GROUND FAULT PROTECTION ON UNGROUNDED AND HIGH RESISTANCE GROUNDED SYSTEMS

APPLICATION GUIDE

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1. Introduction

Ungrounded distribution systems are used in industrial installations due to their ability to provide continuous service with a ground fault on one phase. A single-phase failure to ground does not cause high current to flow, because the current is limited by the capacitance of the other two phases. However, the voltage-to-ground of the other phases can rise by 73%, stressing the insulation of cables and other equipment connected to the system. It is common practice to run a faulted, ungrounded system until it is convenient to shut it down for repairs.

Unfortunately, the ungrounded system is susceptible to a build-up of high voltages (up to six times the nominal system voltage) when the first fault on the system is intermittent. This high transient voltage can initiate a second fault at the weakest insulation point on the system and thus larger, more damaging fault currents can occur. The second phase failure to ground will usually initiate high fault currents flowing between the two insulation failures. The overcurrent devices protecting the circuit involved should operate to clear the fault. However, a phase-to-ground-to-phase fault path impedance between them may create a high resistance arcing fault. The magnitude may not be sufficient to operate the overcurrent devices, and can cause extended shutdown until the equipment can be replaced. Locating and repairing the first ground fault is of prime importance, but in most continuous process plants, this is not an easy job since some portion of the operation would have to be shut down in order to isolate the problem area.

2. Ungrounded Systems

An ungrounded system is defined as a system of conductors with no intentional connection to ground except through potential indicating and/or measuring or other very high impedance devices. This type of system is, in reality, coupled to ground through the distributed capacitance of conductors and transformer or motor phase windings. In the absence of a ground fault, the line-to-ground voltage of the three phases will be approximately equal because of the equally distributed capacitance of the system.

2.1 Effects of Ground Fault

Theoretically, in a balanced three-phase system, the currents in all three lines are equal and 120° apart (**Figure 2.1 (a)**). The vector sum of the three capacitive phase currents (IA, IB and IC) is equal to zero at the ground point, which also results in the system neutral being held at ground potential by the balanced capacitive voltages to ground (VAG, VBG and VCG). Thus, although an ungrounded system does not have an intentional connection to ground, the system is actually capacitively coupled to ground.

The ungrounded system can be regarded as a three wire system only, thus the following discussion is valid for both wye and delta transformer secondaries.

If one system conductor, phase C for example, becomes faulted to ground, then phase C and ground are at the same potential, zero volts (**Figure 2.1 (b)**). The voltages of the other two phases in the reference to ground are increased to the system phase-to-phase voltage. This represents an increase of 73% over the normal line-to-ground voltage. Furthermore, the voltages to ground are now only 60° out of phase.

Figure 2.1 (a): Ungrounded System - Normal Condition

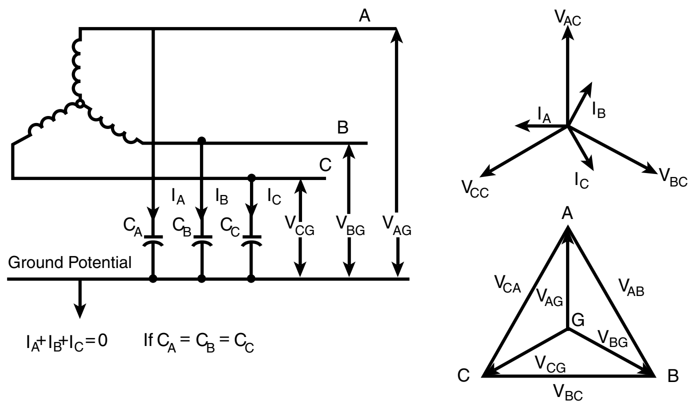
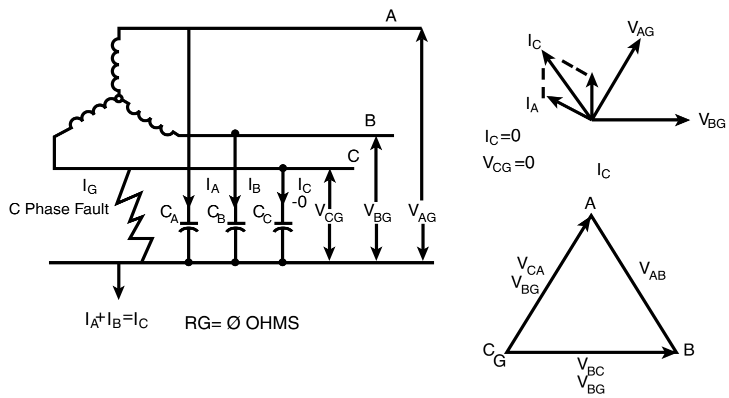


Figure 2.1 (b): Ungrounded System With Fault On Phase C



Even though the capacitive voltages are unequal during a single line-to-ground fault, the phase-to-phase voltages (V_{AB}, V_{AC} and V_{BC}) have not changed in magnitude or phase relationship and the system remains in service. Ground Current in the fault I_G is the vector sum of the two currents 1_A, and 1_{B1}, (which are 90° ahead of their respective voltages V_{AG} and V_{BG}) where $I_A=V_{AG}/X_A$ and $I_B=V_{BG}/X_B$.

X_A and X_B are the system capacitive reactances calculated from the capacitances of the elements of the distribution system. (See **Appendix 1.**) This ground current value is used to determine the maximum ground resistance for high resistance grounding.

If the ground fault is intermittent such as arcing, restriking or vibrating type, then severe overvoltages can occur. Unless the fault disappears as the phase voltage passes through zero, a DC offset voltage will remain on the system capacitance to ground. When the fault reappears, the system voltage to ground will equal the sum of the DC offset and the AC component, which will depend on the point of wave at which the fault is re-established. In this manner, the intermittent fault can cause the system voltage to ground to rise to six or eight times the phase-to-phase voltage, leading to a breakdown of insulation on one of the unfaulted phases and the development of a phase-to-ground-to-phase fault.

An intermittent type of fault is a very real danger. Therefore, early detection of this condition is of primary importance.

2.2 Code Requirements

National Electrical Code 2002 rule 250.21(3)d for alternating current systems requires wiring supplied by an ungrounded system to be equipped with a suitable ground detection device to indicate the presence of a ground fault.

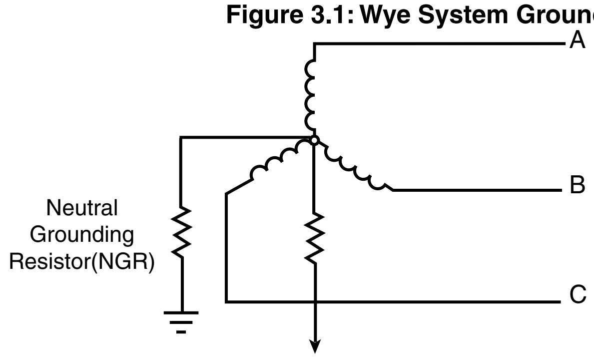
It should be noted that under rule 250.20(B)2, if a system incorporates a neutral conductor, it must be solidly grounded.

The N.E.C. rule 250.36 also recognizes continuously rated neutral grounding resistor systems for low current values. This can be done in various ways–e.g. with ground fault relays, on the feeders or a single relay with a current sensor in the grounding resistor.

