

APPLICATION CONSIDERATIONS FOR HIGH RESISTANCE GROUND RETROFITS IN PULP AND PAPER MILLS

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Abstract - Safety and reliability of Low Voltage-High Resistance Grounding schemes have made them an excellent choice for application in the pulp & paper and other process industries. As facilities shift toward this technology for low voltage substations for improved reliability, retrofitting existing grounded systems requires several critical application considerations. This paper will briefly review different grounding methods and their theory of operation. Then, examples of actual installations will be presented that will identify potential misapplications of high resistance ground retrofits, discuss what typical ground voltages and currents to expect, and present important considerations for reliable and safe installation of HRG equipment.

Index Terms – High Resistance Grounding, Retrofits, Ground Fault Detection, Grounding Transformers, Paper Mills

I. INTRODUCTION

Power systems engineers have developed several methods of effective grounding of industrial power distributions systems over the years. Historically, the method of system grounding selected for various electrical system settings, e.g. industrial, commercial, etc., dates back to the early part of this century when only two methods were considered: solid grounded and ungrounded. Solid grounding with its advantage of high fault levels to drive protective devices into tripping had equally significant disadvantages such as dangers posed by arcs in hazardous areas. Also, the issue of service continuity of critical loads pointed away from this grounding method. The perception that ungrounded systems provide service continuity, at least through the first ground fault, strongly suggested ungrounded systems. In more recent times well accepted, if not misapplied grounding techniques utilizing resistance or reactance, have provided the power systems engineer other alternatives. These techniques as well as solidly grounded and ungrounded systems will be examined next.

A. Principles of Grounding

A grounding system is isolated from other grounding systems by delta windings in three-phase systems. It only takes one delta winding to accomplish isolation; not both primary and secondary windings. Beginning at the main transformer secondary, there are four separate grounding systems illustrated in Fig. 1. System 1 includes all of the 480 volt system including the source generator through all the

primary delta windings of the loads. The wye ungrounded motor and wye-wye solidly grounded transformer secondary is also a part of the 480 volt system. Any grounding problem in the secondary of transformer T1 will affect the 480 volt system. In contrast, any grounding problem in grounding systems 2, 3 or 4 will not effect its respective primary grounding system due to its primary delta windings.

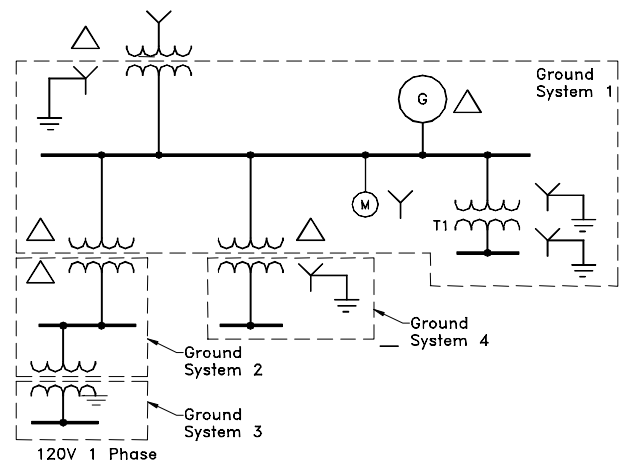


Fig.1. Grounding systems

When the type of grounding to be selected is being addressed within the design stage of an electrical power system, there are two key questions which must be considered:

- 1) Are there any line-to-neutral loads?
- 2) How important is service continuity for this electrical system?

The answers to these questions strongly influence the type of grounding selected. Line-to-neutral loads suggest solid grounding; high continuity of service requirements suggest an ungrounded or something approaching an ungrounded system.

B. Types of System Grounding

1) *Solidly grounded* systems are commonly found in industrial/commercial power systems today. In many cases, solid grounding (NEC-Article 250-5) is mandated. In others, it is selected based on economics. The 480/277 V system in

Fig. 2a is solidly grounded to permit 277 V (line-to-neutral) loads, such as lighting.

