

# Application of a hybrid grounding scheme to a paper mill 13.8 kV generator

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## Abstract

Many paper mills and other industries use turbine generators to supply critical process steam and electrical generation needs within the plant. The loss of a generating unit for an extended period would result in very costly replacement power and repair costs for any paper mill. As machine insulation systems age over decades, aging mechanisms progress to increase the risk of a possible ground fault internal to the generator. An IEEE®/IAS Working Group Report [1][2][3][4] submitted in 2002 discusses grounding and ground fault protection for medium-voltage generator stators, highlighting their merits and drawbacks. The report is intended as a guide for engineers installing new or upgrading existing generator systems to minimize industrial bus connected generator damage from stator ground faults. This paper discusses a 13.8 kV generator upgrade at a paper mill employing the hybrid grounding scheme and ground fault protection evaluated favorably by the IEEE/IAS Working Group. Project tasks are described in detail. Issues and difficulties encountered during the course of the generator grounding upgrade that were not mentioned in the Working Group Report are presented for reference.

## Introduction

An IEEE/IAS Working Group Report presenting methods of protecting medium-voltage industrial generators against extensive damage from internal ground faults was presented at the 2002 IEEE/IAS Annual Meeting. The report comprises four technical papers.

- Part 1 describes the grounding problem, lists user examples of stator ground failure, and provides a theoretical explanation for the problem and resulting generator damage
- Part 2 discusses various grounding methods used in industrial applications and offers a novel grounding approach that maintains continuity of service, controls transient overvoltages, and effectively limits damage to stator iron occurring from internal ground faults
- Part 3 explains various ground protection schemes for the generator grounding and system grounding configurations of Part 2
- Part 4 provides a conclusion and a list of additional resource material

## Working group findings

The conclusions and recommendations of the IEEE/IAS Working Group are repeated here because they are the basis for the Luke Paper Mill generator upgrade. The Working Group Report has shown that the extensive damage due to core burning of faulted generator stators is based upon two factors:

1. As paper mill electrical distribution system complexity increased, the number of source resistor grounds within the system increased, and the total available ground fault current increased. A circuit breaker clearing time of 6 cycles and the increasing magnitude of ground fault current creates significant burning energy within the stator.
2. Ground fault current that rises through the neutral of the generator will not be interrupted by tripping the generator circuit breaker, but will persist for several seconds (after the field breaker trips) until the field demagnetizes. Recent failures have shown that considerable burning damage will be done if the generator is low resistance grounded [1][5]. The time decay of generator ground fault current after initial system clearing is shown in **Figure 1**.



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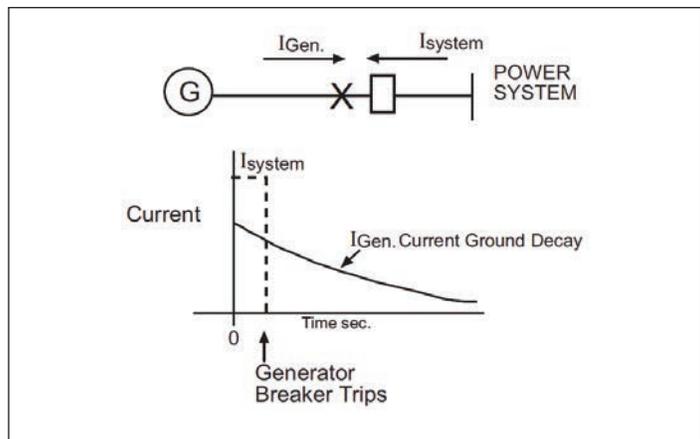


Figure 1. Generator ground fault current

**Working Group solutions summarized**

The Working Group advises that the solutions to this problem should involve several elements, which are briefly summarized below:

1. The number and ratings of low-resistance grounding resistors should be kept to a minimum, to minimize the system source contribution.
2. The generators should be high-resistance grounded, especially during the time after the generator circuit breaker opens and the field excitation is decaying.
3. Hybrid high resistance grounding system (HHRG). Employ high-resistance grounding of the generator and low resistance grounding of the external power source(s).
4. An option to item 3 is to high-resistance ground both the generators and the external sources with the bus being low resistance grounded via a grounding transformer supplied through a circuit breaker. This option is effective only if adequate high resistance grounding can be achieved, but allows system operation during an uncleared high resistance ground fault.

