GROUNDING AND GROUND FAULT PROTECTION OF MULTIPLE GENERATOR INSTALLATIONS ON MEDIUM-VOLTAGE INDUSTRIAL AND COMMERCIAL POWER SYSTEMS

PART 1 – THE PROBLEM DEFINED

An IEEE/IAS Working Group Report


Working Group Chair:
Prafulla Pillai
Kellogg Brown & Root, Inc.
Houston, Texas 77002

Abstract - The paper discusses typical grounding practices and ground fault protection methods for medium voltage generator stators, highlighting their merits and drawbacks. Particular attention is given to applications of multiple generators connected to a single bus. The paper also provides an overview of the generator damage mechanism during stator ground faults. Problem areas associated with each type of grounding are identified and solutions are discussed. The paper also provides a list of references on the topic. The paper is intended as a guide to aid engineers in selecting adequate grounding and ground fault protection schemes for medium voltage industrial and commercial generators for new installations, for evaluating existing systems, and for future expansion of facilities, to minimize generator damage from stator ground faults. The paper will review the issues associated with various grounding practices and ground fault protection methods to minimize iron damage.

The paper summarizes some basic considerations in selecting grounding and ground fault protection of generators installed on medium voltage power systems with multiple ground sources and serving load directly at generator terminal voltage. The discussions also apply to generators installed in parallel with utility transformers. However, the paper excludes installations with special grounding requirements such as Independent Power Producer (IPP) connections and mining applications. Also, rotor ground faults are outside the scope of this paper.

The paper will:

a) Discuss factors requiring consideration in selecting grounding and ground fault protection schemes for medium-voltage industrial generators

b) Identify problem areas associated with grounding and ground fault protection of generators, especially for multiple units operating in parallel on medium-voltage industrial power systems

c) Provide alternate solutions to the identified problems

d) Identify items to be addressed in detail in future working group papers

The paper is organized into four parts. Part 1 covers scope, introduction, user examples of stator ground failure, and theoretical basis for the problem; Part 2 discusses various grounding methods used in industrial applications; Part 3 describes protection methods for the various types of grounding; and Part 4 provides a conclusion and bibliography.

I. SCOPE OF PAPER

In recent years severe damage to bus-connected generators from stator ground faults has been observed in numerous industrial plants. Such generator failures may require extensive stator lamination repairs at the manufacturer’s premises with the associated down time. The primary objective of this paper is to present methods of protecting medium-voltage industrial generators against extensive and expensive stator iron damage from internal...
II. INTRODUCTION

Many existing and new industrial facilities include multiple generators operating on plant distribution buses at the medium-voltage level (see Fig. 1). The trend of in-plant generation on a common bus is increasing due to low cost and simplicity. Also, the average size of bus-connected industrial generators is larger in recent years than in the past. While the economics of bus-connected in-plant generation is attractive, it imposes on the power system engineer concerns and added tasks of careful consideration regarding generator protection and equipment capabilities.

The fault type to which stator windings are most often subjected is a short circuit to ground. Many incidents of severe damage to bus-connected generators from stator ground faults have been reported in recent years. It has been recognized by recent studies that the generator damage is caused more by the ground fault current contribution from the generator itself than from the system. During a stator ground fault in a generator, the fault current persists even after opening the generator breaker, thereby causing more extensive iron damage (see Fig. 2). The damage can be substantial even with high-resistance grounded generators when connected directly to a grounded distribution system bus. The significant increase in such incidents has alerted users and insurers. Also, multiple grounding of sources will result in very high fault currents causing severe damage and coordination problems. Therefore, special attention must be given to generator grounding and ground fault protection.

It should be noted that the method of ground fault protection is directly related to the method of system grounding used. There are many decisions, considerations and alternatives that should be carefully examined while designing an adequate and reliable grounding system for increasing personnel safety, minimizing equipment damage and avoiding unwanted interruptions in plant operation. Standards and other publications which cover generator grounding and ground fault protection are available, but they do not address specific problems associated with bus-connected multiple generator installations on medium voltage industrial systems. Therefore, concern and confusion exists among engineers regarding the appropriate application of grounding and ground fault protection for such installations.