For line-to-neutral loads to be applied, the neutral point of the wye-connected source must be solidly grounded to the system to function properly and safely. If the system is not solidly grounded, the neutral point of the system would "float" with respect to ground as a function of load subjecting the line-to-neutral loads to voltage unbalances and instability.

The 120/208 V wye system in Fig. 2b must be solidly grounded to comply with the 1999 NEC Article 250-20 (all systems with line-to-ground voltages of 150 V or less and for those systems with line-to-neutral loads). It is selected primarily where a lot of 120 V (line-to-neutral) loads are present.

The 240/120 V 3-phase delta system shown in Fig. 2c, typical of commercial power systems, must also be solidly grounded to comply with the N.E.C., the lowest line-to-ground voltage is less than 150 V.

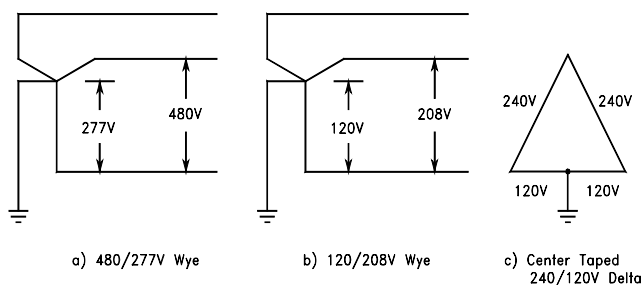


Fig. 2. Examples of solidly grounded circuits.

2) *The ungrounded circuit* historically has been selected for those systems where service continuity is of primary concern. See Fig. 3. for examples. The perception is that ungrounded systems have higher service continuity. This is based on the argument that the ground fault current is small and that negligible burning or heating will occur if the fault is not cleared. Therefore line-to-ground faults can be left on the system until it is convenient to find and clear them. This perception has some validity if one limits the criterion to "bolted" or "hard" faults. However, in industrial electrical systems, the vast majority of all faults start as low level arcing ground faults. When arcing ground faults are considered, the following conditions surface—but are seldom addressed.

- Multiple ground faults
- Transient overvoltages
- Resonant conditions

Multiple ground faults can and do occur on ungrounded systems. While a ground fault on one phase of an ungrounded system does not cause an outage, the longer the ground is allowed to remain the greater is the likelihood of a second ground occurring on another phase because the unfaulted phases have line-to-line voltage impressed on their line-to-ground insulation. The insulation is overstressed by as much as 73 percent. Also, there is an accelerated degradation of the insulation system due to the collective overvoltages impinged upon it, through successive ground-faults over a period of several years.

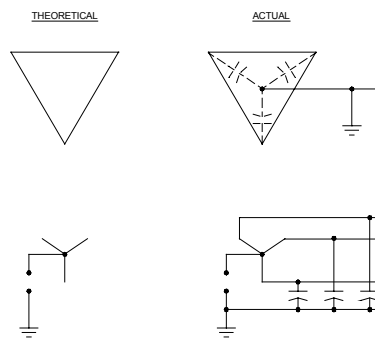


Fig. 3. Examples of ungrounded systems.

Transient overvoltages due to restriking or intermittent ground faults can and do develop substantial overvoltages on ungrounded electrical systems with respect to ground. There have been many documented cases within industry where multiple equipment failures (e.g.-motors) over an entire 480 V system have occurred while trying to find and locate a ground fault. Measured line-to-ground voltages of 1200 V or higher in these instances have been reported. In all instances, the cause has been traced to a low-level intermittent arcing ground fault on an ungrounded system.

The mechanism explaining how this occurs is best explained in conjunction with Fig. 4. Under worst case conditions, there is an energy exchange between the system inductance and the shunt capacitance to ground resulting in significant voltage escalation with respect to ground.