3. High Resistance Grounding

Overvoltages caused by intermittent fault can be eliminated by grounding the system neutral through an impedance, which is generally a resistance which limits the ground current to a value equal to or greater than the capacitive charging current of the system. This can be achieved on a wye-connected system by a neutral grounding resistor, connected between the wye-point and ground, as in **Figure 3.1**. In **Figure 3.2**, a step down transformer may be used for medium-voltage systems to allow the use of a low-voltage resistor. On a delta-connected system, an artificial neutral (see **Figure 3.3**) is required since no star point exists. This can be achieved through use of a zig-zag transformer as shown, or alternatively, three single-phase transformers can be connected to the system and ground to provide the ground path, with secondaries terminated by a current-limiting resistor (see **Figure 3.4**).

Figure 3.1: Wye System Grounding



$R_{NGR} = \frac{V_{LL}}{\sqrt{3} I_G}$ Ohms

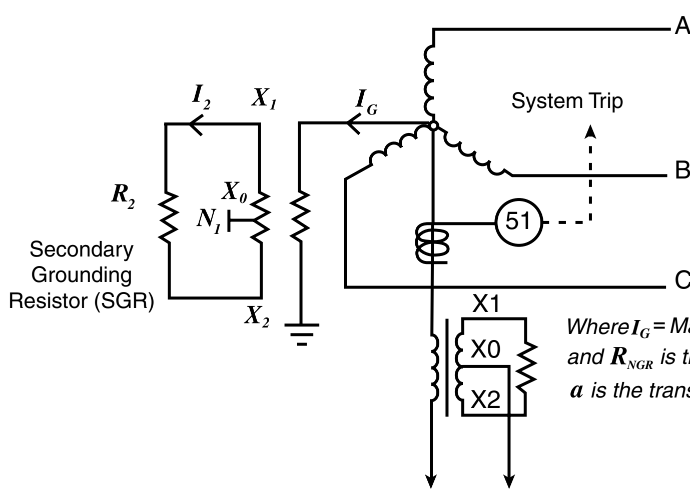
$R_{NGR} = \frac{X_C}{3}$ Ohms

$I_G \geq 3I_{CO}$ Amperes

$P_{NGR} = I_G^2 R_{NGR}$ Watts

Where I_G = Maximum Ground Current (A)

Figure 3.2: Medium-voltage Wye System Grounding



$R_{NGR} = a^2 R^2$ Ohms

$a = \frac{V_{LN}(PR^1)}{V_{LN}(SL^2)}$

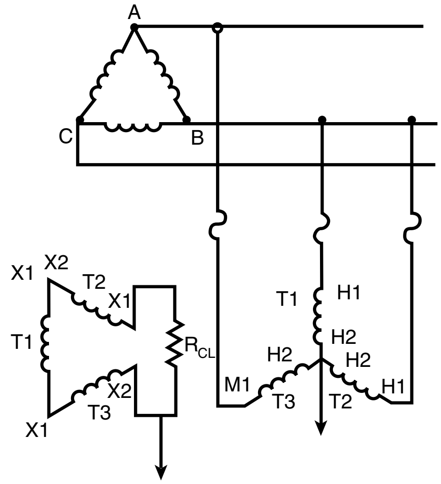
$I_G = \frac{V_{LN}(PR^1)}{R_{NGR}}$ Amps

$I_2 = a I_G$ Amps

$P_{NGR} = I_G V_{LN}(PR^1)$ Watts

Where I_G = Maximum Ground Current (A)
and R_{NGR} is the equivalent primary resistance
a is the transformer turns ratio

Figure 3.3: Delta System Grounding



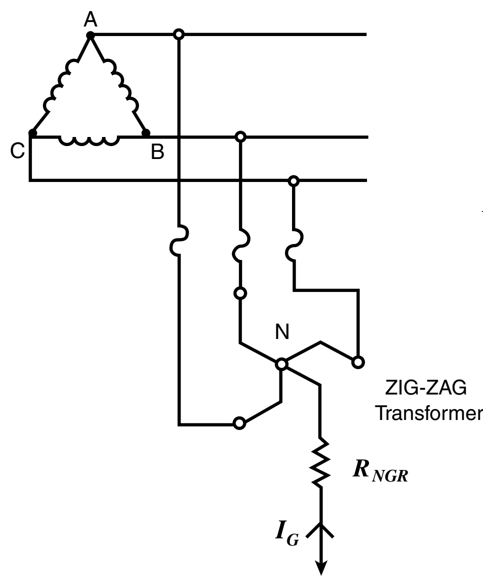
$$S = \frac{V_{LL} \cdot I_a}{3} \text{ VA}$$

$$R = 3\text{x} \frac{\sqrt{3}\, V_{LL}}{I_G} \text{ Ohms}$$

$$I_a \geq 3I_{CO} \text{ Amperes}$$

$$P_R = \frac{V_{LL} \cdot I_a}{\sqrt{3}} \text{ Watts}$$

Figure 3.4: Delta System Grounding For Medium Voltage



$$S = V_{LL} I_a \text{ VA}$$

$$R_{MGR} = \frac{V_{LL}}{\sqrt{3} I_G} \text{ Ohms}$$

$$R_{MGR} \leq \frac{X_{CO}}{3} \text{ Ohms}$$

$$I_G \geq 3I_{CO} \text{ Amperes}$$

$$P_{MGR} = I_G^2 R_{NGR} \text{ Watts}$$

3.1 Neutral Grounding Resistors

If a system has a neutral point, as with a wye-connected transformer or generator, there are two methods for arranging grounding equipment as shown in **Figures 3.1** and **3.2**.

Figure 3.1 shows the simplest method. This involves a resistor approximately equal or slightly lower in (ohms) value than that of the total capacitive reactance to ground of the system. The resistor is connected directly from the neutral point to ground. Direct connected, line-to-neutral voltage rated neutral grounding **Figure 3.1** Wye System Grounding Resistors can be applied to low-voltage and medium-voltage systems up to 15 KV.

The other method, using a single phase transformer connected from the wye point to ground, is shown in **Figure 3.2**. This method is used to allow the use of a low-voltage, current-limiting resistor, in a medium-voltage system.

The transformer is generally rated at system line-to-line voltage on the primary and 120 or 240 volts on the secondary. The resistor selected will have the same equivalent wattage as the direct connected resistor shown in **Figure 3.1**, but reduced in ohmic value by the square of the turns ratio of the transformer. The transformer/resistor type grounding equipment is used to allow easy adjustment of the Ground Current level by changes in the low-voltage secondary resistor value.

3.2 Artificial Neutrals

On delta connection systems, since there is no wye point available for connection to ground, one must be created by artificial means. This can be done with two grounding transformer arrangements. The grounding transformers may be either zig-zag or wye/delta connect as shown in **Figure 3.3** and **Figure 3.4** respectively.

The effect of the zig-zag and wye/delta grounding transformers is very similar. First, both provide a low-impedance path for the zero-sequence currents so that, under a line-to-ground fault, zero-sequence currents can flow into the ground at the point of the fault and back to the star point of the grounding transformer. Second, the impedance of both types of transformers to normal three-phase system current is high, so that when there is no fault on the system, only a small magnetizing current flows in the transformer winding.

