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Original Article

Application of Low Voltage High Resistance Grounding in Nuclear Power Plants

Choong-Koo Chang* and Mostafa Ahmed Fouad Hassan

Nuclear Power Plant Engineering Department, KEPCO International Nuclear Graduate School, 658-91 Haemaji-ro, Seosang-myeon, Ulju-gun, Ulsan 689-882, South Korea

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ABSTRACT

Most nuclear power plants now utilize solid grounded low voltage systems. For safety and reliability reasons, the low voltage (LV) high resistance grounding (HRG) system is also increasingly used in the pulp and paper, petroleum and chemical, and semiconductor industries. Fault detection is easiest and fastest with a solidly grounded system. However, a solidly grounded system has many limitations such as severe fault damage, poor reliability on essential circuits, and electrical noise caused by the high magnitude of ground fault currents. This paper will briefly address the strengths and weaknesses of LV grounding systems. An example of a low voltage HRG system in the LV system of a nuclear power plant will be presented. The HRG system is highly recommended for LV systems of nuclear power plants if sufficient considerations are provided to prevent nuisance tripping of ground fault relays and to avoid the deterioration of system reliability.

1. Introduction

An electrical system grounding method should provide the safety, reliability, and continuity of service required by the power distribution system. In the past, ungrounded systems were preferred when reliability and continuity service were very important. However, ungrounded systems provide no control over a destructive transient overvoltage. In addition, experience with multiple failures due to arcing ground faults has caused a change in philosophy about the use of an ungrounded system. Solidly grounded and high resistance grounded systems have become the standard for large industrial complexes [1–3].

2. Low voltage ground fault protection

Electrical facilities should be inspected periodically before and during operation by authorized institutions. Before the design of a ground fault protection system, applicable laws and regulations must therefore be carefully reviewed. Technical feasibility, reliability, and practicality with respect to the ground fault protection system should be considered.

2.1. Applicable laws and regulations

Based on electrotechnical regulations in Korea, equipment that has exposed metal parts, is rated at a voltage higher than

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* Corresponding author.
E-mail address: ckchang@kings.ac.kr (C.-K. Chang).

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60 V, and supplies electricity to the facilities installed in a place where people can easily come into contact with the equipment should be equipped with a ground fault protection device that can automatically detect and clear any ground fault. However, this equipment is exempt from the installation of ground fault protection if the equipment is maintained by a qualified engineer or installed in a dry area so that the possibility of electric shock is very low. However, the exemption is not applied to low voltage (LV) circuits that are rated higher than 400 V and coupled with high voltage circuits through the transformer.

Since the formation of the World Trade Organization agreement, the industrial standards of Korea have conformed to the related International Electrotechnical Commission (IEC) standards. The electrical regulations have accordingly been revised or admitted as a parallel requirement with the IEC standards, and harmonization of the industrial standards of Korea with the IEC standards is ongoing. The design of the electrical distribution systems of nuclear power plants was developed on the basis of the technologies and practices of the United States of America.

International standards and practices need to be applied to the design of electrical distribution systems while taking into consideration the changes of technical circumstances in the industry. Up-to-date technologies should also be applied to design and construct more reliable and safer electric power systems.

2.2. *Types of LV grounding systems*

Ground fault protection is a part of the safety protections specified in IEC 60364-4-41; this protection has a close relation with the protection against electric shock. Under general conditions, the allowable continuous touch voltage of the human body is 50 V. A protective device is required to limit the touch voltage below the allowable continuous touch voltage when a human body is in contact with the conductive part of equipment.

The fault current circulation path is determined by the grounding system. Therefore, the grounding system of the LV system should be designed before determining the ground fault protection scheme. The LV grounding system is classified as Class 1, 2, and 3 in the conventional system, and as TN, TT, and IT in IEC Standard 60364. In the conventional grounding system, the earthing resistance (i.e., the resistance between the earth and the grounding conductor) is specified by the type of grounding. On the other hand, IEC 60364 evaluates the safety level by the estimated touch voltage and maximum fault clearing time instead of by specifying the earthing resistance. However, the ultimate goal is the same: to limit the magnitude and continuing time of the fault current passing through the human body at safe levels with regard to the average impedance of the human body and expected touch voltage. Table 1 shows the relationship between the expected touch voltage and the maximum clearing time.