**Application to most critical or at-risk units**

A hybrid grounding scheme as applied to a direct bus connected generator typical of many paper mills is shown in Figure 2 [2][5]. The low resistance ground interrupting device is opened as part of the generator tripping sequence for a ground fault within the generator zone (see section "Low resistance grounding redesign and ground fault protection considerations" for controls description). This scheme is especially beneficial to older critical mill turbine generators and/or those generators with known insulation integrity problems.

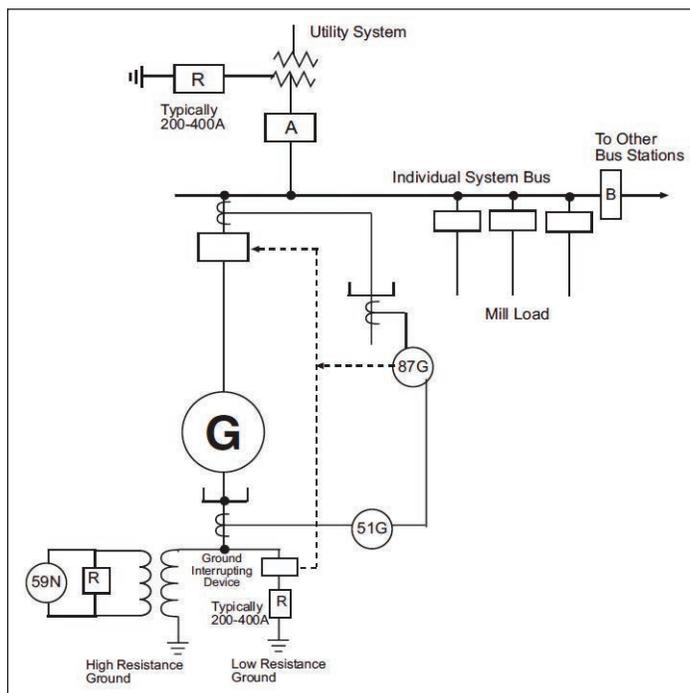


Figure 2. Hybrid high resistance grounding system

The Luke #12 generator (13.8 kV, 40 MVA hydrogen cooled) built in 1979, is such a unit. Online partial discharge testing conducted since 1999 has revealed higher than normal partial discharge (PD) levels for unit #12, which indicate voids in the ground wall insulation system. The PD online activity is sensed by high frequency capacitors (80 pf) connected at the 13.8 kV machine terminals. Unit #12 is an asphalt-mica insulated machine with two turns per coil design. Present paper mill economics favor delaying a planned rewind hopefully until some years into the future. The risk of delaying the rewind is managed by continued use of online PD monitoring together with the added protection of the HHRG protection system. Typical mill economics show that applying the HHRG to units such as #12 yield very good value when compared to the very high combined costs of rewinding the stator, purchasing replacement power and steam system consequences, especially for the extended repair outage periods involved in core damage repair.

