyses the behaviours of different LOE protection schemes, such as R-X, G-B, P-Q and U-I schemes, for a hydro generator, which is connected to an infinite bus. Based on the simulation results, the reliability and stability of existing LOE protection schemes are compared and a preferred scheme is selected. An improvement to the scheme is also proposed to prevent the LOE relay incorrect operation during external faults, such as short-circuit faults on busbar or transmission lines.

1 Introduction

A common excitation system for a utility generator consists of an exciter and an Automatic Voltage Regulator (AVR). The direct field current supplied by the excitation system excites the field winding to establish the rotor flux and the internal voltage in a synchronous generator. When a generator loses its excitation, the rotor current gradually decreases and the field voltage slowly decays as dictated by the field time constant. As a final outcome the generator starts to consume reactive power from the power system instead of supplying it.

Generator loss of excitation can be caused by short circuit of the field winding, unexpected field breaker opening and a failure in the excitation system. According to the statistic in China, the generator failure due to LOE accounts for more than 60% of all generator failures [1]. For these reasons, LOE protection schemes are required to detect the LOE condition as rapidly as possible while remaining insensitive to the external faults and other system disturbances. Reference [2] describes the characteristics of impedance measurement scheme, which is the most common LOE protection scheme. Reference [3] compares the behaviors of impedance scheme and admittance scheme for LOE fault. Reference [4], [5] describe the LOE protection scheme related to the generator capability curve based on P-Q plane. Reference [6], [7] introduce a directional current measurement method. But all these schemes are not compared with each other under the same conditions. As the existing LOE protection schemes are implemented in different ways, it is essential to find the best performing protection scheme for LOE faults detection and protection.

This paper compares the behavior of the above mentioned protection schemes during LOE conditions and external faults. Each scheme is evaluated under the same operating conditions and one with the best performance is selected. Finally additional measures to further improve this scheme are suggested.

2 Existing Protection Schemes

There are five LOE protection schemes used today, namely, R-X scheme, R-X with directional element scheme, G-B scheme, P-Q scheme and U-I scheme. However, R-X schemes is widely used in power systems. In this paper, the calculations of R-X, G-B, P-Q and U-I algorithms are based on the generator current and voltage positive sequence quantities.

2.1 Impedance measurement scheme (R-X)

This protection scheme applies two offset mho impedance circles by using the generator terminal side voltages and stator currents as input signals.

2.1.1 Negative-offset mho elements

The normal setting for the offset-mho relay in the impedance plane has two circles with a diameter of saturated direct axis transient reactance X'_d and a negative offset of $X'_d/2$ for the outer circle and the diameter of 1 per-unit (pu) and a negative offset of $X'_d/2$ for the inner circle which is shown in Fig.1 [2].

Zone 1 and Zone 2 are for detecting LOE with full load and light load respectively. The typical time delays for Zone 1 and Zone 2 are about 0.1s and 0.5-0.6s [2], [8].

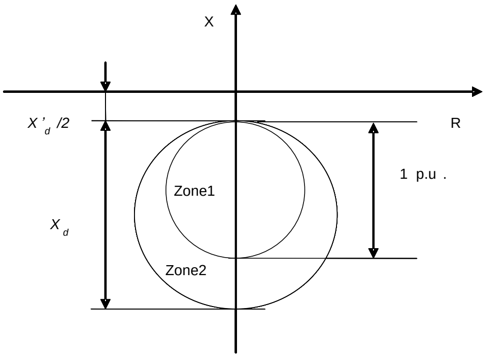


Fig.1. LOE protection scheme with an offset mho element [2]

2.1.2 Offset mho combined with directional element

This scheme also applies two offset mho elements and a directional line to detect the loss of excitation. The first offset mho Zone 1 is set equal to a negative offset of $X'_d/2$ and a diameter of 1.1 times direct axis synchronous reactance X_d. The second offset mho Zone 2 setting is identical to the steady-state stability limit in impedance plane which is a circle centered at $(0,-j(X_d-X_s)/2)$ and with the radius $(X_d+X_s)/2$ [2], where X_s is the system impedance. The setting of the directional line must be coordinated with the under excitation limiter of the generator. The limiter is commonly set to fulfill the reactive power obligation of the generator (e.g. power factor 0.95 underexcited) as specified by the system operator. Fig.2 shows an example of a LOE protection scheme with two negative-offset mho elements and a directional line.