Table 1 – Expected touch voltage and maximum clearing time.[a]

Touch voltage U (V)	Z (Ω)	I (mA)	t (sec)
≤50	1,725	29	∞
75	1,625	46	0.60
100	1,600	62	0.40
125	1,562	80	0.33
220	11,500	147	0.18
300	1,460	205	0.12
400	1,425	280	0.07
500	1,400	350	0.04

[a] See Table A in IEC 61200-413 [11].

2.2.1. *The TN system*

In TN systems, as depicted in Fig. 1, the integrity of the earthing of the installation depends on a reliable and effective connection of the protective earth and neutral (PEN) conductor or the protective earth (PE) conductor to earth. The neutral point or the midpoint of the power supply system is earthed. If a neutral point or midpoint is unavailable or inaccessible, the line conductor is earthed. Exposed conductive parts of the installation are connected by a protective conductor to the main earthing terminal of the installation, which is connected to the earthed point of the power supply system.

In fixed installations, a single conductor may serve as the protective conductor and as a neutral conductor (i.e., PEN conductor), provided that the requirements of section 543.4 of IEC 60364-5-54 are satisfied. No switching or isolating device is inserted in the PEN conductor.

The characteristics of the protective devices and the circuit impedances fulfill the following requirement:

$$Zs \times Ia \leq Uo \qquad (1)$$

in which Zs is the impedance [in ohms (Ω)] of the fault loop, which comprises the source, the line conductor up to the point of the fault, and the protective conductor between the point of the fault and the source; and Ia is the current [in amperes (A)] that causes the automatic operation of the disconnecting device within the time specified in Table 2. When a residual current protective device (RCD) is used, this current is the residual operating current that provides the disconnection in the time specified in 411.3.2.2 or 411.3.2.3 of the IEC 60364-4-41 [4], and Uo is the nominal alternating current (AC) or direct current (DC) line to earth voltage [in volts (V)].

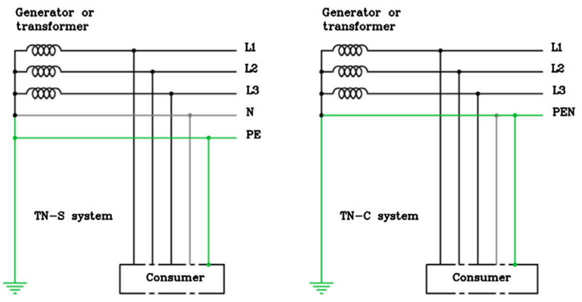

Fig. 1 – The TN grounding system. N, neutral; PE, protective earth; PEN, protective earth and neutral.

2.2.2. *The TT system*

All exposed conductive parts collectively protected by the same protective device are connected by the protective

Table 2 – Maximum disconnection times.

System	TN (s)		TT (s)	
	AC	DC	AC	DC
50 V < Uo ≤ 120 V	0.8	Note[a]	0.3	Note[a]
120 V < Uo ≤ 230 V	0.4	5	0.2	0.4
230 V < Uo ≤ 400 V	0.2	0.4	0.07	0.2
Uo > 400 V	0.1	0.1	0.04	0.1

AC, alternating current; DC, direct current.

[a] Disconnection may be required for reasons other than protection against electric shock.

conductors to an earth electrode common to all of these parts. Where several protective devices are utilized in series, this requirement is applied separately to all exposed conductive parts protected by each device. The neutral point or the midpoint of the power supply system must be earthed. If a neutral point or midpoint is unavailable or inaccessible, the line conductor must be earthed.