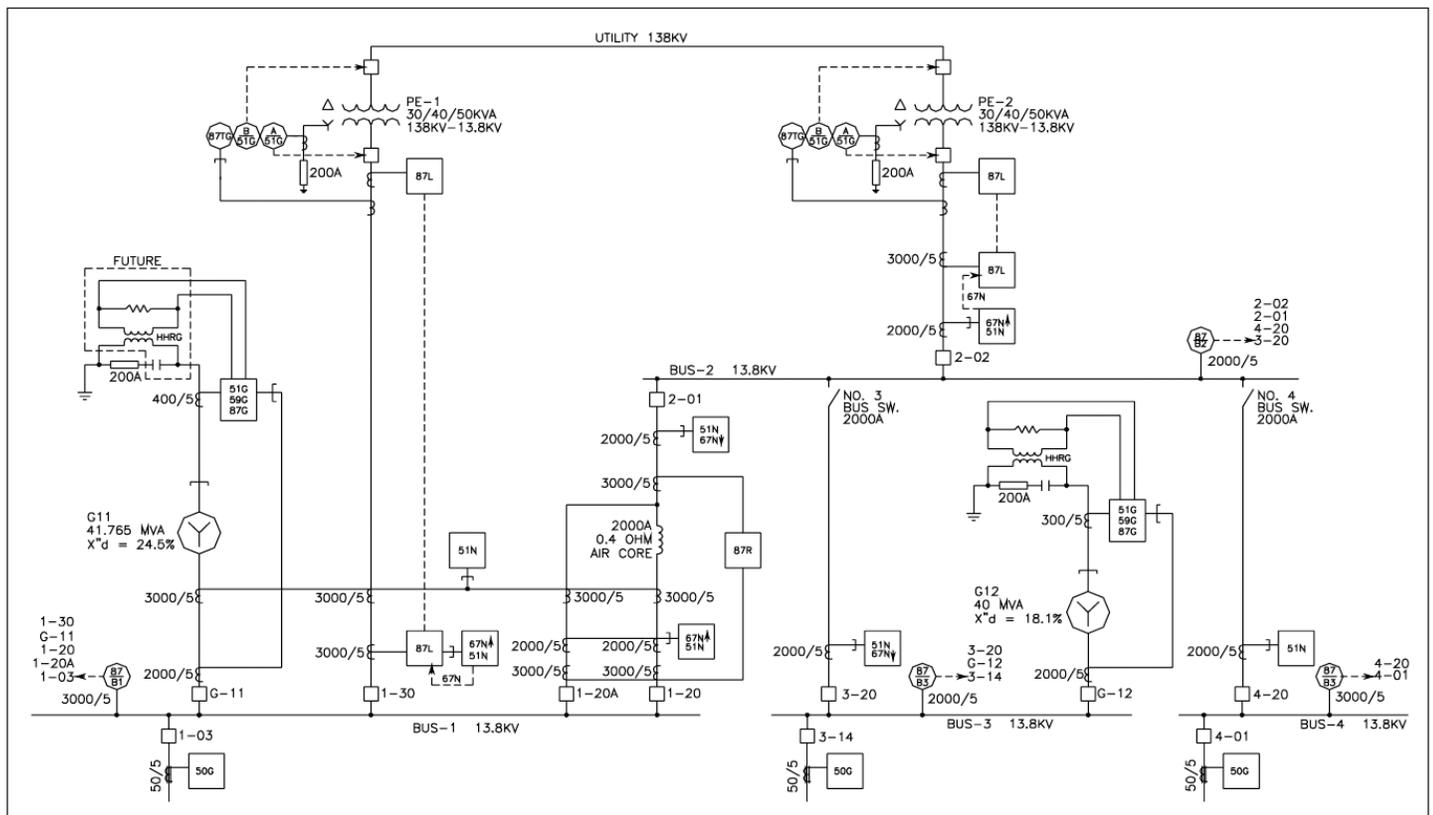
**Mill 13.8 kV system description**

So that the new HHRG system project can be seen from a total mill system standpoint, the Luke Mill simplified 13.8 kV one-line diagram is shown in **Figure 3**. Both the utility ties and both mill generators are normally in operation to supply a total mill load of about 70 MW. The bus tie reactor is in service with all sources energized to limit the total system available fault current to within the interrupting rating of the 1000 MVA switchgear. The reactor is bypassed (by closing breaker 1-20 A) whenever any one source is out of service to prevent excessive reactor voltage drop to mill loads should the loss of the second source occur on the same side of the reactor. Total 13.8 kV system ground fault levels prior to the HHRG project were very high, at 3200 A total. This was comprised of 800 amps from each utility transformer, 400 amps from #11 generator and 1200 amps from #12 generator. In light of the noted IAS Working Group findings and after completing a ground fault study for the Luke Mill, it was planned to reduce the total mill available ground fault current to 800 A. This is further noted in section "Low resistance grounding redesign and ground fault protection considerations."

In summary, the goal to protect the critical mill (#12) generator required that the generator be hybrid grounded and that the system ground fault levels be reduced as noted. This translated to various involved project tasks as noted below:

1. Hybrid grounding for #12 Generator—Size resistor and transformer based on system charging current, select high-speed switching device, and packaging of all components in suitable enclosure.
2. Interface new #12 unit HHRG to existing mill generator relaying and tripping schemes, with operating indications for alarms and status.
3. Install and commission the generator HHRG system.
4. Mill Ground Fault Study to reduce system level and adjust ground relaying accordingly throughout the mill system.
5. Implement reductions in other source resistors and new relay settings.

These tasks were accomplished with close teamwork between the outside equipment manufacturer and mill local engineering efforts.



**Figure 3. Luke Mill ground fault protective relay one-line diagram**

## Description of HHRG cabinet and devices

Part of the design process was how best to retrofit the HHRG physically into the system. This had to also involve the cabinet controls, sizing, packaging, etc. There essentially was no room adjacent to the switchgear itself. Also the switchgear was somewhat removed from the mezzanine location where the generator wye point and existing 200 A (LRG) resistor were located. It was decided to locate the HHRG as close to the wye point as possible. The chosen location had width and height constraints and was somewhat of a wet area. Because the assembly was to be built to metal-enclosed standards, proper internal clearances (internal separation for low voltage and medium voltage) were also factors.