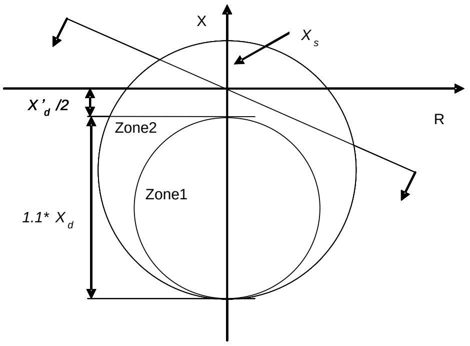


Fig.2. LOE protection with an offset mho and directional elements [2]

The directional line always issues an alarm signal and a time-delayed tripping, typically within the range from 10s to 1 minute [8]. Zone 1 and Zone 2 initiate tripping signals with certain time delays, normally, 0.2s to 0.3s time delay for Zone 1 and approximately 0.75s for Zone 2 to override the power swings [2].

2.2 Admittance measurement scheme (G-B scheme)

The main principle of LOE protection based on admittance measurement is to map the generator stability limit, which is usually defined in the PQ plane, to the admittance plane [3]. When the terminal voltage equals to the reference voltage ($U=U_N=1$ pu), the value in admittance plane is identical to the capability curve in P-Q plane. Fig.3 describes the characteristic of the admittance scheme.

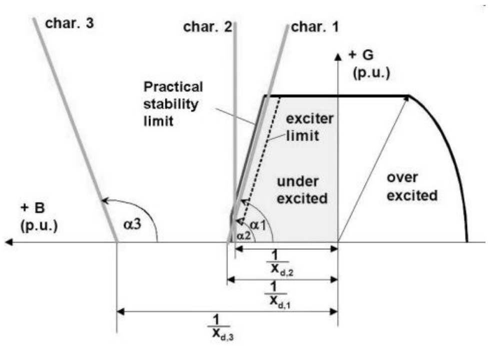


Fig.3.LOE protection scheme based on admittance measurement [3]

The typical relay settings for salient pole generator are [3]:

$$\text{Char1:} 1/X_{d,1} = 1/X_d + (1/X_q - 1/X_d)/2 \quad \alpha1 \approx 80^\circ \quad (1)$$

$$\text{Char2:} 1/X_{d,2} = 1/X_d \quad \alpha2 = 100^\circ \quad (2)$$

$$\text{Char3:} 1/X_{d,3} = 2/X_d \quad \alpha3 \approx 110^\circ \quad (3)$$

When the Char.1 and Char.2 are exceeded and the undervoltage element picks up, a tripping signal is initiated with a short time delay (0.5s to 1.5s). When Char.3 is exceeded, it will initiate a tripping signal with a shorter time delay (typically <0.3 s) or no time delay at all [3].

2.3 P-Q measurement scheme

The generator active and reactive power outputs are limited by the generator capability, System Steady-State Stability Limit (SSSL) and Under Excitation Limit (UEL) [9], [10]. Therefore, the protection region can be directly obtained from the generator capability curve and SSSL. An example of P-Q scheme including an LOE element and an undervoltage element is shown in Fig.4:

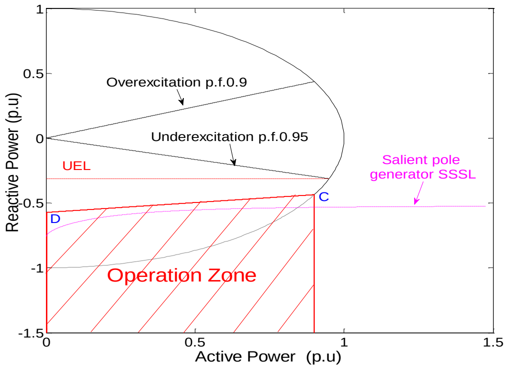


Fig.4. LOE protection scheme representation in P-Q plane

For a salient pole generator, there is no stator end region heating problem [11]. Therefore the SSSL will limit the LOE element and the LOE element characteristic lies just inside the SSSL curve [4]. The upper limit point C is the intersection point of the generator MVA rating and rated active power output (0.9 pu); the lower limit point D is limited by SSSL which is (0, $-U_s^2/X_d$) in P-Q plane. When the generator reactive power output exceeds UEL, the alarm element will pick up. When the operating point falls into the operating region, LOE protection element will be picked up and send a trip signal after 0.75s time delay.