Generally in TT systems (Fig. 2), RCDs are used for fault protection. Overcurrent protective devices may alternatively be used for fault protection, provided a suitably low value of Zs is permanently and reliably assured.

Where an RCD is used for fault protection, the following conditions must be fulfilled [5]. The disconnection time, as required by Table 2 and Eq. (2), is the following:

$$RA \times I\Delta n \leq 50\ \text{V} \tag{2}$$

in which RA is the sum of the resistance in ohms (Ω) of the earth electrode and the protective conductor for the exposed conductive parts, and IΔn is the rated residual operating current of the RCD.

Where an overcurrent protective device is used, the following condition will be fulfilled:

$$Zs \times Ia \leq U_o \tag{3}$$

in which Zs is the impedance in Ω of the fault loop, which comprises the source, the line conductor up to the point of the fault, the protective conductor of the exposed conductive parts, the earthing conductor, the earth electrode of the installation; the earth electrode of the source, Ia, is the current in amperes that causes the automatic operation of the disconnecting device within the time specified in Table 2; Uo is the nominal AC or DC line to earth voltage.

2.2.3. *The IT system*

In IT systems (Fig. 3), live parts are insulated from earth or connected to earth through a sufficiently high impedance. This connection may be formed either at the neutral point or the midpoint of the system or at an artificial neutral point. The latter may be connected directly to earth if the resulting impedance to earth is sufficiently high at the system frequency. Where no neutral point or midpoint exists, a line conductor may be connected to earth through a high impedance.

The fault current is low in the event of a single fault to an exposed conductive part or to the earth, and automatic disconnection in accordance with Table 2 is not imperative, provided the condition in Eqs. (4) and (5) is fulfilled. However, in the event of two faults existing simultaneously, provisions should be taken to avoid the risk of harmful effects on a person in contact with simultaneously accessible exposed conductive parts.

Exposed conductive parts should be earthed individually, in groups, or collectively. The following condition will be fulfilled [6]:

$$\text{In AC systems, } R_A \times I_d \leq 50\ \text{V} \tag{4}$$

$$\text{In DC systems, } R_A \times I_d \leq 120\ \text{V} \tag{5}$$

in which R_A is the sum of the resistance (in ohms) of the earth electrode, protective conductor for the exposed conductive parts, and grounding register (optional); and I_d is the fault current (in amperes) of the first fault of negligible impedance between the line conductor and the exposed conductive part. The value of I_d takes into account the leakage currents and the total earthing impedance of the electrical installation.

In IT systems the following monitoring devices and protective devices may be used: (1) insulation monitoring devices; (2) residual current monitoring devices; (3) insulation fault location systems; (4) overcurrent protective devices; and (5) residual current protective devices.

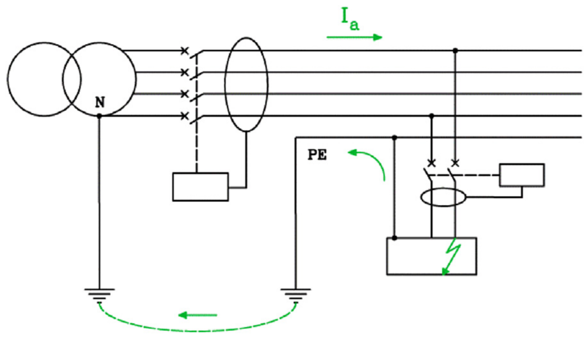

Fig. 2 – The TT grounding system. Ia, current (in amperes); N, neutral; PE, protective earth.

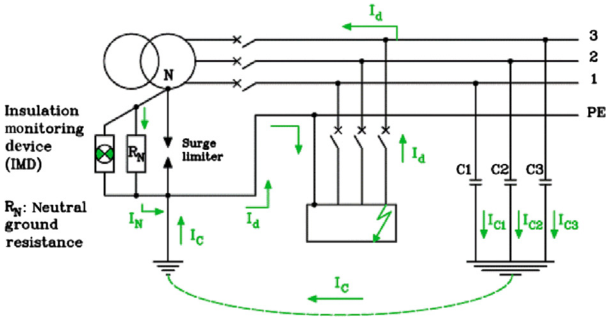

Fig. 3 – The IT grounding system. Ia, current (in amperes); N, neutral; PE, protective earth; R_N, neutral ground resistance.