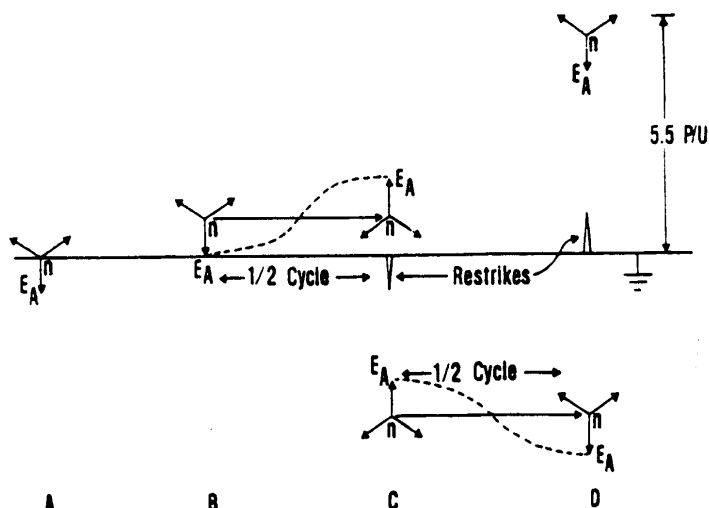


Fig. 4. Transient overvoltages from a restriking ground fault.

- 3) *Low resistance grounding* has been selected for large electrical systems where there is a high investment in capital equipment or prolonged loss of service of equipment has a significant economic impact. A resistor is connected from the

system neutral point to ground and generally sized to permit only 200 A to 1200 A of ground fault current to flow (Fig. 5).

- 4) Enough current must flow such that protective devices can detect the faulted circuit and trip it off-line but not so much current as to create major damage at the fault point. Damage to motors and other rotating equipment is also limited. Since the grounding impedance is in the form of resistance, any transient overvoltages are quickly damped out and the whole transient overvoltage phenomena is no longer applicable. This method is employed on 2400V and 4160V circuits.

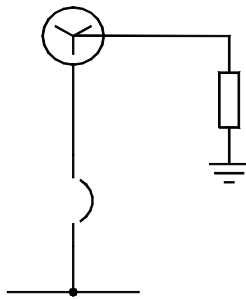


Fig. 5. Resistance grounded circuit.

4) *High resistance grounding* is almost identical to low resistance grounding except that the ground fault current magnitude is typically limited to 10 A or less. High resistance grounding, or HRG, applications in paper mills will be discussed in detail in the next sections.

C. Special Considerations

There are some safety and operational aspects that should be addressed. One of the real hazards with an ungrounded system is the occurrence of a second ground fault. Although nothing happens after a single ground fault, the second ground fault acts like a phase-to-phase fault. Therefore it is important to remove ground faults from ungrounded systems as soon as possible. This is often difficult. A ground fault detection scheme provides a systematic procedure for locating ground faults.

Another area that should be addressed is personnel safety. Many people are of the opinion that an ungrounded system is safer. This opinion says that since contact with a single phase does not complete a circuit, one should not get shocked. This is not the case because capacitive coupling to ground is present. In Fig. 6., a sustained ground fault occurs on a 480 volt wye connected (could be delta) ungrounded system. Since the system is capacitively coupled to ground through a relatively high impedance, the unfaulted phase voltage is displaced above ground potential. The system will remain in this position until the fault is cleared, or another phase breaks down to form a double line-to-ground fault.

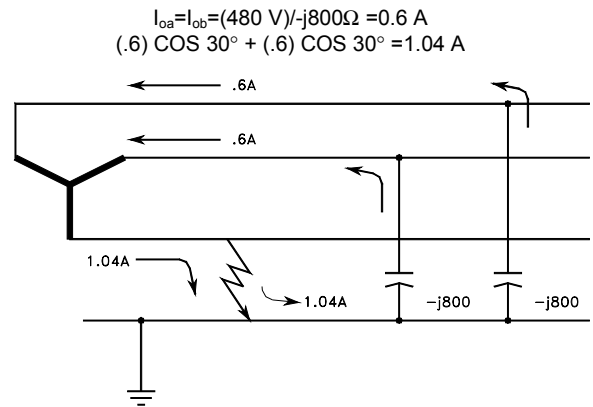


Fig. 6. Ground faults on ungrounded systems

Another area of consideration is continuity of service. A high resistance grounded system limits the ground fault current to a value only slightly higher than an ungrounded system. These values are small enough that it is acceptable to not trip safety devices and let faults remain on the system. The advantages of high resistance grounded systems are easier locating of the fault and because the phase voltages have a fixed reference to ground, transient over voltages magnitudes which can lead to premature insulation failure are limited. In contrast, solidly grounded systems are safer in the sense that there are no high voltages to contend with, but the larger ground fault currents must initiate tripping the faulted portion of the circuit off-line.

