ADVANCED CONCEPTS IN HIGH RESISTANCE GROUNDING

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Abstract - Resistance grounding is relatively simple and easy to apply in radial distribution systems at Low Voltage. When high resistance grounding is applied, using one Neutral Grounding Resistor at the supply transformer, an alarm system to detect and indicate the ground fault is then required by the installation codes. This practice has been in use and is widely applied. This paper explores the application when the distribution systems involve multiple sources operating in parallel, such as multiple transformers, multiple generators or a combination. The sizing of NGR is explored and application of hybrid grounding is suggested for situations where Low resistance grounding needs to be used. In medium voltage systems 15 kV to 36 kV the practice has been to use very low resistance grounding. The paper suggests that the criteria for NGR sizing should be based on the net distributed charging current only.
Application examples are presented showing the selective instantaneous feeder tripping and concept of hybrid grounding in Low and Medium voltage systems

Index Terms *— High resistance grounding, selective second fault tripping, multi-circuit ground fault relay, hybrid generator grounding, stator ground fault, hybrid grounding in Medium Voltage Systems.*

I. INTRODUCTION

The petrochemical Industry has been applying Neutral Grounding Resistors (NGRs) on it's power distribution system for many years. The concept is well known and has been in use as best practice in the petro chemical Industry. This has been driven by three basic factors:

1) Power continuity, nothing needs to trip in the event of a ground fault.
2) Negligible damage at the point of fault resulting in lower repair costs and faster return of faulty equipment to service.
3) In case of accidents, minimal arc flash hazard from phase to ground fault.

It is the best practice to have the low voltage (LV) and medium voltage (MV) applied with High Resistance Grounding (HRG) [1],[2]. This has often taken the form of simple resistor applied between transformer neutral and ground. An alarm is raised on the occurrence of a ground fault in the distribution. The current flows through the resistor or the voltage rise of the neutral or the reduction of voltage to ground on the faulted phase can be used to initiate this alarm. Phase to ground voltage also identifies the faulted phase. To indicate which feeder has a fault, zero sequence sensors with sensitive ground fault relays are applied. The alarm level is usually set for 50%, or less of the resistor let through current. This avoids sympathetic alarms caused by the unbalanced capacitive leakage current in unfaulted feeders [3]. In modern relays the zero sequence sensor signal causes a pick up then the simultaneous presence of unbalanced voltage is verified before alarm is indicated. Often to avoid nuisance alarms caused by inrush currents and non linear loads, the Zero Sequence Current Sensor output is filtered and only fundamental signal is extracted. These measures have been effective in avoiding nuisance alarms and trips in sensitive ground fault relays. This practice has been well accepted and understood. The purpose of this paper is to explore resistance grounding applications and offer suggestions for enhancements for both LV and MV Systems.

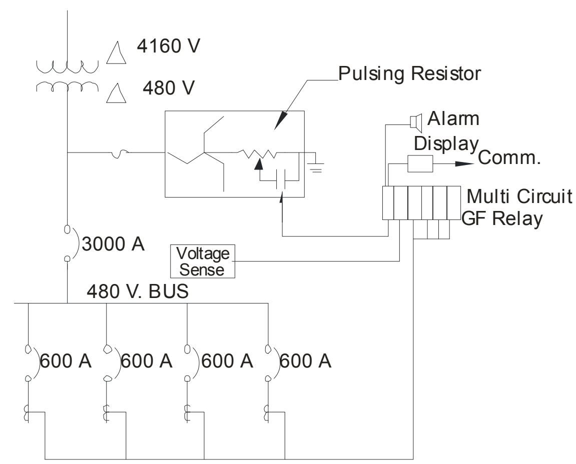

Fig. 1 Typical Delta/Delta installation

II. HIGH RESISTANCE GROUNDING

Fig. 1 illustrates a typical application for delta/delta transformer with 480 V secondary. The grounding resistor is applied on the line side of the main breaker using a zigzag transformer and a 2A let through resistor. All the feeders are monitored and ground alarm identifying faulted feeder and phase is provided by a multi-circuit ground fault relay

