INFLUENCE OF SPECIAL SHORT CIRCUIT ON ELECTRICAL GENERATOR DESIGN

Ding Zhong MENG

(HONG KONG, CHINA)

SUMMARY

Refer to the IEC Standard 34-3, the generator shall be designed without failure, to withstand three-phase short circuit at its terminals while operating at 1.05 p.u. rated voltage. But in recent years, a special type of internal short circuit in generators occurred in China twice, and produced the fault current and mechanical stress much higher than the IEC Standard 34-3 for generator stator winding design, thus resulted to a disastrous damage.

This paper is to review the special generator short circuit fault conditions with analysis and calculations to quantify the fault current and the stress level of this special short circuit, thus compare the probability of the special and three-phase short circuit occurrence, and hence more available to establish the aspect of criteria for the protection against the special short circuit.

The aim for this paper is to contribute the findings as a supplement to the standard of new generator design, so that the stator could sustain and or avoid the special short circuit in a reasonable way.

KEYWORDS

1. OCCURRENCE OF SPECIAL SHORT CIRCUIT

1.1 Internal Single-Phase to Neutral Short Circuit [ K'(1-N) ]

There have been 3x752MVA generators operating at the Shajiao ‘C’ Power Station in China since 1996. Unit-2 generator had tripped at 609MW load by differential protection on 2 Oct. 1997. The trip was caused by a short circuit between phase C line end phase ring (E₃) and its adjacent neutral end phase rings (S₃ & S₁) at the bottom part of phase rings inside the terminal box as shown in FIG.1. FIG.1 also shows the damaged area in the phase rings:

- A 0.95m length of the line end phase ring E₃ (phase C) closing to T piece connecting to the vertical riser was burned away.
- A 0.4m length of neutral end phase ring S₃ was also burned away.
- A 0.25m length of neutral end phase ring S₁ was burned away with a further 0.6m was partially melted.

FIG.2 shows the fault location—short circuit between E₃(C) and S₃ (Z) / S₁ (X), this is called the internal single-phase to neutral short circuit.

![FIG.1 SHAJIAO ‘C’ UNIT 2 GENERATOR STATOR DAMAGE AREA](image1)

Two bolts of the phase ring clamping E₃ and S₁ terminal risers to the floating bracing were found in the bottom of the terminal box. Laboratory tests proved that these bolts had failed by high cycle fatigue and had therefore failed before the incident. This increased the level of vibration on the vertical risers causing cracking of the insulation, allowed water to penetrate on E₃ terminal riser and produced a short circuit between E₃ and its adjacent S₃/S₁ phase rings.

1.2 Internal Double-Phase to Neutral Short Circuit [ K'₁(1-N) ]

There have been 2x829MVA generators operating at the Zhuhai Power Station in China since 1999. On 28 Sept.1999, Unit-1 generator tripped at 680 MW load by differential protection during unit commissioning stage. As seen from the exciter end, the high voltage line end of phase A&B were damaged, particularly the neutral end of phase C was most seriously damaged and melted. According to the analysis by the original equipment manufacturer, the root cause of the failure was suggested...
that the phase rings were damaged by overheating due to the loss of cooling water circulation and/or blocking by gas bubbles in part of the cooling water manifold. The sequence of fault development is shown in TAB.1 which is the result by analysis in accordance with the following:

- Oscillograph record from 220 kV side
- Sequence of event (SOE) record
- Relay protection and circuit breaker operation
- Stator fault damage diagram
- Fault current calculation

<table>
<thead>
<tr>
<th>Time (sec.)</th>
<th>Fault initiation, relay &amp; circuit breaker operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>K(1-N) - Phase B to ground</td>
</tr>
<tr>
<td>0.412</td>
<td>K(2A,1B) - Phase A, B to ground</td>
</tr>
<tr>
<td>0.424</td>
<td>Generator differential protection operated</td>
</tr>
<tr>
<td>0.458</td>
<td>220kV main transformer circuit breaker tripped</td>
</tr>
<tr>
<td>0.500</td>
<td>Generator ground protection (time setting–0.5 sec.) operated</td>
</tr>
<tr>
<td>0.660</td>
<td>K(1B-2A-N) - Phase A, B line end to C neutral end short circuit</td>
</tr>
</tbody>
</table>

The sequence of fault development has shown that the special short circuit [K(1,1-N)] occurred at 0.202 sec. after disconnection with power system by the tripping of 220kV main transformer circuit breaker.

2. ANALYSIS & CALCULATION

2.1 Relevant Data of Shajiao ‘C’ Power Station

- Rated Apparent Power: 752.22 MVA
- Rated Stator Voltage: 19 kV
- Rated Stator Current: 22.86 kA
- Sub-transient X''ds: 19.6%
- Transient X'ds: 29.6%
- Negative Sequence X₂: 20.6%
- Zero Sequence X₀: 7.0%
- Main Transformer Xt: 15.88% (based on 716 MVA)
- 500kV System Fault Level: 28113MVA (30.9kA)

2.2 Three-Phase Terminal Short Circuit Current Level

FIG.3 has shown the fault current distribution during a three-phase short circuit at its terminals at 1.05 p.u. rated voltage (IEC 34-3 Standard). The calculation is based on generator rated capacity.