II. HIGH RESISTANCE GROUNDING

A. Description

High resistance grounding is typically applied to 480V circuits with limited application to 2400V and 4160V systems. The ground fault current magnitude is sufficiently low such that no appreciable damage is done at the fault point and iron damage to any motors is limited. This means that the faulted circuit need not be tripped off-line when the fault first occurs. It also means that location of the ground fault most likely is unknown. In this respect, it performs just like an ungrounded system. Examples are given in Fig. 7.

The second point however, is that HRG can control the transient overvoltage phenomenon if the circuit is designed properly. The significant difference between its performance and that of an ungrounded system is that when the ground fault arc is extinguished at points C and D in Fig. 4., the trapped charge left on the capacitance of the system is continuously dissipated off as heat in the resistor. The result is that the neutral point is held at approximately that position of Fig. 8b. Fig. 8a. shows the voltage vectors prior to a ground fault. For high resistance grounding to be effective, the size of the resistor must be carefully selected for each system. Under

ground fault conditions, the resistance must dominate over the system charging capacitance but not to the point of permitting excessive current to flow and thereby excluding continuous operation.

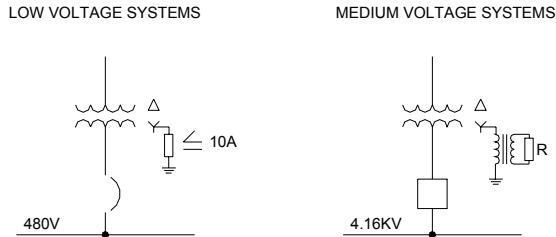


Fig. 7. High resistance grounded systems

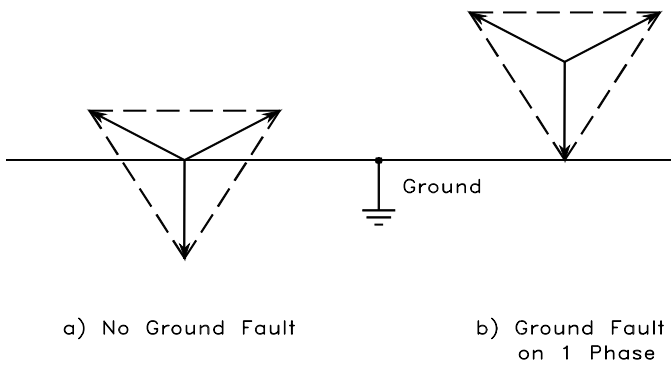


Fig. 8. Voltages during ground fault for an ungrounded system

B. Benefits

The advantages of a high resistance grounded system are as follows:

- Provides maximum service continuity.
- Relatively inexpensive.
- Controls transient overvoltages due to arcing ground faults on ungrounded systems.
- Ground fault detection scheme makes it easy to locate the fault.
- Limit iron damage to motors and generators.

The disadvantages of HRG are:

- Can detect ground faults easily but difficult to find ground fault unless a ground fault detection scheme is employed.
- Not practicable above 5 kV unless tripping is provided.

C. Fault Locating Methods

A pulser circuit is one method which offers a convenient means to locate the faulted feeder and trace the fault to its

origin. The pulser contactor switches a bank of resistors on and off, allowing a momentary increase in the ground current, for example from 5 A to 10 A, above the normal ground fault current. The current pulses can be located with a clamp-on ammeter when the ammeter is placed around the cables or conduit feeding the fault. The operator tests each cable, or set of cables, until the pulsating current is located. By moving the ammeter along the conduit, or checking the conduit periodically along its length, the fault may be traced to its origin. The fault may be located at the point where the pulsating current significantly decreases or stops. A similar method of locating ground faults puts a radio frequency on the grounded phase and the signal can be traced to the fault location.