2.4 U-I measurement scheme

U-I scheme implements a directional overcurrent relay to detect LOE faults by comparing the phase angle difference between voltage and current. The directional overcurrent relay comprises a directional current stage (I_α), with a characteristic angle -120° to +120° and a nondirectional current stage ($I>$) [6], [7]. The typical setting is shown in Fig.5 in P-Q plane with characteristic angle -81.2° and non-directional current stage 0.568 pu.

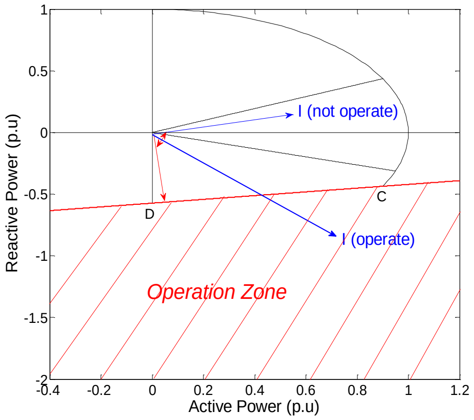


Fig.5. LOE protection scheme based on U-I measurement

The directional overcurrent operating characteristic is set to coincide with the generator thermal capability or the stability limit curve with certain time delay. If the generator is with UEL, the operating characteristic is set as the back-up of UEL [5]. To initiate a tripping signal, the directional overcurrent relay operates together with an undervoltage element which is set to 90% of the rated voltage and an overcurrent element which is set to 110% of the rated current.

3 Simulation Studies

3.1 Model Description

The model is established in PSCAD and simulates the LOE of a hydro generator. The model configuration is shown in Fig.6. The simulation model includes two salient pole generators which are connected to a common bus via Δ-Y connection step-up transformers respectively. The common bus is connected to the infinite bus via two 100 km transmission lines. The transformer primary side voltage is 20kV and secondary side voltage is 230kV.

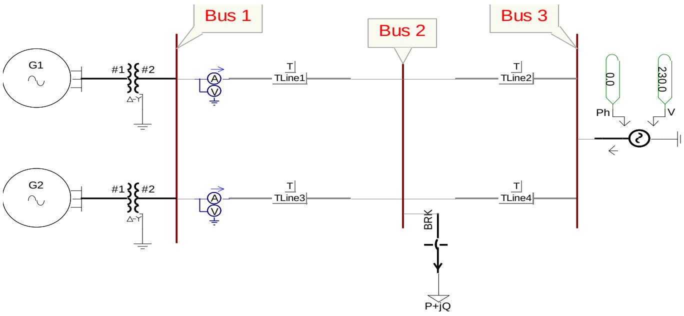


Fig.6. One-line diagram of the simulation model in PSCAD

3.2 Generator model

The generator model comprises a synchronous generator, a hydro turbine with governor, an Automatic Voltage Regulator (AVR) and a Power System Stabilizer (PSS). The block diagram of generator unit is shown in Fig.7:

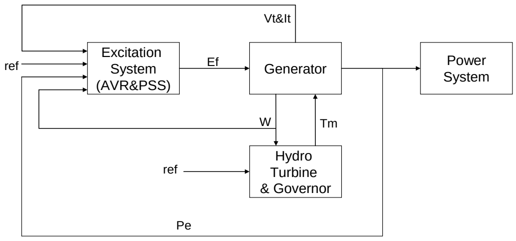


Fig.7. Block diagram of generator unit with control system

The exciter and PSS used in the model are standard IEEE type ST1A and PSS2B [12].