In situations in which an IT system is used for the continuity of supply, an insulation monitoring device indicates the first fault from a live part to exposed conductive parts or to earth. This device initiates an audible and/or visual signal, which continues as long as the fault persists. If there are both audible and visible signals, it is permissible for the audible signal to be cancelled.

Except where a protective device is installed to interrupt the supply in the event of the first earth fault, a residual current monitoring device or an insulation fault location system may be provided to indicate the first fault from a live part to exposed conductive parts or to earth. This device initiates an audible and/or visual signal, which continues as long as the fault persists.

2.3. *Coordination problems in LV grounding*

To date, the TN (i.e., solidly grounded) system is a commonly used method of grounding for nuclear power plants (Fig. 4). The ungrounded system is not recommended because the system is actually grounded through the distributed cable capacitance. As a result of this capacitance, a certain amount of capacitive current will always flow through a line to the ground fault. In addition, arching ground faults on a large "ungrounded" system can cause transient overvoltage of several times the normal voltage, which may cause motor failure [2].

Ground fault protection on a solidly grounded system provides a quicker and more sensitive means of detecting and clearing ground faults, compared to ground fault protection in other grounding systems. However, quick and sensitive detection of a ground fault may result in miscoordination. In many circumstances, the main breaker trips because of a fault at an insignificant downstream feeder or branch. For example, the most common coordination problem in a 480 V system is caused by the ground fault protection system having a downstream phase device that miscoordinates with an upstream ground fault protection device, as illustrated in Fig. 4.

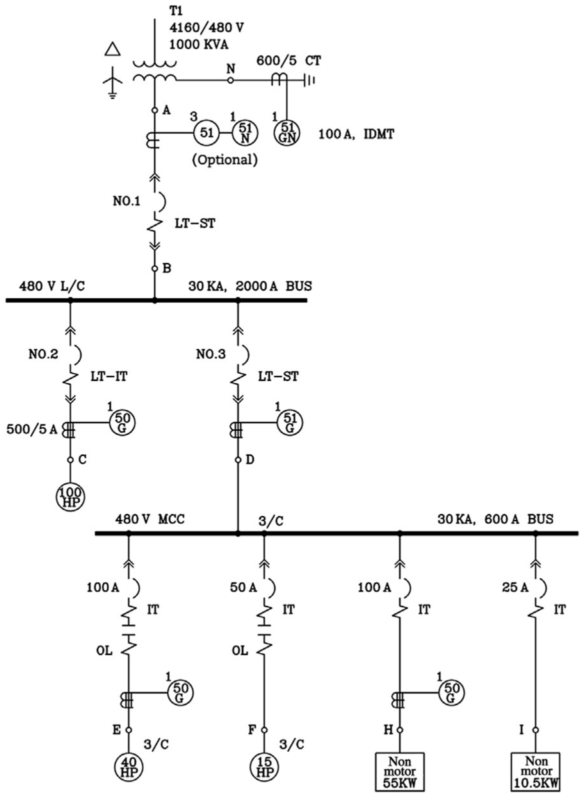

Fig. 4 – The typical ground protection scheme for the LV system.

In Fig. 4, the main breaker of the load center has no ground fault protection (GFP) device. The time GFP relay is instead installed on the neutral ground line of the LV distribution transformer. The load center branch breakers have separate GFP devices that are instantaneous or have a time ground overcurrent relay. The branch breakers of the motor control center (MCC) have a separate ground fault relay (GFR), except circuits in which the molded case circuit breaker (MCCB) is no greater than 30A and load of the motor no greater than 15 horse power.