A. Benefits of High Resistance Grounding

1. Arc Flash and Blast hazard for a line to ground fault is prevented. For systems up to 4160 V where the resistor let through current is 10 A or less, the arc blast is unlikely. Such systems can continue to operate with one ground fault. Fault does not escalate and so the distribution system is safer. Accidents causing Line to ground faults will not produce hazardous blast or arc flash [4].
2. Fault Damage at the point of fault is very low and can be easily repaired. It minimizes maintenance repair costs. This is a significant advantage for protection of machines. Motor and generator laminations will not get burnt and winding repair costs will be small [4].
3. The small current is safely carried continuously by the bonding path without causing harmful step and touch potential rise.
4. For systems up to 4160 V where the resistor let through current is 10 A or less, the line to ground fault can be kept on the system continuously. No fault isolation needs to occur per CEC 10-1100 through 1108 [5], and NEC 250.36, and 250.186 [6]. Power continuity has been a major driver of High Resistance Grounding in North America in the process industry segment initially and data processing sectors more recently.
5. The voltage to ground transients which occur on ungrounded systems are avoided since the system is grounded and the buildup of charge in the distributed capacitance to ground on unfaulted phases is dissipated by the resistor. The voltage rise on the unfaulted phases is limited to the line to line voltage.

On the other hand, four application concerns arise when resistance grounding is applied to distribution.

1. All cables need to have a line to ground voltage rating of line to line voltage for the maximum duration of the line to ground fault. For systems designed for continuous operation with ground fault this line to ground voltage rating will equal phase to phase voltage. This is not an issue at low voltage such as 480 V and 600 V. The standard cables have adequate ratings. For medium voltage application, care must be taken to ensure adequacy. The cable insulation could be rated for L-N voltage and will be subjected to Line to line voltage for the duration of ground fault protection tripping delay on the occurrence of phase to ground fault.
2. Lightning arrestors and surge suppression devices which are connected line to ground will see the voltage to ground rise to phase to phase value and they also need to be adequately rated.
3. Voltage to ground impressed on Capacitors and line and post insulators will also increase to line to line value.
4. The circuit breakers and contactors employed in resistance grounded system must be able to break L-L voltage across one pole of the device. For example a 3 pole 480 V breaker must be able to open fault current and withstand 480 V across one pole. The ground faults could be on two phases on the opposite sides of the breaker. Many breakers only have a 277/ 480 V rating which means they are able to interrupt only 277 V across one pole. The same would apply to contactors.

B. Grounding Resistor Reliability

In resistance grounded systems the resistor becomes a very critical part and any failures in it need to be also detected. Monitoring the resistor integrity has been used in the mining industry for a long time and can be integrated in the ground fault relaying in HRG system. To increase the reliability of the resistor it can be built with redundancy of current path. Instead of a series connection of resistor elements the resistor can be built with parallel paths so a break in one element will not completely open the resistor but instead only cause a change in value which can raise an alarm.

The NGR characteristics become very critical in Low resistance grounding applications. The increase in the resistance value due to its temperature rise should be kept to a minimum so as not to lower the fault current below tolerable limit.

This requires that the NGR temperature coefficient should be as small as possible. The IEEE Standard 32 [7] allows temperature rise of the resistor to 385º C for continuously rated resistors and 760º C for short time rated resistors. Such large excursion of temperature will have significant impact on the resistance value if temperature coefficient of the material is not adequately low. Common practice has been to keep the increase in resistance to less than 20%.

III. LOW VOLTAGE - HIGH RESISTANCE GROUNDING

A. Locating Ground Faults

To provide assistance in locating a fault in High resistance grounded system the fault current is modulated by oscillating it between values such as 5A-10A or 2A-5A at a slow rate, typically at 1 cycle per second. This is accomplished by changing the resistor value using a contactor. This has been called "pulsing" in the industry. The pulsing is manually started when you wish to find the fault location. A flexible zero sequence sensor or a clamp on CT encircling all phase conductors is used to provide an oscillating signal to the hand held multimeter as long as the fault is on the load side of the sensor. Two or three measurements are sufficient to point to the fault location quite quickly. This is done on the outside of the grounded race ways or conduits or busways, while the system is energized and running. Most of the fault current returns in the ground path in the conduit but there is always some that goes elsewhere through other parallel ground paths and this is often sufficient to show the oscillation. This technique has been in use for many years [8][9]. It is quite effective for voltages up to 4160 V, beyond this the safety concerns and switching of higher voltage resistor make it complicated and the usefulness diminishes as very few medium voltage (MV) systems are operated with a ground fault. In most MV systems the faulted circuit is isolated.