The final design provided a modular approach consisting of:

- Separate lockable medium-voltage cabinet
- NEMA® 3R/4 design for the wet environment
- Separate control cabinet mounted on the side, for safety and at eye level
- HR resistor to be mounted externally on top. This installation elected to mount it remotely
- One-foot high legs, to elevate cabinet above any water ingress
- Local/remote switch and local/remote lights

## Hybrid grounding system controls interface

The crucial value and protection of the HHRG system must be insured by a practical and usable controls interface. Controls design must operate the new grounding system in harmony with normal generator operations and without a need for the operator to do additional switching. For all normal conditions, the control system must provide the noted protection together with minimal monitoring to verify the system is active. In the case of a ground fault within the generator zone, the system must instantly apply high resistance grounding, provide positive indication of the event, and lockout against any hasty and dangerous restarting of the unit. For faults out on the mill system, the HHRG must not operate to jeopardize mill loads and steam supply. For ease in retrofitting to existing unit controls, and cost constraints, the necessary wiring and complexity should be kept to a minimum.

### Unit #12 protection overview

The new HHRG retrofit controls must be carefully interfaced with the existing generator protection system. For background, an overview of the existing Luke #12 protection system is given to put the new HHRG controls changes in perspective. In 2001, the #12 system protection was upgraded from 1979 vintage electromechanical relays to digital microprocessor-based protection. For a functional one-line diagram and other details of this upgrade, see [5]. The new system included two digital multifunction relays installed in a redundant protection scheme, with a dedicated (86) lockout device for each relay. At this time, a new 200 A grounding resistor was installed for unit #12 (original was 1200 A).

The HHRG project required a review of existing generator tripping schemes to determine how to involve the new vacuum switch. Initially it was planned to continue LRG operation of the generator and switch to (10 A) HRG only for a fault in the generator zone. However, to take advantage of the existing lockouts and using the flexibility of the digital relays, the HHRG switch was simply added to the existing simultaneous tripping scheme. That is, either generator relay tripping will operate its lockout (86) device to open the low resistance (200 A) grounding path, per **Table 1**. This method also provides some minimal exercising of the HHRG vacuum switch while providing high resistance grounding during coast-down after any system trip. Basically, in coming offline, the only time the HHRG does not operate is on a normal operations shutdown. On a turbine trip and for all electrical trip functions, the unit is switched to high resistance grounding during coast-down. A tripping logic diagram is presented in **Table 1**, which shows the addition of the new HHRG vacuum switch action. Shaded areas note when the HHRG vacuum switch is tripped open.

**Table 1. Tripping logic**

Trip mode/device function	Generator main breaker	Field breaker	Steam turbine	HHRG switch	Auxiliary relay CR-87G
Simultaneous trip: 24,40,46, 51N,51V	X	X	X	X	—
87G, 87	X	X	X	X	X
Sequential trip* 32-1,2	X	X	X	X	—
Normal operator shutdown	X	X	X	—	—
Alarm only 27, 59, 59N	—	—	—	—	—

All trips are processed simultaneously except for turbine trips, which are done sequentially (main stop valve limit switch supervised by the reverse power relay) as shown in **Table 1**. The HHRG vacuum switch is tripped open as part of all relay-based tripping sequences. In the table, “Simultaneous” refers to tripping each item marked “X” at the same time, using the existing lockout relays. Note that for a ground fault in the generator zone, a dedicated output from either generator relay picks up CR-87G, which seals in to hold its lockout relay tripped against restart of the unit. For other details on tripping functions, see reference [5].

It should be noted that operating with the generator(s) LRG resistors open, that is leaving only the utility source resistors on the system, has definite merits. Total ground fault exposure is reduced but total system relaying must be evaluated. At islanding of the generator or for two source operation below 400 A, the controls must automatically switch the LRG resistor back in. At Luke, this option is being revisited as the grounding study is now completed, and a PLC is available to do the logic. The HHRG system hardware is flexible to allow this change.

### HHRG switching device

Vacuum switch device and operation: The new single-pole vacuum switch was available only in ac operating solenoid design so that an interface relay was required for the main breaker (dc) control circuit. The HHRG vacuum switch operation is momentary pulsed to open and pulsed to close.