D. Grounding Transformers

So far this section has discussed system grounding where the neutral point of the source has been readily available. But what does one do when the neutral point is not available? The best way to ground an ungrounded delta system (existing or new) is to derive a neutral point through grounding transformers. This may be accomplished in one of two ways as shown in Fig. 9. In Fig. 9a, high resistance grounding is accomplished through three auxiliary transformers connected wye-broken delta. The resistor inserted in the "broken delta" leg is reflected to the primary under ground fault conditions and limits the current to a nominal value as dictated by its design. Also, sensing the voltage drop across the resistor (device 59G) can be used to signal an alarm advising that a ground fault has occurred. The three lights across each individual transformer will constitute a version of the normal ground detection scheme currently employed on ungrounded systems.

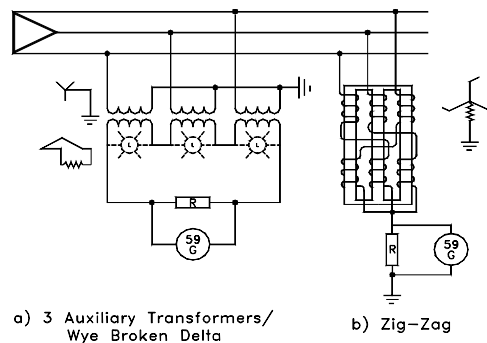


Fig. 9. Grounding Transformers

High resistance grounding can also be achieved alternately by a zig-zag grounding transformer as shown in Fig. 9b. The scheme in Fig. 9a uses the flux in the transformer's iron core to produce secondary voltages with their respective phase relationships. With the zig-zag transformer, the windings are connected in a zig-zag fashion such that the flux in the iron is vectorially summed opposed to vectorially summing the secondary voltages. Consequently it behaves on the system just as the three auxiliary transformers do. It appears

"transparent" to the system except under ground fault conditions. The resistor makes it resistance grounded. In both of these cases, either approach accomplishes the same end. Selection should be based on space, weight, size and/or economics as applicable to the system in question. Although high resistance examples are shown, other variations are available for higher voltage systems.

Advantages of deriving a neutral:

- Previously ungrounded delta systems can be retrofitted with grounding transformers.
- Transient overvoltages due to arcing ground faults are controlled.
- Both Low Resistance and High Resistance Grounding can be achieved.
- Limit damage to system

Disadvantages of deriving a neutral:

- Can be more costly than an original equivalent wye connected systems.
- Is difficult to find ground faults on high resistance grounded systems unless a ground fault detection scheme is employed.
- High resistance grounded systems are not practicable above 5 kV until tripping is provided.

III. HRG RETROFITS

A. 480 V Grounded Circuits

The retrofit of existing equipment to establish a high resistance grounding system is a simple process that can be completed in several steps. First, determine the status of the existing system. If the existing system is solidly grounded and it is desired to obtain the benefits associated with the continuity of service, one must consider all the loads applied to the substation. Do any feeders serve single-phase line-to-neutral connected loads? If so, determine the total KVA per feeder of these loads. The engineer must size and install an isolation transformer to derive a separate ground for that particular feeder. Load KVA measurements should be made over an extended period of time to insure that the isolation transformer is capable of withstanding average and maximum load current requirements. The isolation transformer should be located very near the loads it is intended to feed.

Once the feeders with single phase loads are identified and isolation transformers are installed, install the high resistance grounding panel and remove the solid neutral ground on the transformer. Finally, connect the grounding resistor between the transformer neutral and ground. Many times, this grounding resistor is part of the HRG panel. With this relatively simple modification, a ground fault would be indicated with an alarm or by a panel meter, instead of tripping the circuit breaker. Service continuity is maintained while establishing a predictable reference to ground.

If all the loads on a substation are three-phase, it is simply a matter of removing the transformer neutral ground conductor and installing the HRG equipment, as shown in Fig. 10.