In a zig-zag or interconnected star transformer, there are two identical windings of each leg. The windings are cross-connected such that each core leg is magnetized by the currents from two phases. All windings have the same number of turns, but each pair of windings on a leg is connected so that their magneto-motive forces (MMF) are equal and opposite. The result is that the common (star) point is forced to remain at an equipotential voltage with respect to each phase. When a ground fault occurs, the voltage across the limiting resistor increases from zero to a maximum of:

$$V_{LN} = \frac{V_{LL}}{\sqrt{3}} \text{ volts, depending on the impedance of the fault.}$$

The KVA rating of the zig-zag grounding transformer is equal to:

$$K_{VA} = \frac{V_{LL}}{\sqrt{3}} \; X \; \frac{I_G}{1000} \; K_{VA}$$

where V_{LL} is the rated line-to-line voltage in volts, and I_G is Maximum Ground Current in amperes.

Distribution transformers, either three-phase or three single-phase units connected in wye/delta, can also be used as grounding transformers.

The wye-connected primary should be grounded solidly with the current-limiting resistor connected across the broken delta connected secondary windings, as shown in **Figure 3.4**.

The K_{VA} rating of each of the transformers should be equal to one-third the rated line-to-line voltage times rated ground current for continuous duty.

This type of grounding transformer arrangement can be used on low- and medium-voltage systems up to 15 KV. The application of the zig-zag transformer is recommended because the required capacity of the star/delta transformer is 1.73 times as great as that for the zig-zag transformer for the same performance. When ground current changes are necessary on medium-voltage systems due to operations requirements, star/broken-delta connected single-phase transformers with secondary Grounding Resistors are convenient, permitting low-voltage modifications to be made. Tapped resistors can be used to allow adjustments to be made as systems become larger with the connection of additional equipment.

4. System Capacitance

The line-to-ground capacitance associated with system components determines the magnitude of zero-sequence charging current. This value of current required for proper selection of high resistance grounding equipment.

The capacitance to ground of transformers is negligible. The large spacings between the core and the windings, and shielding effects of the winding adjacent to the core, limit the capacitance to ground to a minimum.

Overhead line and cable capacitance to ground can be very high if considerable lengths are involved. Cable capacitance is many times greater than the capacitance of open-line wire lines. Capacitance of cable–depending upon the conductor size–insulation and construction can be obtained from the manufacturer for any specific cable type, or an approximate value can be calculated using the appropriate formula for the specific cable type. Refer to **Appendix 1**.

Rotating machine (synchronous motors and generators induction motors) are also major contributors to the overall system capacitance to ground. Low-voltage machines usually have larger capacitance values than medium-voltage units of the same rating because of lesser insulation to ground and a greater conductor and slot surface area. Also, high speed machines have normally lower capacitance than slow speed machines. Factors such as number and depth of slots, type of insulation, etc. produce wide variations.

The contribution of surge capacitors applied to rotating machinery can be significant. The surge capacitors are connected to line-to-ground, but selected with rated voltage at least as high as the circuit line-to-line voltage. The positive, negative and zero-sequence capacitance of the three-phase surge capacitors are equal. The ratings and constants for standard surge capacitors are listed in **Table A1.1** in **Appendix 1**.

Although shunt power capacitors (used for power factor correction) have large positive and negative sequence capacitance, they would have no zero-sequence capacitance unless the wye-point of wye-connect banks is grounded. (On industrial power systems the wye-point of the shunt capacitor banks should never be grounded.)

The charging current of a system can be calculated by summing the zero-sequence capacitance or capacitive reactance of all the cable and equipment connected to the system. From this, the current can be calculated from the system voltage, using the formula listed in **Appendix 1**. If actual values are not available, graphs and approximation formula can also be used without considerable errors (see **Appendix 1**). It is preferable to measure the magnitude of the charging current on existing power systems (as described in **Appendix 2**.) for correct grounding equipment selection. The measured values must be adjusted to obtain the maximum current if all system components were not in operation during the tests.

When it is impractical to measure the system charging current, the “Rule of Thumb” method may be used as indicated in **Table 4.1**. Note that surge suppressors add a significant additional amount of current to the total system leakage.

The charging current of a system 6900V and above must be carefully calculated for new systems and measured for existing systems to select the correct rounding resistance value. Due to large variations in system arrangements, no “Rule of Thumb” sizing can be used.

It is recommended that a calculation check should be made when the “Rule of Thumb” method is used to compare the let-through current values with actual system data.

In **Table 4.2**, charging current data is listed at various voltage levels. The indicated values are based on published data of component manufacturers, or derived from actual charging current measurements.

Table 4.1: Rule of Thumb Values of System Charging Current

System Phase-to-Phase Voltage	Estimated Let-Through Current vs. System KVA Capacity Without Suppressors	Additional Current for Each Set of Suppressors
600	1A/2000 KVA	0.5A
2400	1A/1500 KVA	1.0A
4160	1A/1000 KVA	1.5A

Table 4.2: Data for Estimating System Charging Current

System Voltage	Component	Type	Charging Current
Up To 600V	Cables	600 - 1000 MCM in Conduit - 3 Conductor	0.15A/M Ft.
		250 - 500 MCM in Conduit - 3 Conductor	0.10A/M Ft.
		1/0 - 4/0 in Conduit - 3 Conductor	0.05A/M Ft.
		1.0 - 4/0 on Trays - 3 Conductor	0.02A/M Ft.
	Transformers		0.02A/MVA
	Motors		0.01A/1000 HP
2400V	Capacitors	Surge Suppression	0.78A Each Set
	Cables	NON-Shielded in Conduit All Sizes - 3 Conductor	0.05A Ft.
		Shielded All Sizes - 3 Conductor	0.30A/M Ft.
	Transformers		0.05A/MVA
	Motors		0.10A/1000 HP
4160V	Capacitors	Surge Suppression	1.35A Each Set
	Cables	X-Linked-Shielded 1/0 - 350 MCM - 3 Conductor	0.23A/M Ft.
		X-Linked-Shielded 500 - 1000 MCM - 3 Conductor	0.58A/M Ft.
		X-Linked NON-Shielded in Conduit All Sizes - 3 Conductor	0.IA/M Ft.
6900V	Capacitors	Surge Suppression	2.25A Each Set
	Cables	X-Linked-Shielded 1/0 - 350 MCM - 3 Conductor	0.55A/M Ft.
		X-Linked-Shielded 500 - 1000 MCM - 3 Conductor	0.85A/M Ft.
	Transformers		0.05A/MVA
	Motors		0.10A/1000 HP
13,800V	Capacitors	Surge Suppression	2.25A Each Set
	Cables	X-Linked-Shielded 1/0 - 4/0 - 3 Conductor	0.65A/M Ft.
		X-Linked-Shielded 250 - 500 MCM - 3 Conductor	0.75A/M Ft.
		X-Linked-Shielded 600 - 1000 MCM - 3 Conductor	1.15A/M Ft.
	Transformers		.05A/MVA
	Motors		0.15/1000 HP

5. Selection of High Resistance Grounding Equipment

For correct application, the let-through current of the high resistance grounding equipment should be equal to or slightly higher than the capacitive charging current of the system. The installation of a tapped Grounding Resistor unit should be considered when system expansion is expected at a later date.