### Indications at switchgear main breaker

At lower right on door, red and green lamps are provided to show the position of the new HHRG vacuum switch. A third, amber lamp verifies that the HHRG Protection is enabled. See photo below. The enabled lamp should normally be ON to prove power to the HHRG cabinet in the basement and that control switch is in the "Remote" position. These indications are also provided to the operator via the PLC interface as noted below.



At main breaker

### Indications at HHRG cabinet

Field cabinet indications are provided for control power, vacuum switch position, and ground fault lamp status. Note that no operator involvement at this panel is necessary.

### Operator panel alarms and indications

Outputs from the new system to the existing power house loadshed PLC are sent to (lampbox) alarms located above #12 Generator controls at the turbine operator panel. They include HHRG System Enabled and Vacuum Switch Position indications and the alarm – "#12 Generator Ground Fault Trip". This alarm will flash to indicate seriousness of the event.

### Control devices locations summary

A summary of new hardware installed to augment the new HHRG cabinet is as follows.

Devices at the generator breaker cubicle:

- HHRG vacuum switch Open/Closed position indications (LEDs)
- HHRG system enabled LED
- Generator ground fault trip LED
- Interposing relay (CR-152) to breaker close circuit
- CR87G seal-in relay and Reset pushbutton

New alarms/indications at the operator panel:

- HHRG contactor position tripped open
- Generator ground fault trip
- HHRG system disabled

### Relay diagnostics

Where digital relays are used, an auxiliary contact from the HHRG vacuum switch could be wired to an input of the generator relay for time-stamping the switching operation. This was done in the Luke system and aids in checking HHRG vacuum switch action, the interpretation of oscillograph tripping, and sequence of events data for any trip incidents.

## Ground fault protection

Referring to the Tripping Logic in **Table 1**, one new dedicated output from each digital relay was programmed to operate for ground differential or phase differential (87G, 87) functions. This new output operates both lockouts and also picks up a new relay, CR87G, which seals in and prevents operators or maintenance personnel from resetting the 86 devices. Breaking the seal of CR87G is accomplished with special effort by opening the door of the main breaker and operating a reset switch, which is boldly marked to obtain supervisory permission to do so.

### Ground (zero sequence) differential protection improves sensitivity

Because quick sensing and clearing of internal ground faults is critical to limit system iron damage, it is of interest to add or upgrade to ground differential (87G) protection. This protection can provide significant improvement in ground fault sensitivity over conventional phase differential relaying. The increased sensitivity also translates to a significant increase in extent of coverage of the stator windings. The basic 87G protection detail is shown in **Figure 2** (see ref. [5][6] for 87G function description). In the Luke scheme, the 87G function was already provided in the noted digital relays, so only a change of neutral CT ratio was needed. With 2000/5 phase CTs, a neutral CT ratio of 300/5 was selected to stay within the prescribed (phase to neutral) CT matching ratio limits of the relay. To evaluate the 87G sensitivity, directional element becomes inoperative below a minimum neutral CT current (0.2 A) to prevent miss-operation on heavy through faults.

For the 300/5 neutral CT used, the 0.2 A cutoff translates to 12 A primary current. The ratio against the 200 A for a ground fault at winding high side and because the fault driving voltage along the winding to neutral is proportional, this shows that only 12/200 or 6% of winding is below the 87G sensing threshold. Consequently, with the noted CT ratios, the 87G function will protect 94% of the winding. By comparison, conventional phase differential relaying with 2000/5 CTs, and a pickup of 0.2 A (80 A primary) protects only 60% of the winding. The advantage of the 87G function is clearly significant, particularly where the resistor rated current is small compared to phase CT ratio. This is especially important in the case of generator single-source operation where available ground current is limited to 200 A.

### Neutral overvoltage (59G) protection

Directly sensed off the HHRG secondary resistor at the 240 V level and wired to inputs of both the digital relays,

this function provides backup to the differential protection. It also provides generator ground fault protection in the

event that the generator LRG is inadvertently left open. Although pickup of the relay is sensitive, with setting of 5 V, the response must be delayed to coordinate with system ground fault tripping of both feeder and tie circuits, so delays of one second or more are typical. After final considerations, the Luke settings for this function was changed to "Alarm Only."