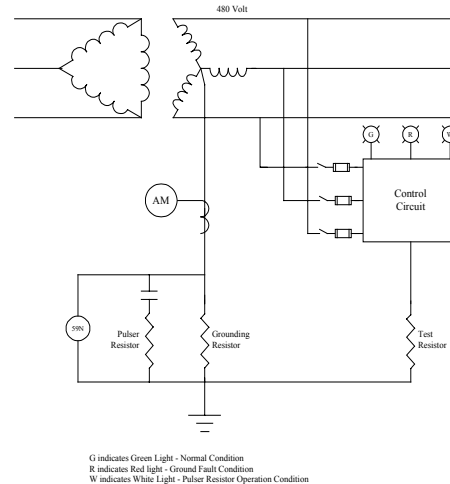


Fig. 10. 480V HRG system

B. 4160 V Grounded Circuits

4160 V or lower voltage medium voltage circuits can also be retrofitted with a high resistance grounding scheme, although this is not common practice. In this case, because of the high neutral to ground voltage, the grounding resistor is typically mounted on the transformer, with possibly a tap on the resistor. Another configuration uses a single phase transformer connected between neutral and ground with a resistor located at the secondary of this additional step-down transformer to permit a lower voltage resistor rating, as shown in Fig. 11. This transformer must be sized to accommodate the load. Typically, the resistor will be rated to provide 10 A of fault current at 120 V or 240 V. This would require a 2 KVA or 4 KVA transformer, respectively. The HRG panel would connect to this transformer secondary or the tap on the neutral-ground resistor mentioned above. The resistor must be rated to allow enough ground fault current to flow so that the detection relays can be set at a higher current magnitude than the capacitive charging current.

All equipment in the HRG system must be rated based on line-line voltages. Surge arresters may require replacement with units with a higher MCOV rating.

C. Ungrounded Circuits

The HRG accomplishes the same purpose as the ungrounded system, but it provides the benefit of establishing a fixed ground reference and reduces the chance of escalating voltages during an arcing ground fault. For a delta-wound transformer secondary, a ground circuit must be established. A zig-zag transformer or a wye- delta transformer with the grounding resistor at the neutral of this additional transformer are two methods of establishing the ground circuit. When the system is low voltage, the zig-zag technique is used, as shown in Fig. 12.

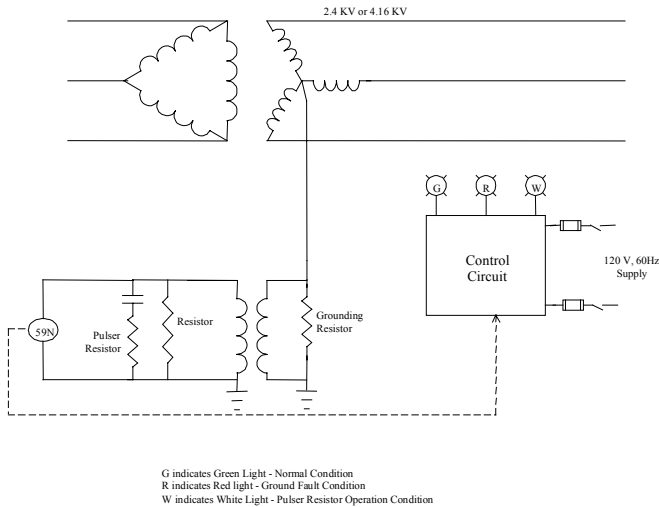


Fig. 11. HRG configuration with an additional step-down transformer

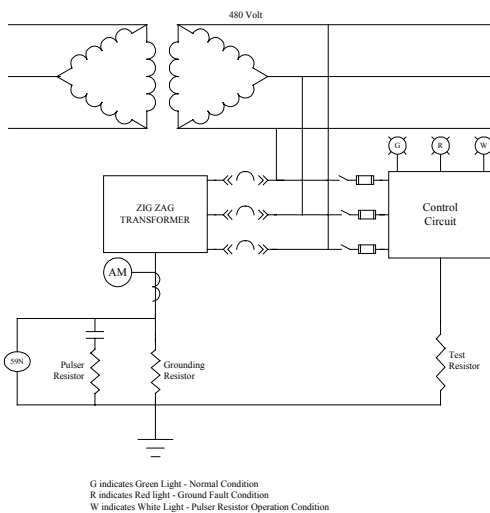


Fig. 12. HRG system with zig-zag transformer

If this ungrounded system is medium voltage, a three-phase transformer with the wye primary grounded is connected to the existing system and the open delta secondary is connected with a resistor to establish the current, as shown in Fig. 13.