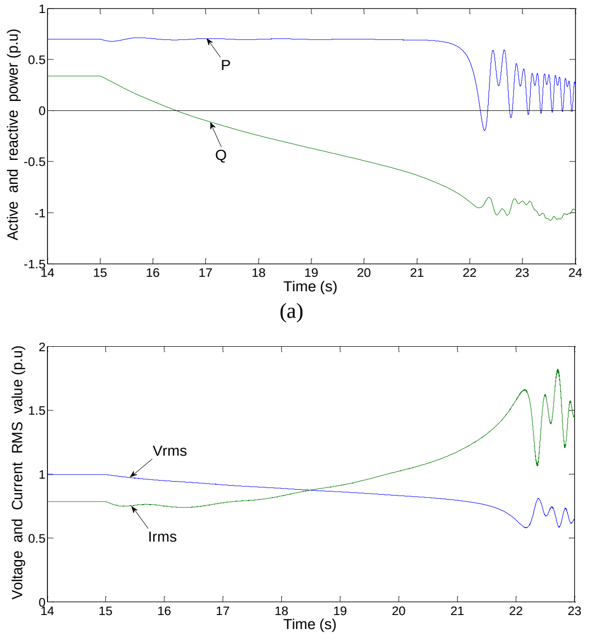
3.3 Simulation cases

The simulation consists of four cases while the first three cases with the LOE occurred on Generator 1 at 15s due to field winding short circuit.

Case 1: Generators 1 and 2 operating at 80% load with p.f. 0.9 overexcited.
Case 2: Generators 1 and 2 operating at 40% load with p.f. 0.9 overexcited.
Case3: Generators 1 and 2 operating as condensers with zero active power and 0.5 pu reactive power outputs.
Case 4: External symmetrical and unsymmetrical faults occur at busbar 1 at 10s respectively. The fault duration is 150ms. Before the fault, the generators carry 80% load with p.f. 0.95 underexcited.

3.4 Simulation results

Case 1: Generator LOE under heavy load condition.
Fig.8 shows the active power, reactive power, phase voltage RMS value and phase current RMS value of Generator 1 before and after the loss of excitation.

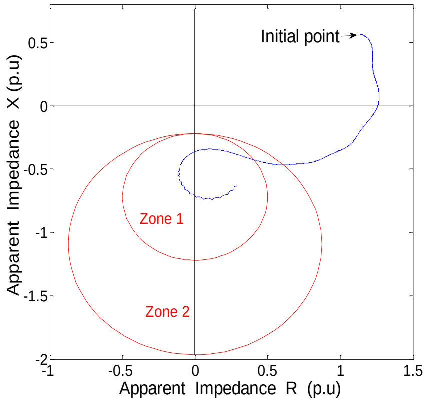


(a)

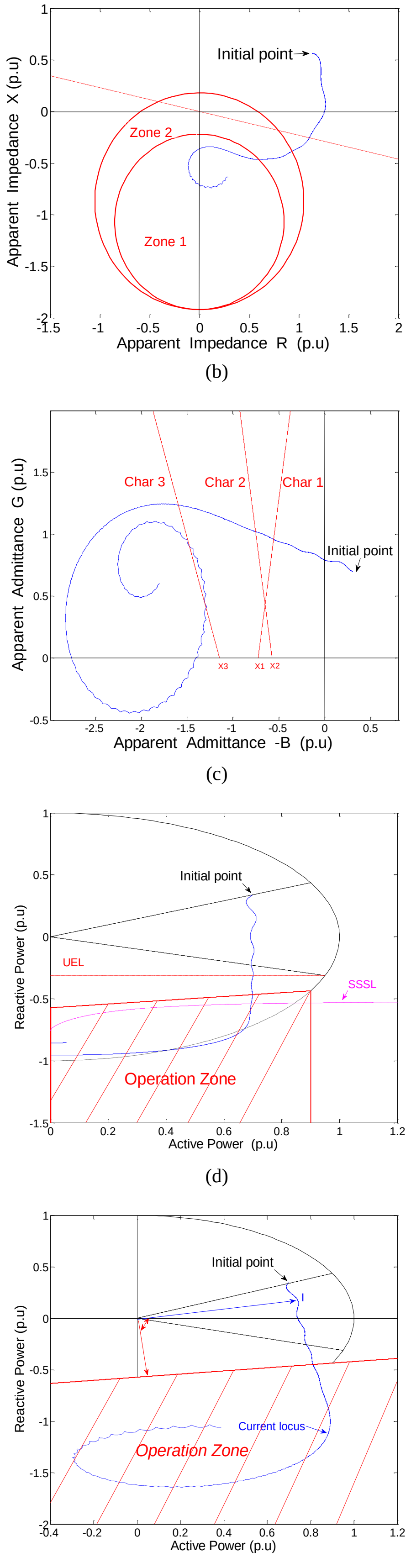
(b)

Fig.8. Generator 1 characteristic curves during complete LOE (a) Active and reactive power (b) phase voltage and current R.M.S. value

When LOE occurs, due to the mechanical inertia, the mechanical input and load angle keep constant temporarily. Meanwhile, the reactive power output decreases to zero quickly and then the generator starts to import the reactive power from the system. The generator internal voltage decays due to field voltage reduction and phase currents increase because the generator begins to absorb a large amount of reactive power. The graphs of Fig. 9 (a) to (e) describe the trajectories of the terminal quantities of Generator 1 in R-X (a), R-X with directional element (b), G-B (c), P-Q (d) and U-I planes (e) respectively.