In that circumstance, the MCC branch breakers, which have no GFR, may not properly coordinate with the GFR on the load center branch breaker, and the MCC feeder breaker can trip a ground fault associated with MCC branch breakers. This type of miscoordination is quite common when a LV system is installed without a coordination study. Better coordination can be obtained by performing a detailed short circuit and coordination study in conjunction with installing downstream GFP devices. However, in most circumstances, compromise is necessary, and maximum reliability may not be attained using a solidly grounded system in the LV system.

2.4. *Arcing faults and arc resistance*

Short circuit and coordination studies commonly focus on only bolted three-phase or phase-to-ground faults. However, failures rarely involve bolted faults in practical equipment. The faults are normally of the arcing type, which has arc resistance, and this resistance must be taken into consideration. On LV equipment, an arc voltage in the range of 150 V has been developed. This voltage is relatively insensitive to current, which indicates the arc resistance is variable [2].

Unlike a bolted fault, an arcing fault uses ionized air as the conductor. The cause of the fault normally burns away during the initial flash and the arc is sustained by the establishment of a highly conductive, intensely hot plasma arc. The intense heat vaporizes the conductors' barriers and superheats the surrounding air, and results in an explosive volume-metric increase within the space. The consequence is an intense pressure wave, deafening sound, blinding light, toxic gases, molten metal, and shrapnel. This is often referred to as an arc blast. Unless action is taken to quickly remove the fault or to redirect the arc blast, the brunt of these items will impact people, equipment, or both. The magnitude of the arcing fault is only 43–57% of a bolted fault, so traditional overcurrent protection may not detect and clear the fault before the full impact of the arc develops and causes damage or injury [7].

For many years, different methods to limit arc flash exposure and incident energy have been introduced. The use of a high resistance grounded system minimizes the amount of damage created from the fault.

3. High resistance grounding

One of the most common reasons for not using a high resistance system is that, in any practical power system, single-phase or three-phase four-wire loads are to be fed. If most loads are three-phase four-wire loads, HRG is most likely impractical. However, if most of the loads are three-phase three wire type loads (i.e., motor loads), a HRG may still be an option [2].

3.1. *Design considerations*

The design of a high resistance grounded system is quite simple for the delta-wye transformer. The first step in the design is to calculate the distributed capacitance, Xc, of the charging current of the system. Table 3 shows the typical charging currents of LV cables [8]. The accuracy of cable capacitance is not critical in this calculation, but measurement of the actual charging current during commissioning is preferable.

To prevent the possibility of transient overvoltage, the zero-sequence resistive ground fault current, I_{RO}, should be equal to or greater than the charging current, I_{CO}. In the zero-sequence circuit shown in Fig. 5, the resistance and equivalent capacitance are parallel. Because the resistor is installed in the neutral of the transformer, the zero-sequence current $3I_0$ will flow through the resistor. As a result, that current makes the apparent resistance of the grounding resistor seem three times as large.

Based on the circuit in Fig. 5 the resistance and current flow are approximated, by the following equations:

$$I_{R0} > I_{C0} \tag{6}$$

$$IC0 = \frac{V_n}{X_{C0}/3}\ [A] \tag{7}$$

$$IR = \frac{V_n}{R}\ [A] \tag{8}$$

Symmetrical component calculations are represented by $I_R = 3I_{R0}$ and $I_C = 3I_{C0}$, and V_n is the phase-to-neutral voltage.

Table 3 – The 480 V low voltage system cable charging current.

Cable size AWG (mm^2)	Charging current/1,000 ft of 3C	Installation type
350–500 MCM	0.10A	Conduit
2/0–3/0	0.05A	Conduit
2/0–3/0	0.02A	Tray
#6	0.05A	With ground wires in water
Transformers	Negligible	
Motors	0.01A/1,000 hp	

AWG, American wire gauge; hp, horse power.

