Generator loss of excitation (LoE) can be caused by a short circuit in the field winding, unexpected field breaker opening and by a failure in the excitation system. According to Chinese statistics, 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 an impedance measurement scheme, which is the most common LoE protection scheme. Reference [3] compares the behaviors of the impedance and admittance schemes for LoE fault. References [4] and [5] describe the LoE protection scheme related to the generator capability curve based on the P-Q plane. References [6] and [7] introduce a directional current measurement method. All of these schemes, however, 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 these protection schemes during LoE conditions and external faults. Each scheme is evaluated under the same operating conditions and the one with the best performance is selected.

Finally, additional measures to further improve this scheme are suggested.

Existing protection schemes

There are five LoE protection schemes used today, namely, R-X; R-X with directional element; and the G-B, P-Q and U-I schemes. R-X schemes, however, are used widely in power systems. In this article, the calculations for R-X; G-B; P-Q and U-I algorithms are based on the generator current and voltage positive sequence quantities.

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.

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 pu and a negative offset of \(X_d'/2\) for the inner circle shown in Fig.1 [2]. Zones 1 and 2 are for detecting LoE with full load and light load respectively. The typical time delays for zones 1 and 2 are about 0.1 s and 0.5 – 0.6 s [2, 8].

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 \(X_s\). The second offset mho zone 2 setting is identical to the steady-state stability limit in the impedance plane, which is a circle centred 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.

The directional line always issues an alarm signal and a time-delayed tripping, typically within the range from 10 s to 1 minute [8]. Zones 1 and 2 initiate tripping signals with certain time delays, normally, 0.2 s to 0.3 s time delay for zone 1 and approximately 0.75 s for zone 2 to override the power swings [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 P-Q plane, the admittance plane [3]. When the terminal voltage equals the reference voltage \(U=U_{\text{N}}=1\ \text{pu}\), the value in the admittance plane is identical to the capability curve in the P-Q plane. Fig. 3 describes the characteristic of the admittance scheme.

Referring to Fig. 3, typical relay settings for the salient pole generator are [3]:

Char. 1: \(1/X_{d1} = 1/X_{d} + (1/X_{q} - 1/X_{d})/2\quad \alpha_{1} \approx 80^\circ\)  

Char. 2: \(1/X_{d2} = 1/X_{d}\quad \alpha_{2} = 100^\circ\)  

Char. 3: \(1/X_{d3} = 2/X_{d}\quad \alpha_{3} \approx 110^\circ\)  

When Char. 1 and Char. 2 are exceeded and the undervoltage element picks up, a tripping signal is initiated with a short time delay (0.5 to 1.5 s). 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].

P-Q measurement scheme

The generator active and reactive power outputs are limited by the generator’s capability, system steady-state stability limit (SSSL) and under excitation limit (UEL) [9, 10]. Therefore, the
protection region can be obtained directly from the generator capability curve and SSSL. An example of a P-Q scheme including LoE and an undervoltage element is shown in Fig. 4.

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 \((-U_2/X_d)\) in the 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 a 0.75 s time delay.

**U-I measurement scheme**

The 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 \(I_\alpha\) with a characteristic angle -120° to +120° and a non-directional current stage \(I_-\) [6, 7]. The typical setting is shown in Fig. 5 in the P-Q plane with characteristic angle -81.2° and a non-directional current stage 0.568 pu.

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.

**Simulation studies**

**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 \(\Delta-Y\) 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 20 kV and secondary side voltage is 230 kV.

**Generator model**

The generator model comprises a synchronous generator, a hydro turbine with governor, an automatic voltage regulator (AVR) and a power system stabiliser (PSS). The block diagram of generator unit is shown in Fig. 7.

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

<table>
<thead>
<tr>
<th>Protection scheme</th>
<th>Protection scheme picked up time</th>
<th>Tripping time</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-X</td>
<td>Zone 2</td>
<td>Zone 1</td>
</tr>
<tr>
<td></td>
<td>5.306 s</td>
<td>6.415 s</td>
</tr>
<tr>
<td>R-X with directional element</td>
<td>Zone 2</td>
<td>Zone 1</td>
</tr>
<tr>
<td></td>
<td>3.421 s</td>
<td>5.436 s</td>
</tr>
<tr>
<td>G-B</td>
<td>Char 1</td>
<td>Char 2</td>
</tr>
<tr>
<td></td>
<td>4.264 s</td>
<td>5.215 s</td>
</tr>
<tr>
<td></td>
<td>4.80 s</td>
<td>6.789 s</td>
</tr>
<tr>
<td>P-Q</td>
<td>4.19 s</td>
<td>4.94 s</td>
</tr>
<tr>
<td>U-I</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Simulation results of generator LoE in case 1.
Simulation cases
The simulation consists of four cases while the first three cases with the LoE occurred on generator 1 at 15 s due to field winding short circuit.
- Case 1: Generators 1 and 2 operating at 80% load with pf 0.9 overexcited.
- Case 2: Generators 1 and 2 operating at 40% load with pf 0.9 overexcited.
- Case 3: Generators 1 and 2 operating as condensers with zero active power and 0.5 pu reactive power outputs.
- Case 4: External symmetrical and asymmetrical faults occur at busbar 1 at 10 s respectively. The fault duration is 150 ms. Before the fault, the generators carry 80% load with pf 0.95 underexcited.