B. Selective Second Fault Tripping

The primary benefit of using high resistance grounding is that the faulted feeder does not need to be isolated on the occurrence of a phase to ground fault. While the faulted system continues to operate there is a possibility that another phase to ground fault may occur on one of the healthy phases in some other weak spot in the distribution system. With the presence of a second fault, the fault current is no longer limited by the resistor. The fault current path is phase to ground to phase through the two faults. It becomes limited by the ground path impedance and the voltage drop in the two faults. If the faults are arcing type then the fault current magnitude is further reduced and a lot of fault damage due to arc fault energy ensues. These double faults have been reported in the automotive systems where the ungrounded systems were introduced in the mid-fifties and sixties [10]. The zero sequence sensors continue to monitor the fault current and if a significantly higher current than that limited by the resistor is detected then it can only occur if there is a phase to ground to phase fault condition involving two feeders. Two sensors will be in the fault path and two relays will sense this current. Only one feeder breaker needs to trip to revert the rest of the system to a one fault condition. A level of priority can be assigned based on the relative importance to all the feeders. The relays communicate to check the priority setting and the one feeder with lower priority is allowed to trip without any intentional delay, instantaneously. Fast operation provides protection and minimizes fault damage. Such systems have been available and have been in use for a long time.

Such a system with first fault alarm and second fault trip should be applied to monitor the loads. If it is applied at the main bus then the isolation of a major feeder will cause disruption to a major portion of the distribution. In such a case, time current coordination with downstream devices has to be undertaken so the tripping will minimize disruption. When time delays are introduced for time-current coordination the potential for damage due to an arcing ground fault increases. With multi-circuit ground fault relays, the cost of application has been reduced so that it is now practical to put ground fault relays on all levels of distribution at a given voltage. Fig. 2 illustrates an example of a grounded transformer using a pulsing resistor. All the loads are monitored using zero sequence sensors. Shunt trips coils of all feeder breakers are connected to the second fault tripping contact of the multi circuit relay. Relay provides communications via RS 485 and send signal to indicate which phase is faulted and how serious the fault is. The relay continues to monitor the system and sends a tripping signal to one feeder should there be a second fault while first fault has not been removed.

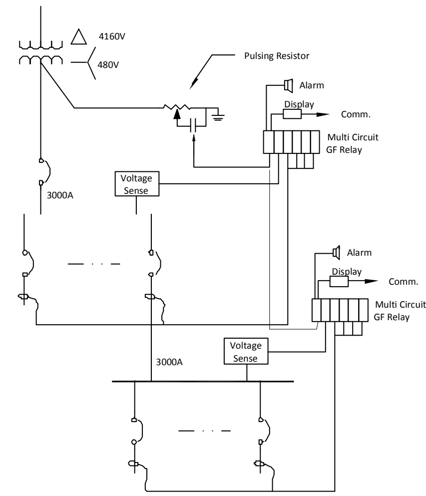

Fig. 2 Fully integrated system

Major functional enhancement occurs when detection and alarm due to ground fault is supplemented with monitoring of all the feeders to indicate which feeder is faulted and assistance for quickly locating it is included

C. Distribution systems with multiple sources

LV and MV distribution is usually more complex than just a simple radial distribution. Transformers get connected in parallel or in double ended arrangements with two mains and tie or triple ended arrangement with three mains and two ties. When systems are solidly grounded and the neutrals are distributed then providing ground fault protection for such systems becomes relatively expensive and cumbersome. Multiple grounding of the neutral adds to this complexity. With three wire distribution, ground fault protection is simplified and when such arrangements are made with high resistance grounding then further simplification occurs as illustrated in the Fig. 3. In distribution schemes with multiple sources applying NGRs to each source, it will lead to a fault current which will be contributed to by all the sources and hence could become higher than the HRG level of 10 A. In such a case, applying the NGR at the main bus keeps the maximum fault current at one level.