The high resistance grounding equipment should have a voltage rating corresponding to the system voltage as follows:

The voltage rating of the Grounding Resistor should be line voltage divided by root 3 (line-to-neutral voltage rating of the system). The voltage rating of the grounding transformer should be the line-to-line voltage rating of the system. All continuously-rated, high resistance grounding equipment is designed to operate at the rating providing:

a) The temperature of the cooling air (ambient temperature) does not exceed 40°C and the average temperature of the cooling air for any 24-hour period does not exceed 30° C.
b) The altitude does not exceed 3300 ft. (1000 m). Standard devices may be applied in locations having an altitude in excess of 3300 ft. (1000 m) but the dielectric strength of air insulated parts and the current-carrying capacity will be affected. At or above 3300 ft. (1000 m), the correction factors of **Table 5.1** should be applied.

Operation at higher ambient temperatures and altitudes exceeding 15,000 ft. (4500 m) or unusual service conditions necessitate special design considerations.

Table 5.I Altitude Correction Factors

Altitude		Dielectric Strength Correction Factor
Metres	Feet	
1,000	3,300	1.00
1,200	4,000	0.98
1,500	5,000	0.95
1,800	6,000	0.92
2,100	7,000	0.89
2,400	8,000	0.86
2,700	9,000	0.83
3,000	9,900	0.80
3,600	12,000	0.75
4,200	14,000	0.70
4,500	15,000	0.67

5.1 Maximum Let-through Current Value

The let-through current is the maximum controlled current which may flow in a neutral grounding resistor during line-to-ground fault for wye or delta systems, and its value can be calculated as follows:

$$I_G = \frac{V_{LL}}{\sqrt{3}R_G}$$

Where I_G = Maximum Ground Current (Let-Through Current) in Amperes

V_L = System Line-to-Line Voltage in Volts

R_G = Grounding Resistor in Ohms

Note–*For broken delta systems, R_G will be the equivalent primary resistance of the Current-Limiting Resistor.*

The high resistance grounding concept (alarm only) can be successfully applied on any low- and medium-voltage system if the ground fault current does not exceed the values shown in **Table 5.2**.

Table 5.2

Voltage Range	Total Ground Current* I_G	Charging Current or Resistor Current I_R
480 - 600V	25 Amps	17.5 Amps
2400 - 4160V	15 Amps	10.6 Amps
6900 - 13800V	10 Amps	7 Amps

**Total Ground Current is the vector sum of the Resistor Current and the Capacitive Charging Current IC which are assumed to be equal in the above Table.*

$$|I_G| = \sqrt{I_R^2 + I_C^2}$$

Particularly on medium voltage systems–at higher ground fault current values than shown–tripping on the first fault will be required to limit the damage. Indefinite persistence of a high resistance ground fault in a motor winding may damage the turn insulation to the extent that a turn-failure occurs, resulting in a shorted turn fault current of many times the rated current. At first, phase overcurrent relays may not detect this current since the overcurrent may be slight. The fault current in the short-circuited turn is likely to produce local heating and further damage the insulation to the degree that the fault escalates to a phase-to-phase fault, causing considerable motor damage.

The fault current capacity of the conductor and metallic shield of a cable are related principally to their heat capacities and are limited by the maximum temperature under fault conditions (at conductor 250°C, at shield 150°C). Standard power cable conductor shields–e.g. helically-applied copper tape–have very low fault current capacity, so a higher than rated sustained ground current will increase the temperature above the limit. After damaging the shield and the insulation, it may escalate to a two-phase or three-phase fault. Even for low-voltage Resistance Grounded systems, it may be desirable to clear the first ground fault with a relay. For example, when equipment protection has a higher priority than service continuity.

The high resistance grounding equipment (zig-zag transformer and Grounding Resistor) should have a continuous-duty rating when the service continuity (alarm on first fault) is prime concern. Short-time rated devices (10 seconds, 1 minute or 10 minutes) are used on systems where the first fault is cleared automatically with a relay. With these devices, the fault must be removed within a time period of the short-time rating. Note–these devices should be ideally protected by a relay with inverse Time Current characteristics. The relay should be set to pick-up at or below the Maximum CONTINUOUS current rating of the Resistor. The time duration will be increased according to $I^2t=K$ (a constant). For example, at 50% rated current, a 10 second rated Resistor can only carry current for 40 seconds. In any case the relay characteristics must co-ordinate with the characteristic de-rating curve of the Grounding Resistor to prevent damage to the resistor.

5.2 Overcurrent Protection

Where an artificial neutral is used, protection against internal faults should be provided with current-limiting fuses or other overcurrent devices of appropriate voltage rating. The overcurrent protection will operate for internal faults but will not operate from the current, which will flow in the windings due to the ground fault in another circuit. The overcurrent protective device should be rated or set at a current not exceeding 125% of the grounding (auto) transformer continuous current rating and generally about 50% of the rating as per **Table 5.3**.

Table 5.3: Recommended Fuse Sizes for Continuous-Duty Rated Artificial Neutral

Artificial Neutral Current Rating	Fuse Size Amps
1A	0.5
2A	1.0
5A	3.0
10A	5.0

It would be preferable to use an overcurrent protective device of adequate short circuit rating which simultaneously opens all ungrounded conductors in lieu of fuses to prevent single phasing. Presently, however, there are no suitable low-voltage devices on the market for the required current settings and the high cost of the medium-voltage devices makes their application prohibitive.

If desired, on low-voltage systems the protective current limiting fuses can be monitored by a blown fuse relay which may be used directly or through an auxiliary relay to activate the shunt trip mechanism of a non-automatic circuit breaker or a three-pole contractor. Short-time rated neutral Grounding Resistors should also be protected by inverse current relays as previously described in Section 5.1.

6. System Insulation Levels for Medium-voltage Systems

The Insulated Power Cable Engineers Association (IPCEA) have requirements in which conductor insulation thickness for a particular voltage is determined by the length of time that a phase-to-ground fault is allowed to persist. Three thickness sizes are specified and are related by the terms 100%, 133% and 173% levels to be applied as follows:

a) 100% level–where the clearing time will not exceed 1 minute
b) 133% level–where the clearing time exceeds 1 minute, but does not exceed 1 hour
c) 173% level–where the clearing time exceeds 1 hour

Obviously the 100% level can be used on any system whether solidly or resistance grounded, providing phase-to-ground faults are cleared in the specified time. This will almost inevitably require fault relaying.

The 133% and 173% levels will apply mainly to ungrounded and high resistance grounded systems, since other forms of grounding will most probably involve ground fault currents that could not be tolerated even for the time permitted. Selection between the 133% and 173% level of insulation will be determined by the time required–after identification of the faulted feeder–to perform an orderly shutdown of the process being served. The effect of full line-to-line voltage appearing on the unfaulted phases of all other system components such as monitors, controllers, switchgear, transformers and capacitors does not require special consideration, but it should be expected that some life may be sacrificed when they operate frequently for extended periods of time.

7. *Application of High Resistance Grounding with Non-selective Indicators*

Most electrical codes require that some kind of ground detector such as three wye-connected and grounded voltmeters, neon lamps, resistor or transformer-type indicating lights be installed on each ungrounded system. These indicators are connected to the busses through current-limiting fuses to indicate that one of the phases is grounded somewhere on the system, and hence the term Non-Selective, which means that the indication does not distinguish which branch circuit is faulted.

Since the phase-to-ground voltages change substantially when a ground fault occurs, the presence of the fault is detected by any of these devices by monitoring the phase-to-ground voltages of the system. Under normal conditions, the phase-to-ground voltages are equal because the distributed capacitance of the phases are equal (as discussed in Section 2.1). When a ground fault occurs, the voltage-to-ground of the faulted phase is reduced and those of the other two phases increased. Indicator lights connected across the line-to-ground can, therefore, be used to show the faulted condition i.e. the light on the faulted phase will turn off to show that phase is faulted.