1 p.u. = 752.22 / (√3 x 19) = 22.86 kA (Rated stator current)

\[ I^{(3)} = 1.05 / X''ds = 1.05 / 0.196 = 5.36 \text{ p.u.} \]
2.3 Internal Phase C to Neutral Short Circuit \[ K^{(1-N)} \]

2.3.1 Equivalent Circuit of \( K^{(1-N)} \)

FIG.4 has shown the equivalent circuit of \( K^{(1-N)} \)

![Equivalent Circuit of K(1-N)]

MVAb : 752.22 MVA

Main Transformer : \( \frac{752.22}{716} \times 0.1588 = 0.1668 \) p.u.

2.3.2 Result of Calculation

It is assumed that the current in two parallel paths (windings) of each phase are equally distributed. The result of calculation is shown in FIG.5.

2.3.3 Fault Current Change in Each Phase C Winding

FIG.6 shows fault current change in each C winding.

After the tripping of the Generator Circuit Breaker (GCB), the fault current in each phase C winding dropped down rapidly from 89kA (3.9 p.u.) to 63 kA (2.8 p.u.), it was due to:

- Automatic change of generator reactance from \( X''_{ds} \) to \( X'_{ds} \).
- Disconnected with power system.

Then the fault current started from 63 kA would drop down slowly, it was due to:

- Even the field switch tripped as well as GCB, the excitation (stator voltage) would reduce slowly.
- The time constant of fault path is very high (high reactance, low resistance), the fault current would also gradually reduce to zero.
According to the reset current of differential protection and its reset time recorded in SOE, the current attenuation curve is shown in FIG.6, by which the time constant of this curve is 2 sec.

2.4 Internal Phase B,C to Neutral Short Circuit [\( K^{(1,1-N)} \)]


In addition to the calculations based on the actual condition in the Final Report, the calculations listed in this paper is based on the same parameters and condition of Shajiao ‘C’ Power Station for the comparison of these two kinds of special internal short circuit and provide useful data for the design reference.

2.4.1 Equivalent Circuit of [\( K^{(1,1-N)} \)]

2.4.2 Result of Calculation

2.5 Comparison of Fault Current and Stress between Special & Three-Phase Short Circuit

It is considered that the electromagnetic force and stress acting on the same part of stator slot and end winding produced by the fault current is increased approximately by the square of the fault current. TAB.2 and FIG.9 have shown the comparison of fault current and stress between the special and three-phase short circuit

<table>
<thead>
<tr>
<th>Type of Fault</th>
<th>Winding, Line/End or Neutral End</th>
<th>Fault Current (p.u.)</th>
<th>Current Ratio ([ I^{(1-N)} / I^{(3)} ) or ([ I^{(1,1-N)} / I^{(3)} )]</th>
<th>Stress Ratio ([ (I^{(1-N)})^2 / (I^{(3)})^2 ) or ([ (I^{(1,1-N)})^2 / (I^{(3)})^2 )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^{(3)} )</td>
<td>Windings &amp; Ends</td>
<td>2.68</td>
<td>2.68/2.68 = 1.00</td>
<td>1.0</td>
</tr>
<tr>
<td>( K^{(1-N)} )</td>
<td>Phase C Winding</td>
<td>3.895</td>
<td>3.895/2.68 = 1.45</td>
<td>(1.45)^2 = 2.10</td>
</tr>
<tr>
<td></td>
<td>Phase C Line End</td>
<td>7.90</td>
<td>7.90/2.68 = 2.95</td>
<td>(2.95)^2 = 8.70</td>
</tr>
<tr>
<td></td>
<td>Phase A Neutral End</td>
<td>4.90</td>
<td>4.90/2.68 = 1.83</td>
<td>(1.83)^2 = 3.34</td>
</tr>
<tr>
<td>( K^{(1,1-N)} )</td>
<td>Phase B,C Windings</td>
<td>3.61</td>
<td>3.61/2.68 = 1.35</td>
<td>(1.35)^2 = 1.82</td>
</tr>
<tr>
<td></td>
<td>Phase B,C Line End</td>
<td>8.00</td>
<td>8.00/2.68 = 2.99</td>
<td>(2.99)^2 = 8.94</td>
</tr>
<tr>
<td></td>
<td>Phase C Neutral End</td>
<td>10.83</td>
<td>10.83/2.68 = 4.04</td>
<td>(4.04)^2 = 16.33</td>
</tr>
</tbody>
</table>
As indicated in TAB.2 and FIG.9, the fault current and stress of the special short circuit over the three-phase short circuit are different for stator windings, line ends and neutral ends:

- **Stator windings**

  During $K^{(1\text{-}N)}$, the current developed $I^{(1\text{-}N)}$ is 1.45 times of the $I^{(3)}$ (IEC Design Standard), and the forces acted on the stator windings is 2.1 times of the design standard.