The grounding resistors normally applied on the neutral of transformers are removed. Individual transformers are not grounded, the grounding is moved to the main bus. Only the main busses need to be grounded. Ground fault relays can be set for a level which suits the grounding resistor let through. The source side conductors including the transformer secondary winding on the line side can be monitored for ground fault by adding zero sequence sensors to the supply conductors as well as the feeders. Fig. 3 shows an example of two generator buses, each is grounded using zigzag transformer. The two utility supplies are each grounded using a pulsing resistor. If all tie breakers are closed then the net contribution to the fault will come from the four resistors since each is 2 A resistor it will be 8 A and if only one bus is feeding the load then one resistor will contribute 2 A.

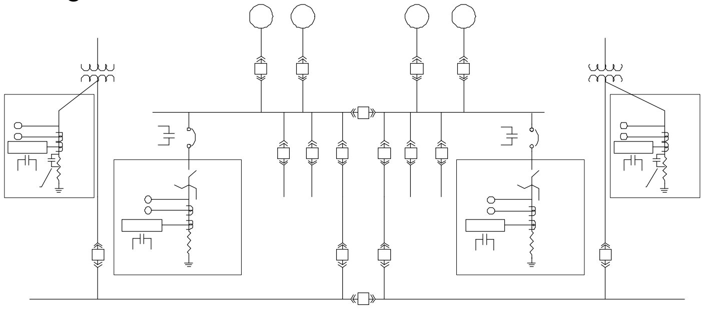

Fig. 3 Two generator busses

D. Integrating Standby power

In solidly grounded systems with distributed neutrals, if the standby generator is also grounded then the bonding path becomes parallel to the neutral and code violation occurs, per CEC 10-200 [5],and NEC 250.6 [6]. Two methods are popular to avoid this issue

a) Use 4 pole transfer switches or,

b) Remove the ground on the generator thereby having only one ground on the service neutral. Ground fault protection of the generator now becomes very involved.

These issues with the standby power are avoided when 3 wire distribution is used and further the distribution is made more reliable when generator is grounded with high resistance.

This approach allows the use of 3 pole transfer switches and allows the standby power to be resistance grounded even if the normal power from the utility is solidly grounded Fig. 4 shows an example.

Fig 4 shows an example where generator bus is grounded by a zigzag transformer, all loads are 3 phase 3 wire and the utility supply is solidly grounded and 3 pole transfer switches are used.

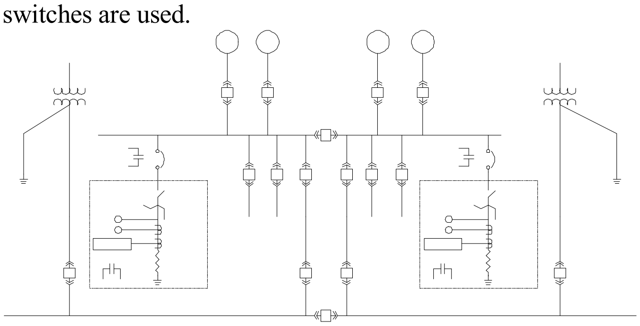

Fig. 4 Stand by generation protection

Fig 5 shows another example of grounding at the generator bus. The generator feeds are monitored by placing zero sequence sensors on each generator breaker. This monitors the generator cables and the generator windings for ground fault.