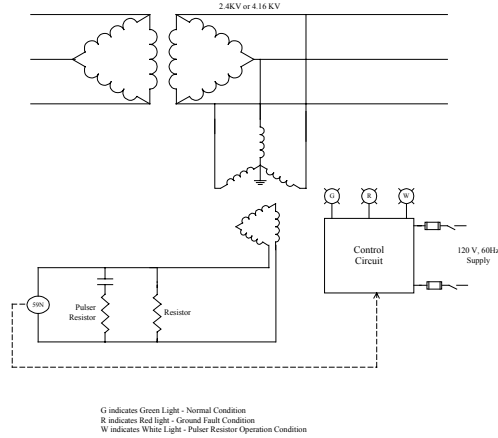


Fig. 13. HRG system with wye grounded-delta transformer.

The following items must be considered when applying high resistance grounding retrofits:

- 1) The distribution system requires continuity of service.
- 2) The system leakage capacitance must be less than the minimum magnitude of the ground fault current established by the grounding resistor rating.
- 3) High resistance grounding should only be applied on systems whose voltage does not exceed 4160 V line-line. Care must be taken for 2400V and 4160V circuits to insure that the capacitor charging current is not excessive and all components are applied within their ratings.
- 4) All loads must be balanced three phase, or line-to-line connected. Single-phase-ground loads on feeders must have isolation transformers to derive a new solidly grounded system.

IV. HRG APPLICATIONS IN PAPER MILLS

The following sections describe actual installations of high resistance grounding systems in paper mills.

A. Installation and Startup

The installation of high resistance grounding requires some special consideration. Consider a 480V circuit. If the HRG is being used to modify an existing solidly grounded system the cabinet containing the controls must be installed and the neutral to ground connection of the transformer in question must be removed. In place of this ground link, the resistor is connected that will limit the ground fault current to the prescribed minimal value. The minimum magnitude of allowable fault current must be greater than the capacitive charging current so that the sensing scheme responds only to a ground fault. In addition, the sensing wiring must be connected back to the control panel. Typical charging current usually ranges from 0 A to 2 A and the HRG fault current is usually 5 A to 10 A.

The electrical personnel responsible for the operation and maintenance must be trained to fully understand the application of high resistance grounding systems. When the control panel is energized, the sensing circuit may indicate a ground current and a voltage developed across the resistor. Consider the first example. The mill electrician described how this newly installed high resistance ground system was indicating 167 V to ground and presumed unsafe. He disconnected the system, declaring it too dangerous to allow further operation. Unfortunately, he also disconnected the grounding resistor, leaving the transformer ungrounded and susceptible to potentially damaging transient overvoltages.

The typical HRG panel has a test switch that simulates a ground fault. Initiating the test switch immediately after installation is a good practice to confirm that it actually works. This is also a convenient time to set up the pulsing system by adjusting the timers and to set the alarm relay to the appropriate levels of detection.

A second example is described. The HRG was installed and energized. All sensing circuits were adjusted, set, and functioned properly. While the electrical personnel were still enjoying the successful job completion, the voltmeter jumped to 270 V, the ammeter jumped to 4 A, and the alarm sounded. The electrical personnel immediately began pointing and proclaiming how poorly this new system works. They wanted to know what was wrong with this detection system because they have never had any ground fault problems in the past. An examination of the low voltage drawout feeder breakers showed trip units with no ground fault elements. Since they were all 800 ampere units with no main breaker, no ground fault detection was required; and that circuit had never experienced any ground fault trip problems in the past. An examination of loads on an adjacent motor control center showed a motor with a ground fault.