III. EXAMPLES OF STATOR GROUND FAILURES

A large paper mill had the experience of having two generator failures approximately one year apart. Each of the two air cooled units, installed in 1971, was rated 15,625 kVA, 13,800 V. Each generator was wye-connected and grounded through its own 400 A grounding resistor. See Fig. 3 for simplified single-line diagram of the generator protection system. The protective scheme included the standard electromechanical relay protection as listed in Table 1. The total system ground current available was 2,000 A from three generators and two utility tie transformers.
Table 1

<table>
<thead>
<tr>
<th>No.</th>
<th>CT</th>
<th>Tap</th>
<th>TD</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>51G</td>
<td>Ground overcurrent</td>
<td>150:5</td>
<td>2.5</td>
<td>9.5</td>
</tr>
<tr>
<td>51V</td>
<td>Overcurrent with voltage controlled</td>
<td>1000:5</td>
<td>4.0</td>
<td>10</td>
</tr>
<tr>
<td>87</td>
<td>Phase differential</td>
<td>1000:5</td>
<td>Factory set at 0.14 A</td>
<td>SA-1</td>
</tr>
<tr>
<td>87GN</td>
<td>Ground differential</td>
<td>1000:5</td>
<td>1A</td>
<td>M=1</td>
</tr>
</tbody>
</table>

The first unit to fail tripped off line as the result of a winding failure at a position approximately 25% electrically from the line terminals of Phase 3 winding. The stator winding was burned over an area of approximately 8 inches in length. The core steel was also burned approximately 8 inches, thus requiring its replacement. The restacking of the core steel could only be accomplished by removing the stator and shipping it to the manufacturer’s plant.

The generator field was shipped to a service shop and the retaining rings were removed. There was splattered copper and steel with burned insulation from the stator winding imbedded in the field winding end turns. Copper contamination was also located in the field’s cooling passages.

The total cost to rebuild the stator core, rewind the stator, rewind the field, and upgrade the generator protection was approximate $1,500,000. The incremental cost to remove, ship, replace the core steel, and reinstall the stator contributed approximately $500,000 of this total cost.

Subsequent investigation revealed that the 400 A grounding resistor was installed in such a manner that the ground lead could possibly short out 25% of the resistor grid. As a result, the actual ground fault current could have been as much as 20% greater than the design value. The second unit was tripped off line due to phase differential relay (device 87) operation. The winding failed in the middle of the Phase 1 coil, in a similar manner to the previous unit. The coil burning was approximately 10 inches long. The field winding also had splattered copper from the stator failure on the end turns. The stator core of this unit also had to be restacked due to the damage.

Investigation of the second unit revealed that the operating times of the phase differential (device 87) and ground differential (device 87GN) relays allowed the 87 device to pickup prior to the 87GN device. Both units utilized field breakers that were opened when the fault was detected. It was felt that both of these units failed initially due to an internal turn-to-turn short in the coil which quickly escalated to a phase-to-ground fault.

Figures 4 and 5 below show photographs of the generator parts that failed as described above. Fig. 4 shows the generator winding failure as viewed from inside the unit. Fig. 5 shows the burning of a stator lamination resulting from winding failure. Fig. 5 photograph was taken after removal of the laminations from the stator up to the area of the failure.

Fig. 4. Generator Winding Failure

Fig. 5. Core Damage
IV. THEORETICAL BASIS FOR THE PROBLEM

The one-line diagram, shown in Fig. 6, depicts a simplified industrial system of a medium voltage bus with one generator and one utility step-down transformer. While any resistor rating could be chosen for this example, to make it as general as possible, both resistors will be assumed to be rated 400 A, for a maximum system ground fault level of 800 A.

Fig. 6. Typical One-Line Diagram

Faults inside generators and transformers will be limited by the impedance of the generator or transformer winding and therefore will be lower in magnitude than faults on the bus. Therefore, the most severe fault condition for a generator (or motor) is a fault directly at the terminals on the first turn of the stator winding. For the system illustrated in Fig. 6, this fault will have a magnitude equal to the system maximum of 800 A, with 400 A flowing into the generator from external sources (“system sources”) and 400 A generated within the generator itself. The potential damage associated with each of these currents can be considered separately and the total damage determined by superposition.

An intuitive expectation is that the damage caused by a fault inside a generator is proportional to the energy released in the arc at the fault point. A general expression for the energy released in a fault is

\[ \text{Energy} = \int i^k \, dt \quad (1) \]

Therefore, the damage associated with a fault is a function of two variables, the magnitude of current, \( i \), and the duration of the fault, \( t \).

The value of \( k \) in (1) is also a factor. A value of 2 would apply in the case of purely resistive heating. Various researchers have predicted values for \( k \) for an arc in the range of 1 to 2 [2, 3]. The purpose of this paper is to address the system design implications of stator fault point damage, not to suggest an exact value of \( k \). Therefore, it is sufficient for this analysis to arbitrarily pick a value (\( k=1.5 \)) for the purpose of illustration.

a) Stator Damage Due to Current Through the Transformer Neutral (System Current)

The technology of stator ground fault detection ranges from the conventional stator differential relay to modern detection modalities that can detect faults very close to the neutral end of the winding. For this hypothetical worst case scenario, therefore, it is reasonable to assume that the fault will be detected and tripping will be triggered with no intentional time delay. Allowing for one cycle of relay time with a five-cycle breaker, the 400 A current from the resistor on the utility step-down transformer will persist for six cycles (0.1 seconds on 60Hz systems). Therefore, a damage parameter associated with the externally-sourced ground fault can be determined by evaluating this integral expression of (1) over the six-cycle period during which this current will flow.