The conventional ground detectors provide the minimum requirement of phase indication, but cannot stabilize the system voltage. To provide protection against over-voltages-to-ground due to intermittent ground faults, it is still necessary to apply high resistance grounding of some type, as previously described.

8. *Fault Locating Systems - Pulsing Systems*

The main advantage of Resistance Grounded systems is the ability to continue to use the system with a single fault. It is, therefore, very important that the first ground fault should be located and removed as soon as possible to prevent unnecessary trip-outs before a second fault develops. Ground-locating devices are available and may be incorporated in high resistance grounding schemes. One may even use the traditional method of tripping breakers in sequence to see when the fault disappears, but this defeats one of the principal advantages of high resistance grounding–i.e. power continuity and the ability to locate a ground fault without shutting down the system.

To take maximum advantage of the full capabilities of the high resistance grounding, there are various systems for locating faults without interruption of the service.

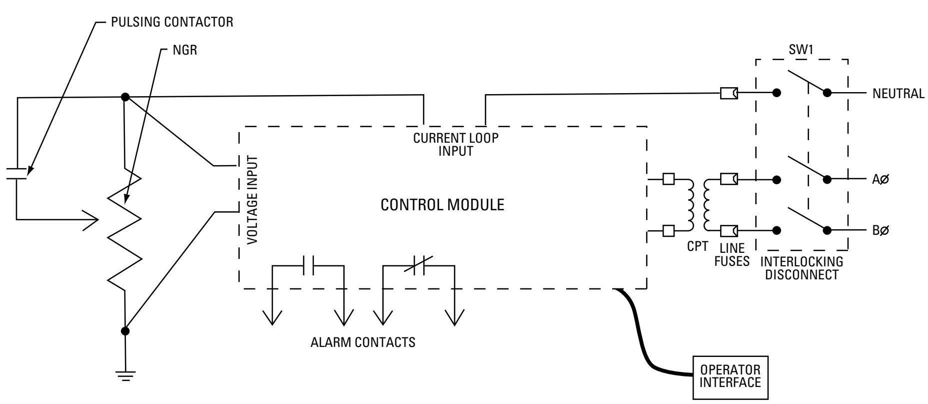


Figure 8.2 (a) Pulser Plus Wye-Connected Low Voltage Pulse System

A cost-effective way to locate faults is by use of a scheme, which uses a clip-on ammeter to trace the fault current. The ammeter is sometimes affected by external fields, which may swamp the ground fault current reading, and so an alternative scheme commonly used is to pulse the fault current to make the signal more visible during measurements. Such schemes are shown in **Figures 8.2(a)** to **8.2(c)**. The pulse system includes a pulsing contractor to short-out a portion of the Grounding Resistor (or adding a second Grounding Resistor in parallel), a cycle timer to energize the pulsing contractor about 20 times per minute and a manual NORMAL/PULSE switch to start and stop the pulsing. It includes a Ground Fault Relay to detect the resistor current to allow the pulse operation, such that it can only pulse when a fault is detected. Such schemes usually include indicator lights to show the status–e.g. NORMAL, FAULTED and PULSE ON. An ammeter is also a useful option.

The current pulse may be anywhere from two to five amperes higher than the continuous ground fault current. Generally, a 2A pulse in addition to the continuous ground current is recommended, but it should not exceed 10 amps maximum. **Figure 8.2(a)** indicates a directly connected low voltage, wye system. **Figure 8.2(b)** uses a step-down transformer for medium-voltage wye systems.

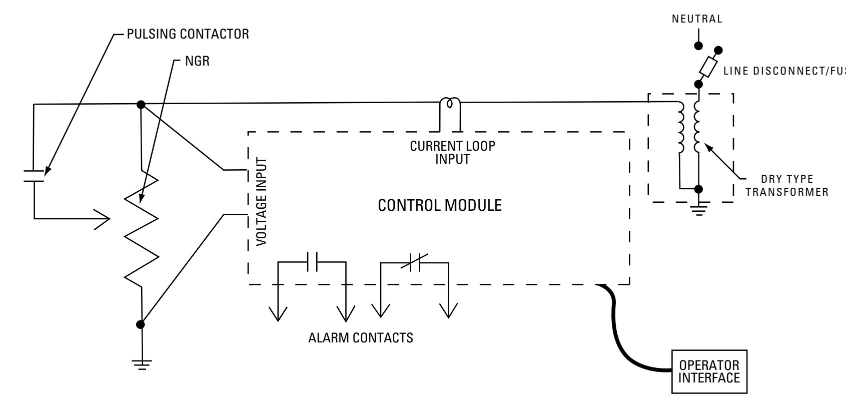


Figure 8.2 (b) Pulser Plus Wye-Connected Medium Voltage Pulse System

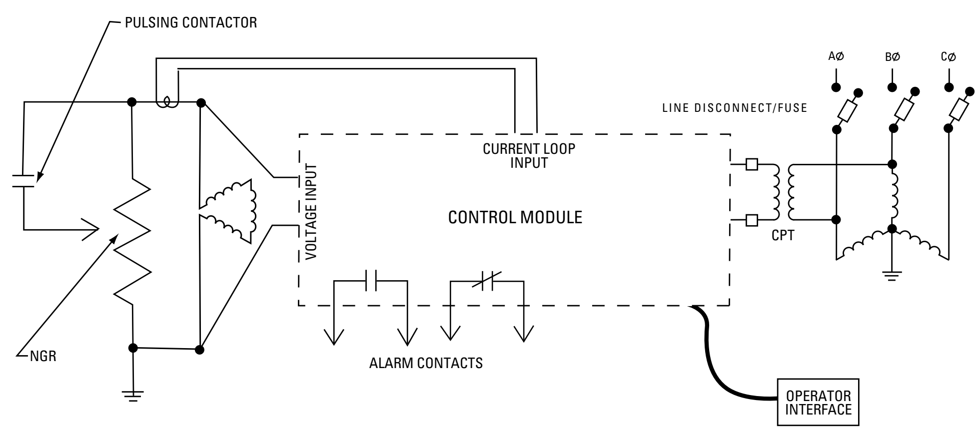


Figure 8.2 (c) Pulser Plus Medium Voltage Broken Delta Connected Pulse System

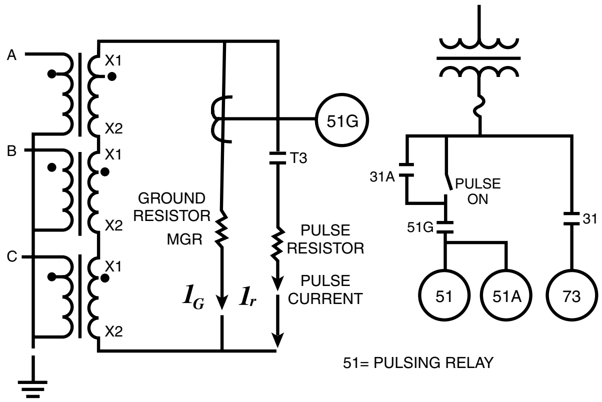


Figure 8.2 (d): Shows the Connection of a Medium-Voltage, Broken-Delta Arrangement

The clip-on ammeter required for signal tracing can be purchased from a number of sources. The method is to clamp the probe around all three conductors for a suspected branch circuit and observe on the indicator if a pulsing current is present or not. If it is not, then the branch does not carry fault current and another branch is selected and tested. The process continues until one is located which indicates a fault. The branch circuits of this cable are then tested similarly, and so on, until the fault is located.