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.

When LoE occurs due to 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’s 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 in 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.

To simplify the operation time, the simulation results are listed in Table 1 and the tripping is initiated after a 0.75 s time delay.

From the simulation results of Case 1, R-X with directional element is the fastest protection scheme to detect the fault. It initiates a tripping signal after 0.75 s time delay when LoE occurs on generator 1 under heavy load. However, R-X and P-Q schemes need more 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 5.014 and 4.94 s respectively.

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

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

Case 3:
Generator LoE under condenser operation mode. 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. 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 detects the LoE fault at 10.88 s and 11.12 s respectively. However, G-B, G-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 asymmetrical faults occur at busbar 1 at 10 s. The fault duration is 150 ms. Before the fault, the generators carry 80% load with pf 0.95 leading.

- Scenario 2: phase-to-phase fault.
- Scenario 3: Single-phase-to-ground fault with 0.1 Ω fault resistance.

This case tests the stability of protection at 0 s and terminates just after loss of synchronism. The simulation results are listed in Table 1 and the tripping is initiated after a 0.75 s time delay.

Fig. 9: Representation of LoE in different protection schemes.
schemes during generator external faults. Fig. 10 shows the behaviour of the G-B and P-Q schemes during the busbar 1 three-phase short-circuit fault under case 4.

The simulation results show that the characteristic curves entered the LoE protection zones of the G-B and P-Q schemes during the busbar 1 symmetrical fault. For the P-Q scheme, it passed the protection zone several times during the fault. Table 3 lists the maximum time during which the terminal characteristics stay in the relay operation zone.

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

Prevention of incorrect operation of LoE relays

Two blocking elements may be implemented to block the LoE relay when external faults occur.

Negative-sequence supervision element

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

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

DC component supervision element

During an 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 faults, as the three-phase voltage cannot be the same at the fault point and the generator impedance is predominantly reactance at the 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 may be added in the logic to avoid possible incorrect operation once the external fault is switched off.

References


Table 2: Simulation results of generator LoE in Case 2.

<table>
<thead>
<tr>
<th>Protection scheme</th>
<th>Protection scheme picked up time</th>
<th>Tripping time</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-X</td>
<td>Zone 2</td>
<td>8.141 s</td>
</tr>
<tr>
<td></td>
<td>Zone 1</td>
<td>7.391 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.08 s</td>
</tr>
<tr>
<td>R-X with directional element</td>
<td>Zone 2</td>
<td>6.181 s</td>
</tr>
<tr>
<td></td>
<td>Zone 1</td>
<td>7.63 s</td>
</tr>
<tr>
<td>G-B</td>
<td>Char1</td>
<td>9.98 s</td>
</tr>
<tr>
<td></td>
<td>Char2</td>
<td>17.51 s</td>
</tr>
<tr>
<td></td>
<td>Char3</td>
<td></td>
</tr>
<tr>
<td>P-Q</td>
<td></td>
<td>10.1 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.85 s</td>
</tr>
<tr>
<td>U-I</td>
<td></td>
<td>7.98 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.73 s</td>
</tr>
</tbody>
</table>

Table 3: Simulation results of busbar three phase short faults.

<table>
<thead>
<tr>
<th>Protection schemes</th>
<th>Entering LoE protection zone during the fault (Y/N)</th>
<th>Maximum duration time</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-X (directional)</td>
<td>N</td>
<td>-</td>
</tr>
<tr>
<td>R-X</td>
<td>N</td>
<td>-</td>
</tr>
<tr>
<td>G-B</td>
<td>Y</td>
<td>0.01 s</td>
</tr>
<tr>
<td>P-Q</td>
<td>Y</td>
<td>0.0025 s</td>
</tr>
<tr>
<td>U-I</td>
<td>N</td>
<td>-</td>
</tr>
</tbody>
</table>