The curves shown in Fig. 7 depict the damage indices viewed in two ways. Fig. 7a shows that the potential damage increases as the current rating of the neutral grounding resistor on the transformer becomes larger. Fig. 7b shows how the damage accumulates with time for the singular case of a 400 A resistor on the transformer neutral. This curve is plotted on semi-logarithmic axes in order to depict more clearly the way that the damage accumulated during the six-cycle period of time prior to opening the generator breaker. Note that all of the damage associated with current from the resistor on the step-down transformer takes place during this short period.

Tripping the generator breaker does not interrupt the current that rises through the generator neutral. This current will flow as long as the generator field remains excited as a forcing function. Tripping the generator breaker should also trigger tripping the field, but the excitation will decay gradually under the control of the generator single-line-to-ground short-circuit time constant, \( \tau \). While this parameter does vary from one generator to the next, it falls in the range of 0.8-1.1 sec. Thus, the damage index associated with current produced by the faulted generator itself can be calculated using an expression similar to (1) in which the current is a decaying exponential. This integral must be evaluated over the entire period of time required for the current to decay to zero.
Fig. 7a. Energy due to “System Current – for Various Magnitudes of Current

b) Current From the Faulted Generator

\[
\text{Energy} = \int \left( \frac{-t}{I_e \tau} \right)^k \, dt \quad (2)
\]

Fig. 8a shows the damage associated with the generator current for various ratings of the generator resistor up to a maximum of 400 A. Again, it is apparent that higher resistor ratings will result in greater damage. But note that in this instance, the maximum value of this damage parameter is about 5,200 watt-seconds compared with about 800 watt-seconds in Fig. 7a.

The reason for this difference is apparent in examining Fig. 8b. Note that the fault energy associated with current through the generator neutral resistor accumulates for several seconds of time, not just the 0.1 seconds depicted in Fig. 7b. This is because the fault current continues to flow until the generator field de-magnetizes; there is no breaker to interrupt fault current through the generator neutral itself.

Comparing Figs. 7 and 8 yields two very important observations.

1) In this simple case with one generator and one transformer, each of which is low-resistance grounded, most of the damage in the faulted generator is attributable to current from the generator itself. That is, most of the generator damage is self-inflicted. Therefore, changing generator grounding practices would have far more impact on reducing stator ground fault damage than changing system (transformer) grounding practices. Obviously, increasing the number of “system sources” will result in increased damage, and with enough external sources, the damage due to system current could exceed the damage due to current through the neutral of the faulted generator.

2) Most of the “self-inflicted” damage takes place after the generator breaker trips. Thus, while the importance of fast generator protection cannot be overemphasized, faster protection does not necessarily mean less damage because tripping the generator breaker does not interrupt the flow of current through the generator neutral.

Large generators are rarely bus-connected. Instead, the generator is associated with a dedicated step-up transformer, and other than perhaps station auxiliaries, no load is served at generator terminal voltage. This is known as a “unit-connected” generator (see Part 2 of the paper for details). Because there is no distribution system selectivity requirement, these generators are almost always grounded through distribution transformers equipped with secondary loading resistors. In these applications, the worst case ground fault current is typically limited to 10 A. Fig. 9 shows how potential fault damage increases through time, assuming that the initial magnitude of ground fault current is limited to 10 A.
It is interesting to observe that while the frequency of iron burning on bus-connected industrial generators is increasing, there are no anecdotal reports of iron burning on unit-connected generators with stator ground faults. One researcher demonstrated that a generator can withstand fault currents up to 10 A in magnitude indefinitely without iron burning [4].
V. SUMMARY

This paper presented Part 1 of a four-part Working Group Report on generator grounding and ground fault protection. Part 1 has introduced the mechanism of generator damage during stator ground faults. Actual examples are given where extensive damage occurred even after opening of the generator circuit breaker. This damage is due to the extended time required for the field to decay; thereby, maintaining the flow of current to the fault.

Part 2 of this Working Group Report discusses various grounding methods used in industrial applications, highlighting their advantages and limitations. Part 3 describes the protection methods for the various types of grounding. Part 4 of the report provides a conclusion and a bibliography of additional resource material on the subject of generator grounding and ground fault protection.

VI. REFERENCES


Fig. 10. Fault Energy Accumulation