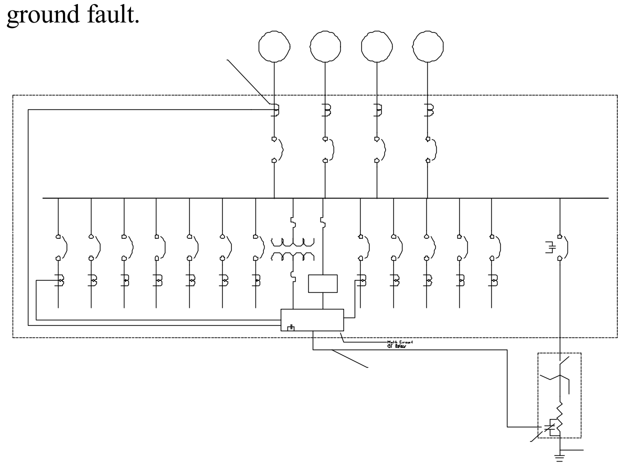

Fig. 5 HRG at the main bus

On many occasions the standby power comprises of multiple generators with provision for any number to operate in parallel. On solidly grounded systems to avoid parallel paths between neutrals and bonding when generator neutrals are interconnected, the common generator neutral must be grounded in the generator switchgear. This causes circulating current to flow on the neutral between generators which requires generator derating. Generator manufacturers provide guidance in regards to how much derating is required. When 3 wire distribution is used neutrals need not be interconnected. The generators are not grounded, the system grounding is applied at the main stand by bus through grounding transformer. No circulating current will flow, generator derating is not required, three pole transfer switches can be used and the ground fault relaying is simplified. For the generators and for the stand by feeders when HRG is used then first line to ground fault need only raise an alarm. This enhances the reliability of the stand by distribution [11].

IV. MEDIUM VOLTAGE HIGH/LOW RESISTANCE GROUNDING

A. Medium Voltage Application

Applying resistance grounding to Medium Voltage systems reduces the line to ground fault current and the potential damage at the fault location. The general rule for application of resistance grounding has been to make sure the resistor let through current (I_R) is equal to or higher than the net capacitive charging contributed by the distributed capacitance to ground in the subsystem($3I_{co}$)[4]. Using this approach most MV systems will have low resistance grounding with let through currents of 25 to 100 A.

As system voltage increases, the higher line to ground voltage, the net current contributed $3I_{co}$ becomes larger. The resistor let through current also needs to be increased and the total fault current (I_R+ $3I_{co}$) becomes substantial. The phase-to-ground fault cannot be left on the subsystem as the fault could escalate to become phase-to-phase or three phase giving rise to potentially catastrophic damage. In practice, 10 A or below can be chosen and one has the option of not tripping on the first fault. The assessment of risk of escalation is challenging above 10 A and above 5 kV. This needs to be further reviewed with modeling and tests to determine at what voltage and fault current the fault does not escalate. This will need to be investigated further for various apparatus such as cables [12], [13] and machines.

With present application rules, as indicated by the codes [5] [6], allow continuous operation for let through currents of up to 10 A and up to 4160 V. The fault can be isolated or kept energized based on the fault current and the application voltage. At 15 KV and above the fault current contributed by the distributed cable capacitance $3I_{co}$ could become larger than 10 A and the resistor let through current has to be higher than 3Ico. This causes the fault current to be high enough that it cannot be left energized and the faulted circuit should be tripped.

In resistance grounded systems, sympathetic capacitive leakage current appears on all the feeders in addition to the feeder that is faulted. The ground fault pick up level for the ground element needs to set higher than the individual feeder's $3I_{co}$. This becomes challenging when the feeder has other ground fault relays downstream. The current pickup levels and time delays have to be set apart and conventional time coordination applied.

B. Medium Voltage Generators

Generator zero sequence impedance is usually smaller than the positive sequence impedance and a line-to-ground fault close to a generator could exceed the three phase short circuit current. According to the IEEE std C37.101[14] , the generators are braced to withstand 3 phase short circuit current. It has been the practice in the past to simply add low impedance grounding to each generator. Low impedances allowing ground fault current of 1000 A or more have been applied. This practice allows a large fault current to flow. In case of a fault in the stator winding, the energy dissipation at the fault location in the stator winding can cause significant core-iron damage. Modern practice is to use hybrid grounding. The low resistance grounding provides adequate fault current to allow time-current coordination of ground fault relays and a normally closed series breaker or contactor that opens should there be a stator fault. In parallel with this low resistance is a high resistance of typically 5 A let through current which remains connected controlling the fault current until the generator comes to a standstill. This reduces the fault damage and protects the stator winding. Hybrid grounding has become of serious interest to retrofit aging older generators that are more likely to be exposed to stator failure.

C. MV distribution Systems

In the medium voltage distribution systems, typically between 5 kV and 36 kV the net charging current contributed by the distributed capacitance 3Ico can be between 10 A and 100 A. The grounding resistor thus needs to allow more than the 3Ico. A grounding resistor typically rated to allow between 20 A and 100 A can be used. These resistors need only be short time rated since ground fault protection trips and isolates the faulty feeder. Time coordinated relaying can be easily applied to ensure selectivity.