NOTE–Tracing the signal on systems where the conductors are in conduits can be more difficult because the fault current tends to return through the conduit of the circuit involved. To the extent that this happens, the return current in the conduit cancels-out the tracing current flowing out through the conductor to the point of the fault. Fortunately, this cancellation effect is not usually 100%, assuming that no ground conductor runs in the same conduit. The return current may divide into unpredictable patterns and return to the source partly on the equipment grounding system (steel structures, etc.).

With the recommended very sensitive clip-on ammeters, which are relatively insensitive to other magnetic effects, the definite rhythmic pulse of the ground fault current can usually be traced.

8.1 High Resistance Grounding Equipment for Pulsing Systems

As for all resistance grounded systems, grounding can be applied to any low- and medium-voltage three-wire system by a neutral grounding resistor connected between the wye point and ground when the neutral point is available, and by connecting an artificial neutral on a delta-connected system. However, the grounding equipment, for pulsed systems must be designed for continuous duty and at rated pulsing current.

8.1.1 Neutral Grounding Resistors for Pulsing Systems

The resistor may be equipped with taps which allows the resistor to be shorted out to increase the current, or alternatively, a second resistor can be connected in parallel to increase the current during the pulse period. In the former case, half of the resistor must be designed to take double the current than the other half, which necessarily increases the size of the unit.

8.1.2 Artificial Neutrals for Pulsing Systems

Artificial neutral devices involve transformers and Grounding Resistors. The grounding transformers, either standard single-phase distribution type or zig-zag three-phase autotransformer type, are usually designed for 5 amps and 10 amps pulsing current. The single-phase transformers, used as grounding transformers on medium-voltage systems must be rated to take the pulse current as well as the continuous current.

8.1.3 Current-limiting Resistors for Broken Delta Artificial Neutrals

Standard high resistance grounding equipment (neutral grounding resistors and artificial neutrals) can be used on low-voltage systems only. To reduce the high cost of the switching (pulsing) contractors on medium-voltage systems, it is necessary to apply alternative grounding packages that permit low-voltage pulsing such as broken delta, single-phase transformers as discussed in Section 3.2.

For medium-voltage systems, a broken delta transformer will be normally employed, as in **Figure 8.2(d)**. The secondaries of the transformers are connected in series with a current-limiting resistor. For pulse operation, tapped or dual resistors can be used to increase the current as for low-voltage systems. The possible configurations are numerous.

8.2 Pulsing Systems Operation

During normal conditions, with no ground fault on the system, no current will flow in the Grounding Resistor. When a ground fault occurs anywhere on the system, current will flow in the resistor. This current is sensed by the ground current sensor and operates the ground fault relay. Operation of the ground relay permits the pulsing sequence via an auxiliary relay to be initiated manually by switch. Additional SPDT contacts are available for remote indication and annunciation of a ground. An audible alarm with a silencing relay may also be included.

The built-in test circuit provides a functional test to assure correct operation of the ground fault relay.

Appendix 1

In charging current calculation, the following formula are used:

Capacitive Reactance

$$X_C = \frac{10^6}{2\pi f C_O} \quad \text{ohms/phase}$$

Zero-sequence Capacitance

$$C_0 = \frac{10^6}{2\pi f x_0} \quad \text{microFarads } (\mu X)\text{/phase}$$

Charging Current

$$3I_{C0} = \frac{2\sqrt{3}\pi f C_0 E}{10^6} \quad \text{Amperes}$$

Where

f = Frequency in Hz

C_0 = Capacitance to Ground in µF

E = Line-to-Line System Voltage

Cable Capacitance

The capacitance of any type of cable may be calculated from the specific inductive capacitance (also called SIC, dielectric constant or permittivity) as follows:

Single-conductor cable or three-conductor shielded cable

$$C_0 = \frac{0.00736\epsilon}{Log_{10}\left(\frac{D}{d}\right)} \quad \mu\text{F}/1000\text{Ft.}$$

For three-conductor cable

$$C_0 = \frac{0.00834\epsilon}{Log_{10}\left(\frac{D_1}{d}\right)} \quad \mu\text{F}/1000\text{Ft.}$$

Where:

C_0 = capacitance to ground in mF per 1000 feet

ϵ = specific inductive capacitance of insulation

D = diameter over insulation for single-conductor cable

D_1 = d + 3c + b for three-conductor cable

d = diameter over conductor

c = thickness of insulation of conductor

b = thickness of belt insulation

Values of ϵ at 15°C (60°F)	
Air	1.0
Impregnated Paper	3.0 - 5.0
Varnished Cambric (VC)	4.0 - 6.0
Varnished Dacron Glass (VDG)	2.3
Valcanized Rubber	2.7 - 6.5
Magnesium Oxide (MI)	6.0 - 9.0
Silcon Rubber (SR)	3.2 - 3.5
Polypropylene (EPM or EPDM)	2.2 - 2.5
Butyl Rubber (IIR)	3.6 - 3.8
Ethylene Propylene Rubber (EPR)	3.5 - 3.8
Styrene Butadiene Rubber (SBR)	3.5 - 3.8
Versatol	3.5 - 4.0
Polyvinyl Chloride (PVC)	3.5 - 4.6
Polyethlene (PE)	3.7 - 8.0
Kynar	7.7
Vinyl	5.8 - 6.0
Polytetrafluoroethlene	2.1 - 2.5
Nylon	3.5 - 4.6
Polychloroprene - Neoprene	8.0 - 10.0
Geoprene	8.0 - 10.0
Polyurethane	5.6 - 7.6

Charging Current Estimation

For rough estimation, the following approximate capacitance values can be used:

Transformers

$C_0 = 0.01 - 0.001 \mu F$

Overhead Line

$C_0 = 0.01\ \mu F/\text{mile}$

Charging Current

$$3I_{C0} = \frac{2.14(LE)}{1000\sqrt{3}} \quad \text{Amperes}$$

Where:
L = line length in ft./1000
E = line-to-line operating voltage in KV

Cable

Typical C_o values are plotted in **Figure 1.1** for paper or varnish cambric insulated cables. Ten percent of the values may be used for single-conductor, nonshielded cables when in metallic conduit.