## Low resistance grounding redesign and ground fault protection considerations

The low resistance grounding (LRG) and ground fault protection system at the mill are key factors in controlling ground fault damage. As concluded by the IEEE/IAS Working Group, the increase in available fault current and the clearing time of the ground fault protection is one of the two factors that impact the extent of generator damage due to core burning of faulted generator stators. Up to this point, this paper concentrated on the internal ground fault component of the generator ground fault. However, the total external ground fault in-feed must also be controlled. For example, extrapolating the arc energy released as determined in [1][10], the energy from the internal 400 A resistor is approximately equal to 1400 A system in-feed for six cycles. It is therefore important to evaluate the LRG and ground fault protection systems and look for ways to improve them. In addition to limiting generator damage, this exercise can also improve overall system protection and damage limitation.

After evaluating the existing LRG system at the mill, it was determined that the total available ground fault current was at an unacceptably high level. This section discusses the resulting LRG redesign, which has been proposed for the paper mill and ground fault protection issues associated with it.

### Purpose

The main purpose of the LRG redesign is to limit the available ground fault current to 1000 A or less while maintaining adequate system protection. Presently, the ground fault current of the 13.8 kV system is limited to 2200 A. Limiting the ground fault current to a value under 1000 A will greatly reduce equipment damage that would normally result during a ground fault. In order to prevent cable shield damage during ground faults, 1000 A is considered a safe maximum ground fault current level for LRG systems [9]. Because ground faults are the most common type of fault that occurs in electrical distribution systems, reducing the amount of equipment damage during a ground fault will result in significant economical savings.

The result of the LRG analysis was to limit the ground fault current to 800 A. This will be achieved by installing 200 A grounding resistors at all four system sources. In some cases, the existing LRG grounding resistors can be reconfigured to achieve the desired current. In this case, however, they could not be reconfigured, and new grounding resistors will have to be installed.

**Fault energy and equipment damage considerations**

The amount of equipment damage that occurs during a ground fault can be gauged by looking at the amount of energy released during the fault. The amount of energy released during a fault is proportional to the  $I^2t$  of the fault, where  $I$  is the fault current and  $t$  is the fault duration in seconds.  $K$  is between 1 and 2 with  $k=2$  being a purely resistive arc [1][10]. **Table 2** illustrates the  $I^2t$  for different fault values of  $I$ , and  $t$  ( $k=1.5$  and  $2$  are shown in **Table 2**). Limiting the ground fault current to 800 A will reduce  $I^2t$  fault energy to between 13% and 22% of what is available with the present system configuration. A design goal of 800 A maximum ground fault current was selected for this system for the following reasons:

- It is below the approximate 1400 A damage threshold for 6 cycle system clearing noted in section “Low resistance grounding redesign and ground fault protection considerations” and low enough to keep over-all equipment damage to a minimum and not compromise cable shield integrity (provided that proper ground fault protection is applied).
- It is high enough for most of the existing protective relays to sense and properly operate during a ground fault.

**Table 2. Relative fault energy**

Fault time: Cycles	$I^2T \times 10^3$ for fault current of:			$I^{1.5}T \times 10^3$ for fault current of:		
	2200 A	800 A	% Energy	2200 A	800 A	% Energy
0.5	40.2	5.3	13%	0.9	0.2	22%
1.0	80.8	10.7	13%	1.7	0.4	22%
5.0	403.2	53.3	13%	8.6	1.9	22%
6.0	484.0	64.0	13%	10.3	2.3	22%
30.0	2,420.0	320.0	13%	51.6	11.3	22%
60.0	4,840.0	640.0	13%	103.2	22.6	22%

**Relay sensitivity requirements**

The overall system configuration is shown in **Figure 3**. Typically, the system is operated with all four sources in service and all breakers closed (except breaker 1–20 A). When three (or less) sources are in service, the reactor is bypassed by closing breaker 1–20 A and opening breaker 1–20.

Normally, all four 13.8 kV sources are in service (exceptions are listed below). The ground fault protection scheme must, however, be able to reasonably handle all the following contingency operation scenarios:

1. Generator outages: No.11 Generator is taken down for one week, approximately twice a year. No.12 Generator is taken down approximately once every two years. Major Turbine-Generator outages are scheduled once every seven years, for about three weeks duration (this is the longest scheduled unit outage).
2. Total mill scheduled outages: scheduled approximately once every 30 months, mostly for cleaning mill 13.8 kV switchgear and field distribution equipment.
3. Planned utility outages: One tie line only—substation maintenance is typically scheduled about once every two years for either transformer/ breaker supply.
4. Island operation (generators only, no utility service): Very infrequently, only with major substation problems involving the total station or from an unexpected utility transfer trip to both paper mill substation breakers. This may occur about once every three years.