(a)



(b)

(c)

(d)

(e)

Fig.9. Representation of LOE in different protection schemes

In order to simplify the operation time, the simulation time is offset by 15 s, which means the loss of excitation occurs at 0 second, and terminates just after loss of synchronism. The simulation results are listed in Table 1, and the tripping is initiated after 0.75s time delay.

Protection Scheme	Protection scheme picked up time			Tripping time
R-X	Zone 2	Zone 1		**6.056s**
	5.306s	6.415s		
R-X with directional element	Zone 2	Zone 1		**4.175s**
	3.421s	5.436s		
G-B	Char1	Char2	Char3	**5.014s**
	4.264s	5.215s	6.789s	
P-Q	4.80s			**5.55s**
U-I	4.19s			**4.94s**

Table 1: Simulation Results of Generator LOE in Case 1

From the simulation results of Case 1, R-X with directional element is the fastest protection scheme to detect the fault and initiates a tripping signal after 0.75s time delay when LOE occurs on Generator 1 under heavy load. However, R-X and P-Q schemes need longer time to detect the LOE fault compared to the other three schemes. G-B and U-I schemes can detect the LOE fault correctly as well and both initiate the tripping signals at 5.014s and 4.94s respectively.

Case 2: Generator LOE under light load condition.
The initial condition of Case 2 is almost the same as Case 1, but the generator carried 40% load in this case. The simulation results are listed in the table below:

Protection Scheme	Protection scheme picked up time			Tripping time
R-X	Zone 2	Zone 1		**8.141s**
	7.391s	14.08s		
R-X with directional element	Zone 2	Zone 1		**6.931s**
	6.181s	7.63s		
G-B	Char1	Char2	Char3	**9.98s**
	9.23s	9.23s	17.51s	
P-Q	10.10s			**10.85s**
U-I	7.98s			**8.73s**

Table 2: Simulation Results of Generator LOE in Case 2

From the simulation results of Case 2, the protection schemes need longer time to detect the LOE fault compared with Case 1, as the generator terminal characteristics during LOE highly depends on the initial load condition. In this case, R-X with directional element scheme responds much faster than other four schemes.

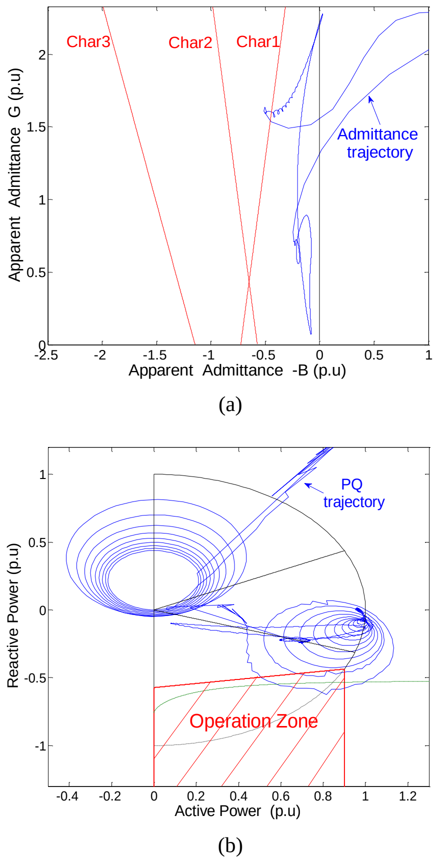
Case 3: Generator LOE under condenser operation mode.
Sometimes the hydro generator may operate as a synchronous condenser to adjust the system voltage or maintain the reactive power balance. In this case, the active power output remains zero and reactive power output decreases from 0.5 pu to -0.4 pu after loss of excitation. And finally, Generator 1 operates as an induction generator without loss of synchronism after the transient period.

According to the simulation results, R-X scheme and R-X with directional scheme detect the LOE fault at 10.88s and 11.12s respectively. However, G-B, P-Q and U-I schemes cannot detect the LOE fault in this case, as the endpoints of LOE characteristics are located outside the protection zones of these three protection schemes.