Motors

The approximate charging current of a motor can be calculated by the following formula:

$$3I_{C_0} = 0.05\frac{HP}{RPM} \quad \text{Amperes}$$

Surge Capacitors

Surge capacitors, if connected from line-to-ground, also contribute to the charging current. Standard ratings and constants are tabulated in **Table 1.1**. The charging current of non-standard surge capacitors also can be calculated:

$$3I_{C_0} = \sqrt{3}\left(\frac{2\pi f C E}{10^6}\right) \quad \text{Amperes}$$

E = line voltage (V)

C = capacitance in μF

Figure A1.1: Cable Capacitance

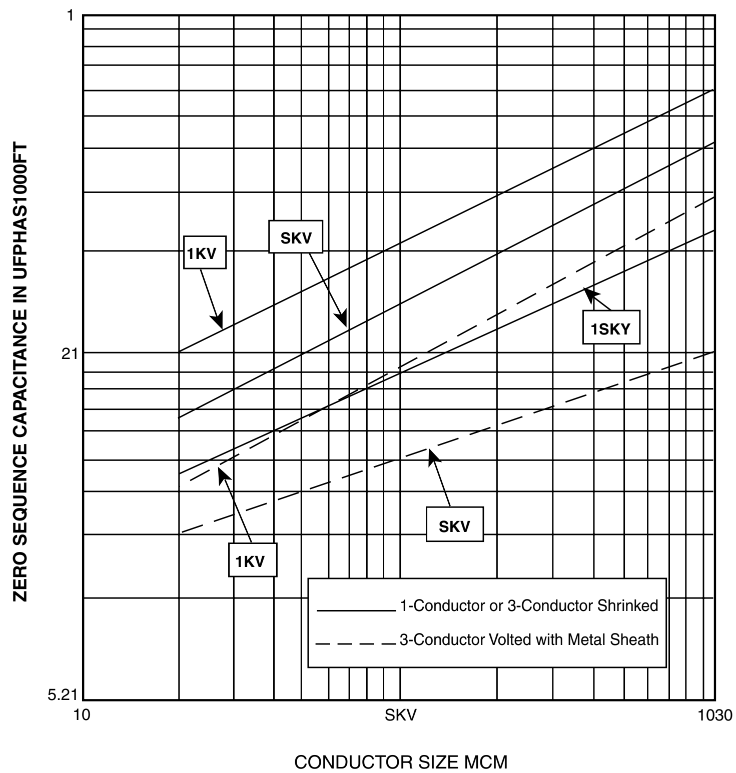


Figure A1.3: Motor Capacitance to Ground Values

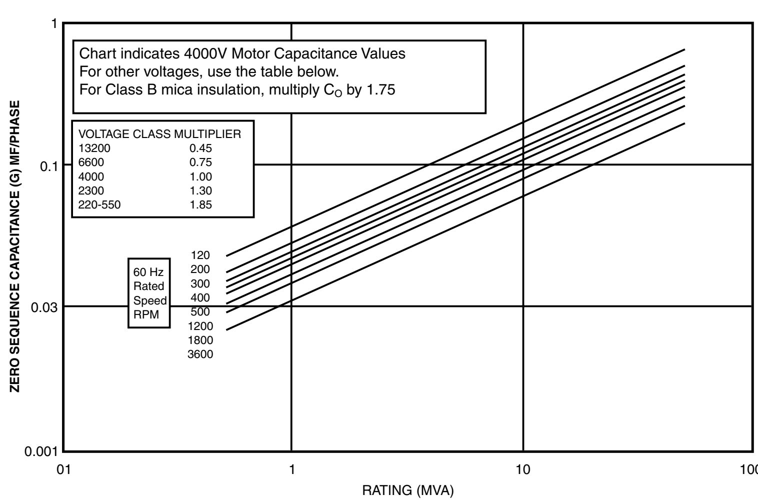


Figure A1.2: Cable Charging Currents for Common Cable Sizes.

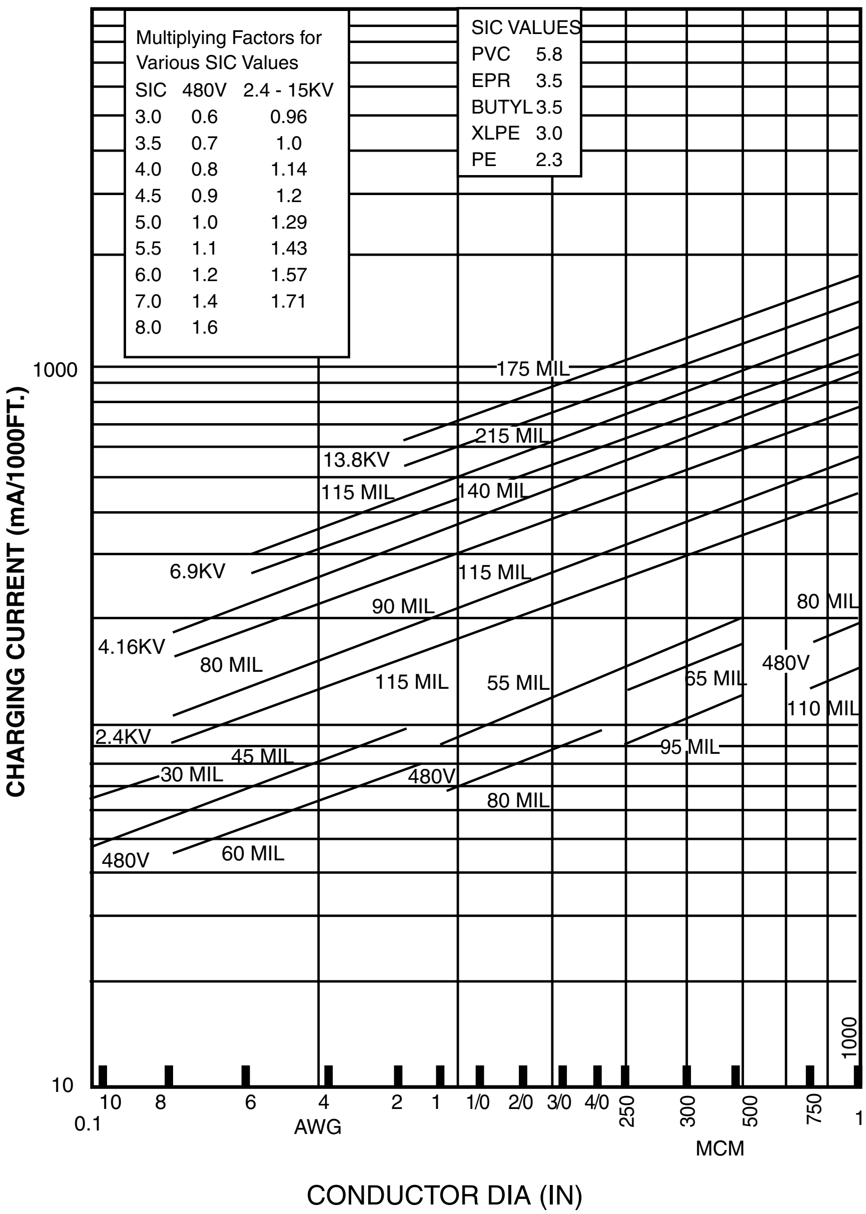


Table AI.I: Surge Capacitor Values

Rated Volts	Capacitance µF/Pole	Capacitance Reactance Ohms/Pole	$3I_{C0}$ Amps.
480	1.00	2650	0.313
600	1.00	2650	0.393
2400	0.50	5300	0.783
4160	0.50	5300	1.360
4800	0.50	5300	1.566
6900	0.50	5300	2.250
11500	0.25	10600	1.875
13800	0.25	10600	2.250

Appendix 2

Charging Current Measurement

⚠ DANGER

Hazard of Electric Shock or Burn

- **Verify that power is off before making any connection.**
- **Ensure that safety fuses are installed in the test circuit**
- **Only properly rated components should be used for the test circuit**
- **If you do not fully understand what you are about to do, consider alternative methods**

Failure to observe these precautions will result in death or severe personal injury.

The measurement of system charging current $3I_{C0}$ is a relatively simple procedure but, as on all occasions when one deals with energized distribution systems, a careful consideration of the problem followed by the use of the proper precautions is essential.

On low-voltage systems, the charging current can be measured by intentionally grounding one phase as shown in **Table A2.1**.