Based on these contingency operating conditions, implementing the grounding redesign will result in the following:

- The maximum available ground current under normal operation will be 800 A
- The practical minimum available will be 400 A with two sources in service
- The absolute minimum available ground fault current will be 200 A with one source in service (occurred once in 15 years for 30 minutes)
- HRG normal operation (versus LRG) of both generators would result just over 400 A total and is being considered as noted at end of section “Hybrid grounding system controls interface”

Therefore, the ground fault protection scheme must operate adequately for the 400 A to 800 A available ground fault conditions. For the rare case of the 200 A condition, the ground fault protection will be expected to operate at a tolerably reduced performance level.

**Adequacy of ground fault protection**

For the ideal situation, all ground fault protective devices would be able to detect 10% of the available ground fault current. However, because of the complexity/size of this system, the existing protective relay types, and existing CT ratios (some at 3000/5), it is not practical (both from an economic and systems reliability perspective) to meet the 10% criterion everywhere. As is with all fault protection schemes, some compromises must be made. Based on the fact that most ground faults are expected to be in the range of 60% to 70% of the maximum available, a more realistic (yet adequate) design criteria was developed for this system. Therefore, in order to provide adequate ground fault protection, the following protective relay sensitivity criterion was established for the paper mill. All were readily accomplished with existing relaying except as noted.

1. Primary ground fault protection on feeders (50G devices using zero-sequence CTs) must be able to detect at least 10% of the minimum available ground fault current. This covers high impedance faults in load transformer windings.
2. Primary bus and inter-tie protection relays (87B and 87R) must be able to detect at least 50% (preferably 10% to 40%) of the available ground fault current with two sources in service (i.e., must be able to detect at least 200 A). This will require changing the Bus 1 (87B) relays.
3. Secondary ground fault protection (51G devices on utility transformer source neutrals) must be able to detect at least 50% (preferably 10% to 40%) of minimum available. These will actually be set about 25% per the utility engineers.
4. 67N devices must be able to detect at least 50% (preferably 10% to 40%) of available ground fault current when two sources are available. This means that the 67N applied at the source breakers will have to detect at least 100 A, and the 67N at the bus tie breakers will have to detect at least 100 A.
5. 51N devices at source breakers and bus tie breakers should be able to detect at least 50% (preferably 10% to 40%) of available ground fault current when only two sources are available. This means that the 51N applied at the sources should detect at least 200 A, and the 51N at the bus tie breakers should detect at least 100 A.

6. The 87PW relays (pilot wire differential on 3000/5 CT's) on the incoming utility lines are not sensitive enough to adequately detect ground fault currents for any of the contingencies. Due to the high cost of replacing these relays, it is instead planned that the 67N trip output at breakers 1–30 and 2–02, be tied into the associated 87PW relays as an external transfer trip. The 87PW at the paper mill bus should then send a trip signal to the utility end; thereby giving relatively faster tripping than waiting for the fault to burn into a major phase-to-phase or three-phase fault before the 87PW would otherwise trip.

In summary, low-level ground faults in the utility tie circuits will be taken care of by using the control aspects of the 87PW relay. The effect will be rather fast clearing (within 0.32 seconds). Because the utility service cables are aerial on messenger, they are easily accessible. Ground faults here would be easily fixed at minimal costs compared to the damage that might occur to the generators if the LRG system is left "as is."

In order to achieve the above listed sensitivity requirements, some relay changes will be necessary. At Luke, relaying upgrades [5] in 2000 provided digital relays sensitive enough to meet most of the requirements. The following is a summary of changes required:

- Change ground settings, most relays
- Replace one set of bus differentials
- Commission Zero Sequence feeder protection
- Add 87G relays for utility transformers
- Install new CTs for sensitive generator 87G
- Change utility grounding resistors/CTs
- Add 67N transfer trip from mill to pilot wire relays on utility lines

### Things to remember

Because this was the first known installation using this design concept, a very thorough evaluation on all design aspects had to be considered. Because some were almost overlooked, a review list is noted for reference:

### Checklist of significant items to address

1. Vacuum switch: It has to be rated for the duty complete with clearing time comparable to the breaker clearing time (< 7 cycles).
2. Vacuum switch control power: Most come with 120 Vac. The switchgear has 125 Vdc.
3. Wye point surge protection: Applying a lightning arrester at the wye point ensures that any vacuum switch induced switching transients do not compromise generator insulation.
4. Cabinet packaging: This had to match confined space, environment, maintain clearances for BIL, and cable bending radius within cabinet.
5. Out of sight / out of mind: Designed remote switch position indication such that operators would not forget the HHRG.
6. Harmonics: A third harmonic filter was installed to keep third harmonic voltage out of the controls and protective relaying.
7. Generator protective relaying: Must simultaneously trip vacuum switch with main breaker. Decide if only generator ground protection or all the generator protection trips the switch.
8. Generator breaker: As the main breaker closes, the vacuum switch must close—including with the generator breaker in the Test position.
9. Control power: Feed only critical control from UPS (e.g., not the cooling fans).
10. 59G relay: Decide to locate the 59G relay at HHRG or at the generator protection location.
11. Maintenance: Develop a schedule for HHRG system in line with other switchgear/relay testing schedules.

## HHRG installation

The HHRG equipment is well designed and comes well packaged in three component enclosures: medium voltage, control, and the HRG ground resistor (set for 6.4 A). The control enclosure typically comes from the factory mounted on the side of the medium-voltage enclosures, but could be off mounted if required. The ground resistor for the system is also normally designed to be mounted on the top of the medium-voltage enclosure. This too, can be off mounted to fit the user's needs. (In the Luke system, the secondary resistor was off mounted next to the original 200 A resistor below the generator.) Assembled as a three-component unit, the HHRG equipment is compact. The assembly is 49 inches wide, 24 inches deep, and 92 inches high (with the resistor mounted on top) and 72 inches without the resistor. A separate surge arrester is off mounted and was installed as close as possible to the neutral summing point (applied Y point to ground) of the generator.

The external wiring requirements for the system are usually going to be small. The HHRG cabinet requires a 120 Vac source for its controls and heater/fan units. In the Luke mill project, an existing Uninterruptible Power Supply (UPS) feed was used for HHRG critical controls supply. Other cabinet interconnections are required to the normal low resistance ground resistor and a trip signal to and/or from the generator breaker for the vacuum switch. A 59G relay is included in the control section of the HHRG unit and terminals are provided to supply voltage to an external protection quality relay with a 59G function. Installing the surge arrester and properly tying the grounding together is the final step. The installation at the Luke mill required approximately five (12-hour) shifts to complete and was completed during the scheduled October 2002 Total Turbine-Generator Internal Outage. The Luke installation also duplicated the local HHRG cabinet indication lights at the generator breaker as described in the "Controls" section. Though optional, this is recommended because it provides valuable monitoring of the HHRG system from the remote main breaker. This feature required a seven-conductor cable between the main breaker and the HHRG unit. A second similar cable was installed from the HHRG system cabinet to the mill's existing Load Shedding PLC cabinet for routing HHRG status/alarms to the Turbine Control Room.

A final word on the installation—the three things in the installation of this system that require the most attention are: GROUNDING – GROUNDING – GROUNDING. The new HHRG installation provided the incentive and opportunity to completely inspect and upgrade the ground wiring for this machine. All connections were opened, cleaned, and remade. Where necessary, new cable was installed. (For example, a new and shorter cable from the new phase surge arrester to machine frame.) New grounding conductors were added for the HHRG components, resulting in a reconfiguration of some parts of the original grounding. The main thing to remember is that the generator frame ground, the low resistance resistor ground, and the high resistance ground resistor ground are all grounded to the same point. On older units, it is typical to find corroded, loose grounding joints or poorly grounded arresters, etc., so these remedial efforts are important for the grounding integrity of the new HHRG system and also to ensure effective transient protection for the generator.

## Conclusion

The HHRG system was installed and operational after the October 2002 total internal outage on the Luke #12 turbine generator unit. Startup of the system went well, and the design has been well received by Operations and Maintenance. To date, the HHRG system has performed as per design over several months of operation. This period included one turbine trip incident where reverse power relaying operated to activate the HHRG transition on coast-down (as per **Table 1**). As for status of the generator, no immediate plans exist to rewind the unit, but continued online PD monitoring data will be trended to assess the insulation integrity. This monitoring, together with the protection afforded by the new hybrid grounding, has significantly delayed concerns for a rewind of the generator and hopefully some years of additional service for this critical unit can be realized. The option of normal HRG operation of generator(s) is seriously being considered pending logic and wiring needed for automatic switching to LRG as needed to handle islanding and two source contingencies.

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