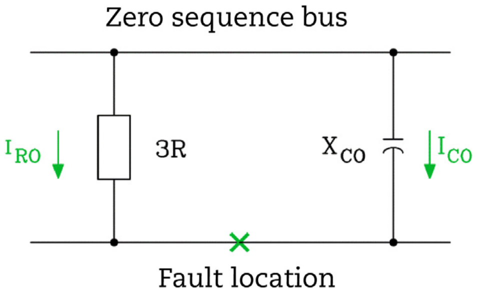

Fig. 5 – The zero-sequence network of high resistance grounded system.

The neutral grounding resistance size (R_n) and capacity are determined by the following equation:

$$Rn = \frac{V_n}{I_R}\ [\Omega] \tag{9}$$

$$\text{Resistance capacity} = I_R^2 {*} R_n\ [W] \tag{10}$$

In an APR 1400 nuclear power plant, the total power cable length of the LV circuits—fed from a typical Class 1E distribution transformer rated at 1,000 kVA—is 65,882 feet. The size and length of cables, installation types, and charging currents are shown in Table 4. The total charging current of all the cables is 2.29A. It can be assumed that the charging current of all cables is 0.05A per 1,000 ft of three wire cables, based on the cable installation type. The charging currents of the transformers and motors are negligible. Therefore, I_R can be determined as 3.0A, based on the safety margin. Thus, the following applies:

$$Rn = \frac{V_n}{I_R} = \frac{480/\sqrt{3}}{3.0} = 92.37\Omega \tag{11}$$

$$\text{Resistance capacity} = 3^2 \times 92.37 = 831.33\ \text{W} \tag{12}$$

Typical resistance and wattage range for 480 V grounding resistors are 60–300 Ω and 260–1,300 W, respectively [1].

Table 4 – The charging current of 480 V low voltage cables for a class 1E load center and the motor control center belong to the load center.

Cable size	Length (ft)	Charging current (A)	
		Ampere/3C	Installation
1C-750KCM	28,516	0.48	Tray
1/C-500KCM	1,640	0.03	Tray
3/C-350KCM	434	0.02	Tray
3/C-#4/0	3,000	0.15	Conduit
3/C-#1/0	1,658	0.08	Conduit
3/C-#4	2,142	0.11	Conduit
3/C-#6	300	0.02	Conduit
3/C-#8	8,252	0.41	Conduit
3/C-#10	6,624	0.33	Conduit
3/C-#12	13,316	0.67	Conduit
Total	65,882	2.29	

MCC, motor control center.

Fig. 6 is an example of a ground fault detection scheme of a high resistance grounded system. The grounding resistor has taps, which allow fine tuning of the resistance during installation and commissioning. A voltage monitoring relay (VMR), a GFR, a pulse generator, and a control circuit are provided with the resistor to detect and locate ground faults.

Low voltage systems with loads, which produce harmonic currents, may result in false alarms or trips of GFRs. The harmonics are produced by rectifiers, DC drivers, variable speed AC drivers, and other electronic switching devices that are connected to the power system. In that circumstance, installing a harmonic filter on the HRG system or an isolation transformer at an individual driver is a good practice that may alleviate nuisance alarms or trips [9].

3.2. *Operation theory of the HRG system*

If a ground fault occurs in a LV circuit, the voltage is induced on the resistor by the ground fault current. When the induced voltage is greater than the setting, the VMR is activated, which energizes the trip and/or the alarm circuit. The auxiliary contact of the VMR and the GFR is connected in series and gives a trip or alarm signal to the incoming Air Circuit Breaker (ACB) of the load center, as shown in Fig. 4.

The pulse generator aids locating the ground fault. The closing and opening of the shorting contact changes the magnitude of the grounding resistor. The pulse current then follows through the ground faulted feeder and grounding resistor. In that situation, a portable hook-on detector is used to locate the feeder, which creates a fluctuation in the detector. The ground fault current is limited by the ground resistor. Therefore, all grounding resistors should not be shorted at the same time. If not, very high ground fault currents may flow through the neutral line of the distribution transformer.