The apparatus required for measurement on low-voltage systems consists of an ammeter with ranges up to 10 amps, an HRC fuse and a disconnecting switch with adequate continuous and interrupting rating–such as a QMQB switch or a circuit breaker connected in series as shown in the diagram. The fuse is provided for equipment and personal protection against the occurrence of a ground fault on one of the other phases whilst the measurement is being made. For this test, the entire system should be energized if possible.

It is recommended that a properly rated variable resistor should also be connected in the circuit to minimize transient changes in the system charging current when the phase conductor is brought to ground potential by progressively decreasing the resistance to zero.

With the resistance set for maximum, the current should be limited to half the estimated charging current as shown in (**Table A2.1**).

$$R_{MAX} = \frac{2V_{LL}}{\sqrt{3} \cdot 3I_{C0}} \text{ (Ohms), where}$$

$3I_{C0}$ = the estimated charging current

V_{LL} = the system line to line voltage

Table A2.1: Typical Charging Currents

System Voltage	Charging Current ($3I_{C0}$) Amps/1000 KVA of System Capacity
480	0.1 - 2.0
600	0.1 - 2.0
2400	2.0 - 5.0
4160	2.0 - 5.0
13800	5.0 - 10.0

NOTE–Contribution of surge capacitors are not included in **Table A2.1**.

An essential requirement is a firm electrical connection to one phase of the system. As the measurement can be made anywhere on the system, one of the best ways is to de-energize a part of the system. Bolt or clamp the ground, bolt or clamp on the electrical apparatus to one phase, and then re-energize the system. During the tests it is required that the entire system be energized.

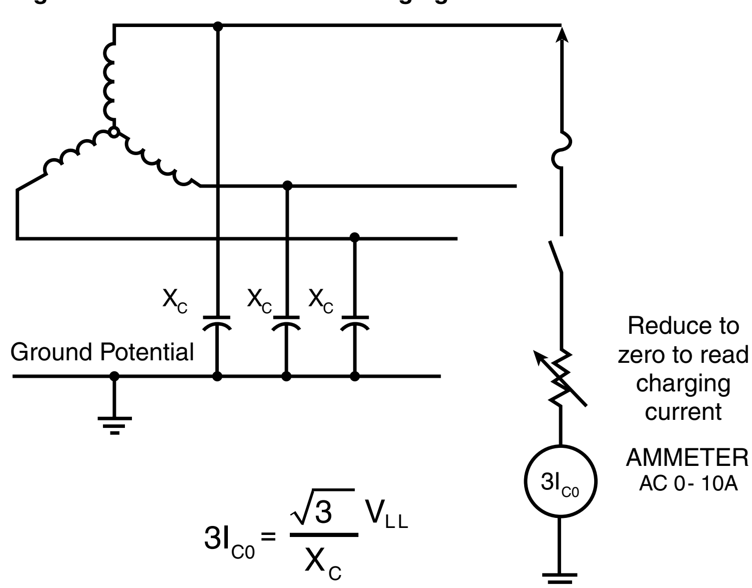
The test procedure should adhere to the following sequence. All resistance of the variable resistors should be in before closing the disconnect switch ahead of the fuse. After closing the disconnect switch slowly, reduce the resistance to zero, the ammeter will indicate the system (31_{C0}) charging current. It is advisable to have several ranges available on the ammeter but the disconnecting switch should always be opened before a range change is made to eliminate the possibility of opening the circuit with the range switch.

To remove the test connections, the sequence should be reversed. First, increase the resistance to maximum and then open the disconnecting switch.

Although the three phases usually have approximately equal charging currents, all three should be measured and the average value used.

By using properly rated equipment, similar measurements may be made on medium-voltage systems also.

Figure A2.1: Measurement of Charging Current



$$3I_{C0} = \frac{\sqrt{3}\ V_{LL}}{X_C}$$

Summary

Ground Fault Protection on Ungrounded and High Resistance Grounded Systems

Introduction

Ungrounded distribution systems are used in industrial installations due to their ability to provide continuous service with a ground fault on one phase. A single-phase failure to ground does not cause high current to flow because the current is limited by the capacitance of the other two phases, but the voltage-to-ground of the other phases rises 73%, stressing the insulation of cables and other equipment connected to the system. It is a common practice to run a faulted ungrounded system until it is convenient to shut it down for repairs.

Unfortunately, the ungrounded system is susceptible to a build-up of high voltages (up to six times the nominal system voltage) when the first fault on the system is of the intermittent (arcing) type. This high voltage can initiate a second fault at the weakest insulation point on the system and thus larger, more damaging fault currents can occur. The second phase failure to ground on the same feeder will usually cause high fault currents to flow between the two insulation failures. The overcurrent devices protecting the circuit involved should operate to clear the fault. However, a phase-to-ground-to-phase fault on two different feeders with a high ground path impedance between them or insulation failure that may not be complete causes a high resistance fault to develop, resulting in smaller magnitudes of current flowing into the faulted areas. The magnitude will not be sufficient to operate the overcurrent devices and will cause extensive damage to the equipment requiring expensive repairs or an extended shutdown until the equipment can be replaced.

Locating and repairing the first ground fault is of prime importance, but in most continuous process plants, this is not an easy job since some portion of the operation would have to be shut down in order to isolate the problem area.

Overvoltages caused by intermittent (arcing) faults, can be held at phase-to-phase voltage by grounding the system neutral through a resistance which limits the ground current to a value equal to or greater than the capacitive charging current of the system. This can be achieved on a wye-connected system by a neutral grounding resistor, connected between the wye point and ground and on a delta-connected system by applying an artificial neutral.

System Capacitance

The line-to-ground capacitance associated with system components determines the magnitude of zero-sequence charging current. This value of current is required for proper selection of high resistance grounding equipment.

The charging current of a system can be calculated by summing the zero-sequence capacitance or determining capacitive reactance of all the cable and equipment connected to the system. From this the current can be calculated. If actual values are not available, graphs and approximation formulae can also be used.

Selection of High Resistance Grounding Equipment

For correct application, the let-through current of the high resistance grounding equipment should be equal to or slightly higher than the capacitive charging current of the system. The installation of a tapped ground resistor unit is recommended when a system expansion is expected at a later date or the designer is unsure of the charging current value.

High resistance grounding concept can be applied to any low-voltage system (1000V) if the ground fault current is limited to a “low value” by NEC.

At higher ground fault currents values, tripping on the first fault is required to limit the burning damage on systems.

The high resistance grounding equipment should have a continuous-duty rating when the service continuity is a prime concern. Short-time rated devices (10 seconds, 1 minute or 10 minutes) can also be applied, but the fault must be removed within the time period of the short-time rating.

The Design Process

The ground fault protection system is usually the last step in the distribution system design, but it should be considered from the beginning and implemented in the total protection scheme. Therefore, it is required that all necessary information be available before a commencing with the design, if possible.

A complete single line diagram, containing the transformer data, type and size of the interrupters, the type and current rating of the overcurrent devices, the size, type and length of all feeders, load types and sizes, etc., is required for the ground fault protection system design. Additional information, such as operating modes and interlocking systems, special switching arrangements, etc., will influence the design. The state of supervision can also be a major factor: unattended systems may require fully automatic protection schemes, while selective indication may be sufficient for attended ones, where preventative and corrective maintenance is scheduled in weekly or monthly periods.

Notes

Notes

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