Case 4: Generator external symmetrical and unsymmetrical faults occur at Busbar 1 at 10s respectively. The fault duration is 150ms. Before the fault, the generators carry 80% load with p.f. 0.95 leading.

- Scenario 1: Three-phase-short-circuit fault;
- Scenario 2: Phase-to-phase fault;
- Scenario 3: Single-phase-to-ground fault with 0.1 ohm fault resistance;

This case is to test the stability of protection schemes during generator external faults. Fig.10 shows the behaviors of G-B, P-Q schemes during the Busbar 1 three-phase-short-circuit fault under case 4 as below:



(a)

(b)

Fig.10. Representation of Busbar 1 three-phase-short-circuit in LOE schemes (a) G-B scheme (b) P-Q scheme

From the simulation results, the characteristic curves entered the LOE protection zones of G-B and P-Q schemes during Busbar 1 symmetrical fault. For P-Q scheme, it passed the protection zone several times during the fault. The maximum time during which the terminal characteristics stay in the relay operation zone is listed in Table 3:

Protection Schemes	Entering LOE protection zone during the fault (Y/N)	Maximum duration time
R-X (directional)	N	-
R-X	N	-
G-B	Y	**0.01 s**
P-Q	Y	**0.0025 s**
U-I	**N**	-

Table3: Simulation Results of Busbar Three Phase Short Faults

In some extreme cases, the LOE relay may operate incorrectly during generator external faults if the maximum duration time is longer than relay operation time delay setting.

3.5 Prevention of LOE relay incorrect operation during and after external faults

In order to prevent the LOE relay incorrect operations, two blocking elements can be implemented to block the LOE relay for certain time (e.g. 0.5s), when the external faults occur.

3.5.1 Negative-sequence supervision element

Fig.11 shows the sequence components in the phase voltage at generator terminal measurement point during the Busbar 1 phase-to-phase and phase-to-ground faults:

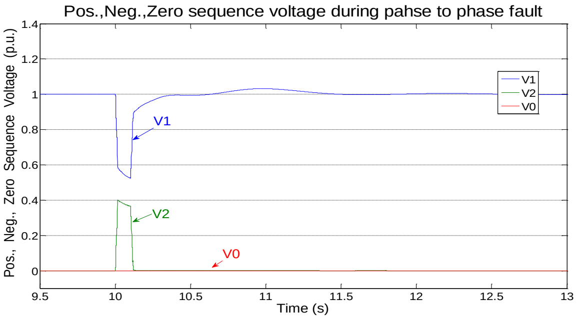


Fig.11. Sequence component voltages during Busbar 1 phase to phase fault

A negative sequence supervision element can be implemented to block the LOE relay operation for a short time during external unsymmetrical faults. The typical setting could be U2>20% rated voltage and a timer logic is required to keep the stability of this algorithm.

3.5.2 DC component supervision element

During LOE fault, there is no DC component in phase currents. However, the DC component will exist in the phase currents and decay with a certain time constant during external symmetrical fault, as the three phase voltage cannot be the same at the fault point and the generator impedance is predominantly reactance at generator terminal. The DC component element could be implemented to initiate a short time blocking signal during external symmetrical faults. The typical setting could be Idc > 20% rated current. A proper timer might be added in the logic in order to avoid possible incorrect operation once the external fault is switched off.

4 Conclusions

This paper analyzes the common existing protection schemes for LOE faults and compares the reliability and stability among these schemes based on the simulation study in PSCAD. The simulation results show that R-X with directional element scheme responds faster for LOE faults than other schemes. However, R-X, G-B and P-Q schemes need longer time to detect the LOE faults. Besides, G-B, P-Q and U-I schemes may not respond to the LOE faults under synchronous condenser operating mode. Sometimes, the generator external faults may cause the LOE protection schemes incorrect operation, if the characteristic curve stays in the protection zone longer than protection scheme time delay setting. To prevent the LOE relay incorrect operation, this paper introduces DC component supervision element and negative sequence supervision element as blocking elements for LOE relays.

In conclusion, R-X with directional element scheme combined with DC and negative sequence blocking elements is recommended for LOE protection, which gives a satisfactory operation for LOE faults and remains insensitive to other faults and abnormal conditions.

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