  During $K^{(1,1\text{-}N)}$, the current and stress developed are comparatively less than that of $K^{(1\text{-}N)}$, but still higher than IEC Design Standard.

- **Line ends of winding**

  The current and stress developed during both $K^{(1\text{-}N)}$ and $K^{(1,1\text{-}N)}$ are nearly the same level, the fault current and stress is nearly 3 and 9 times that of design standard respectively.

- **Neutral ends of winding**

  The most serious case is that the fault current and stress developed during $K^{(1,1\text{-}N)}$ is about 4 and 16 times the IEC Design Standard respectively. That is why the faulty neutral end of Unit-1 generator of Zhuhai Power Station during $K^{(1,1\text{-}N)}$ on 28 Sept. 1999 was completely evaporated.

### 2.6 Comparison of Special & Three-Phase Short Circuit Current Ratio at Different 500kV System Fault Level

TAB.3 & FIG.10 have shown the ratio of the special to three-phase fault current at different 500 kV system fault level.

#### TAB.3  COMPARISON OF SPECIAL AND THREE-PHASE SHORT CIRCUIT CURRENT RATIO AT DIFFERENT 500kV SYSTEM FAULT LEVEL

<table>
<thead>
<tr>
<th>Type of Fault</th>
<th>Winding, Line end Neutral end</th>
<th>$I^{(C\text{-}N)}/I^{(3)}$ or $I^{(B,C\text{-}N)}/I^{(3)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{(C\text{-}N)}$</td>
<td>Phase C Winding</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Phase C Line End</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Phase A Neutral End</td>
<td>1.25</td>
</tr>
<tr>
<td>$K^{(B,C\text{-}N)}$</td>
<td>Phase B,C Windings</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>Phase B,C Line Ends</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>Phase C Neutral End</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Remark: 0 kA* means that the generator is disconnected with power system by the opening of GCB or main transformer H.V. circuit breaker.
The fault current of the special short circuit at maximum system fault level is only slightly higher than others, it is because of the equivalent system reactance, which is much less than the main transformer reactance as shown in FIG. 4 & 7. The fault current of the special short circuit current at GCB open condition (0 kA) is much less than normal operating condition.

It is recommended that the effect of power system on the special fault current at maximum system fault level should be considered for the generator design.

3. PROBABILITY OF FAULT OCCURRENCE

The stator phase rings are usually arranged as shown in FIG.1, the high voltage line end rings are adjacent to the neutral end rings. This arrangement may be designed for the purpose of reducing the leakage flux or shortening the line and neutral ends. But the special short circuit would occur if the adjacent rings cause flashover by any reason, such as the fault developed in Shajiao ‘C’ and Zhuhai Power Station.

To protect the generator against phase-to-phase short circuit, the Isolated Phase Buses (IPB) have to be installed to separate each phase between generator, GCB and main transformer. It will not be possible to initiate a three-phase short circuit with such an arrangement.

For example, there were 46 units (200 ~ 600 MW) of turbo-generators operated in North-East China, statistics have shown that phase-to-phase fault occurred 10 times in the past 20 years; single phase to ground fault occurred only 3 times, but no three-phase fault reported. The probability of the special short circuit occurrence is much higher than three-phase short circuit, therefore, both types of short circuit should be considered in users and design specifications for generator.

4. STATOR REWIND OF SHAJIAO ‘C’ POWER STATION

Discussion had been carried out by the representatives from Shajiao ‘C’ Power Station, the J-V Companies and Chinese Generator Experts and the manufacturer for the modification of existing generators. It was decided to rewind all three 752.22 MVA stators windings with a new design in Europe. The rewind of those two stators had been completed in 2001 and 2002, the last one would be completed at the end of 2003.
During the discussion, I recommended that the re-design of the stator winding should sustain such special short circuit which is more serious than three-phase short circuit. In addition, I also recommended that the stator phase rings and their connections should be so designed by every means to avoid such short circuit.

Both recommendations had been accepted for the modification of these generator stators.

The configuration of stator end winding supporting system has been greatly reinforced by cone support in stead of the previous basket support.

The arrangement of phase rings has also been improved as shown in FIG.11, all the high voltage line end rings are arranged on one side, and the neutral end rings on another side.

5. CONCLUSION

- The analysis shows that a very dangerous high current could be resulted from the special short circuit between stator high voltage lines (single or double phases) to the neutral. The mechanical stresses (electromagnetic forces) developed by the fault current increase approximately with the square of the current for the same parts of stator. Therefore, the fault current and particularly the stresses are much higher than the IEC 34-3 generator design standard.

- The probability of the special short circuit occurrence is much higher than three-phase short circuit. It is recommended that the design of stator windings should also sustain such special short circuits.

- The phase ring arrangement and its connection should be so designed by every means to avoid such special short circuit between high voltage line terminals and the neutral.

- For the safe and reliable operation of generators, it is recommended that the requirement for the protection against the special short circuit should be included in the customer specifications.

- How could the stator windings sustain and/or avoid such special short circuit in a reasonable and economical way? It is expected that a suitable study result would be supplemented in the future for the generator design standard.