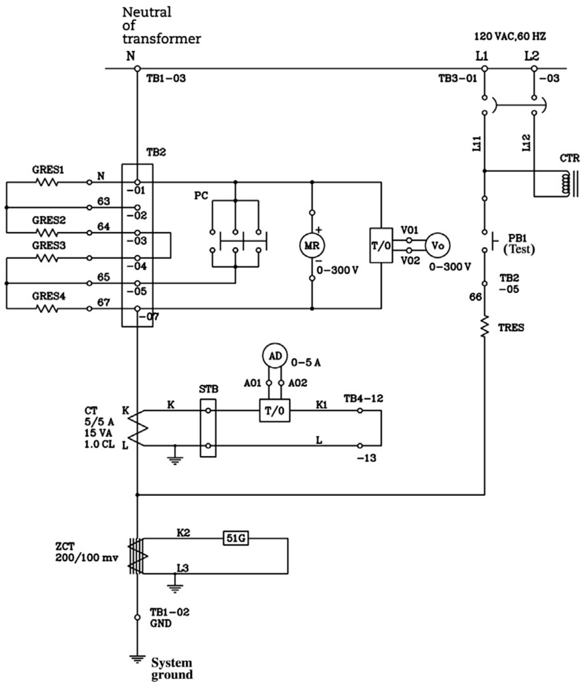

Fig. 6 – Scheme of the high resistance grounding system ground fault detection. AD: Ampere Device, CL: Current Limit, CTR: Control Transformer, GND: Ground, GRES: Ground Resistor, MR: Meter, PC: Pulse Contact, STB: Short Terminal Block, TRES: Test Resistor.

3.3. *Setting of the ground fault relay*

The following is an example of the relay setting for the above proposed HRG system. When a solidly grounded fault occurs in a feeder with zero ground resistance, 277.12 V is induced on the grounding resistor. However, solidly grounded faults rarely occur. Therefore, the VMR is set at a voltage lower than 277.12 V. The resistive current I_{RO} during a ground fault should be equal to or greater than $I_{CO.}$ The setting voltage is accordingly determined as a little higher than 211.5 V (i.e., 92.37 Ω × 2.29 A).

The time ground fault current relay (51G) is also set at the current slightly higher than the cable charging current. Approximately 2.5A ($\cong 2.29 \times 1.1$) is recommended as a pickup current. However, the actual pickup level is determined by the cable charging current measured during the test operation.

4. Conclusion

The HRG system corresponds to the IT grounding system described previously in section 2.2 and in IEC 60364-4-41. The HRG system offers the best compromise of the service continuity of ungrounded circuits and the safety of solidly grounded circuits in LV systems (i.e., 440–600 V). The capacitive current on LV systems is sufficiently low (i.e., less than 5A) so that the resistive controlled current remains low to avoid escalating the fault current and causing equipment damage. Proper application of a high resistance grounded system will limit the transient overvoltage of arching faults to an acceptable value.

Therefore, the HRG system is highly recommended for LV systems in nuclear power plants, especially for the Class 1E system, which is required to operate under any operation condition. The HRG system was allegedly inapplicable to three-phase four-wire systems. However, three-phase four-wire loads and/or single-phase loads can be accommodated by using an isolation transformer.

The HRG system may be used to trip a breaker or initiate an alarm. If it is used for alarming, the ground fault should be located and cleared within a predetermined timescale. While the ground fault persists, the voltage on the two ungrounded phases can elevate up to 73% greater than the nominal line-to-ground voltage.

The complete HRG system—resistor, fault detection and location scheme, alarm, and relays with control circuits—should be adequately designed and installed to take advantage of all benefits of high resistance grounding. In addition, a systematic assessment should be conducted for all systems important to nuclear safety to confirm that the design achieves the reliability requirements of the system design bases

[10]. Thus, the HRG system provides the safety and reliability necessary for the LV systems of nuclear power plants.

Conflicts of interest

All authors have no conflicts of interest to declare.

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