B. Line-to-neutral Loads

Another HRG installation in a paper mill was in a 480 V circuit which served three-phase motor and lighting loads connected line-neutral. The detection and locating scheme worked all too well and alarmed frequently indicating ground faults. Most of the alarms indicated ground faults in the lighting circuits, and were becoming a nuisance. Mill electrical personnel installed isolation transformers to serve all lighting loads. The transformer was connected wye-secondary-solidly-grounded and was sized to accommodate the feeder load current. The new separately derived ground circuit for the lighting loads will allow effective operation of the high resistance grounded source system and eliminate the alarms indicating ground faults on the lighting circuits..

C. Drive systems

When applying high resistance grounding to drive systems the harmonic currents may result in the detection of non-existent ground fault conditions. Applying power factor correction capacitors may aggravate the frequency of ground fault alarms if the capacitors establish a resonance circuit whose frequency aligns with one of the harmonics produced by a drive. Installing an isolation transformer at individual drives is a good practice which may alleviate the nuisance alarms.

A medium voltage variable frequency drive was applied at 2300 V. The transformer supplying the circuit was high resistance grounded. Two induction motor loads with electronic motor protection relays were also part of the circuit. Mill production complained that every time the drive system was in service, the operating induction motor would trip off line on a ground fault condition. Mill personnel, investigation the cause of the tripping, measured the current seen by the zero sequence current transformer applied to the electronic motor protection relay. Every harmonic current was well represented, particularly the triplens. These currents could add algebraically to provide a sufficient magnitude to actuate the ground fault trip circuit.

Two issues related to the problem are discussed. First, why was ground fault trip applied on a high resistance grounded system? The mill electrical supervisor was told that ground fault protection for the motor was very important because it would minimize damage in the event of a ground fault in a motor winding. The mill electrical supervisor was not told that high resistance grounding also minimized damage in the event of a ground fault. Secondly, the combination of the cable length to the motor, transformer inductance, and the capacitor at the motor terminals established a resonance circuit which distorted the voltage. The magnitudes of the distorted voltage peaks caused the MOV arresters to discharge periodically to ground. Enough surge and capacitive charging current was produced to trip the zero sequence detection circuit on the electronic motor protection relay.

D. The Complete HRG System

Consider purchasing an HRG system which includes the ground fault detection scheme. The final paper mill example describes an HRG installation at the transformer secondary serving water pumps at a landfill. Ground faults were commonplace at the landfill site but the HRG did not include the ground fault locator and ground faults went undetected for some time. A construction crew was called in to do some work at the landfill and created a second ground fault. Equipment was damaged but fortunately no one was injured.

Purchase the complete HRG system, and if it installed at a remote location insure that the detection circuit alarms are heard and/or seen by mill personnel.

V. CONCLUSIONS

High resistance grounding offers the best compromise of service continuity of ungrounded circuits and the safety of solidly grounded circuits. A complete HRG system with ground fault detection and alarming also provides the user with voltage and current information not typically available from ungrounded circuits. To help insure the success and acceptance of HRG at a paper mill, the following steps are essential:

- Mill electrical personnel should be trained to understand HRG theory and operation. The voltages and current magnitudes which indicate the occurrence of a ground fault should not cause mistrust with the HRG, but should convey a course of action to locate and correct the fault.

- The complete HRG system - resistor, fault detection scheme, alarm, grounding transformer, if required - should be purchased and used to take advantages of all of the benefits of high resistance grounding.

VI. REFERENCES

- [1] Baldwin Bridger, "High-Resistance Grounding", *IEEE Transactions on Industry Applications*, Vol. IA-19, NO.1, January/February 1983.
- [2] Gary L. Skibinski, Barry M. Wood, John J. Nichols, and Lois A. Barrios, "Effect of Adjustable Speed Drives on the Operation of Low Voltage Ground Fault Indicators", PCIC-99-04.
- [3] Cutler-Hammer, *Consulting Application Guide*, January 1999.