D. Hybrid grounding in MV - HRG on Generator and Additional LRG on the Main Bus

Hybrid grounding became a viable option in MV systems due to larger charging current. When generators are added and if they are individually resistance grounded then the fault current will depend upon how many generators are connected and running. This causes difficulty in setting ground fault pick up levels in relays. To avoid this, variable hybrid grounding can be applied. Each generator is high resistance grounded with a 5 A resistor. The main generator bus is grounded using a grounding transformer with an additional low resistance let through to overcome the estimated capacitive charging current. Fig. 6 shows an example of such an application.

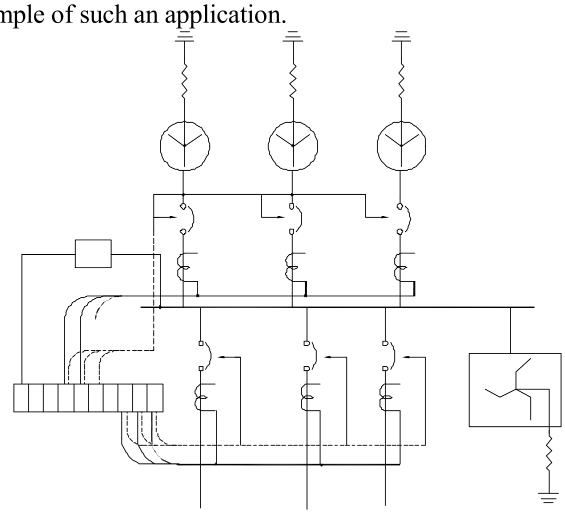

Fig. 6 Extended medium voltage hybrid system

On new installations, one or more generators, can each be high-resistance grounded and supplementary ground let through current required to overcome the net capacitive current 3Ico, can be added on the generator main bus. This allows the use of zero sequence sensors with ground fault relays to be applied for conventional time coordinated protection on the distribution. At the same time, zero sequence sensors when applied on the generator feeds at the main bus will sense phase to ground faults towards the generator and will include the stator winding as shown in the Fig. 6.

E. Hybrid Grounding for Single Large MV Generator for the Stator Winding Protection – HRG and LRG in Parallel

There are many MV generators in the 10MW to 50 MW ranges that are grounded with low resistance. This was essentially done to ensure the phase to ground current is lower than the three phase short circuit current for a fault close to a generator as the generator winding bracing is normally based on the three phase short circuit current [14]. The grounding resistor let through current is usually in the range of 400 A to 1000 A. This allows sufficient current to flow so that the electro mechanical ground fault sensing relays would operate satisfactorily using 5A secondary zero sequence CTs and the relays in the distribution systems can be coordinated. Such systems have been in use since the 50s. The generator insulation system has aged and is now more susceptible to stator winding fault to ground. Even if a stator winding ground fault is detected by a fast acting ground differential relay and if the generator is isolated, the fault continues to be fed until the generator comes to a halt after the DC excitation is removed and the prime mover is shut down. The damage at the fault location is very high due to large fault current and long time for the generator to come to a stop. Large generator damage has been reported in the literature [15] [16].–To protect the stator from such damage, the fault current has to be reduced by opening the neutral - ground path through the resistor. Since the machine should not be left ungrounded a high resistance grounding such as 5A is added in parallel with the low resistance grounding. This allows the generator to remain connected to ground while the low resistance fault current path is opened to reduce the current which then minimizes the fault damage to the windings and the machine laminations [13].

A ground differential relay that initiates the generator shut down sequence upon detection of a stator winding fault also opens the low resistance ground path and keeps the HRG in circuit. This allows very small ground current to flow and protects the machine from extensive damage. This is a very useful enhancement which can be retrofitted to existing generators which are low resistance grounded with high let through currents. Fig. 7 shows an example of generator hybrid grounded.

V MV APPLICATION EXAMPLES

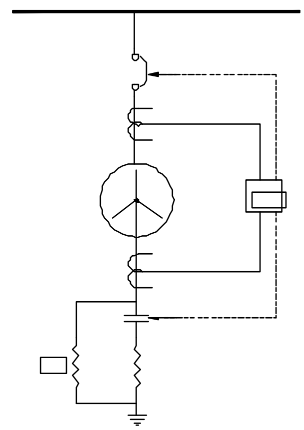

Fig. 7 Hybrid grounding system

Two medium voltage application examples are presented to illustrate the use of Resistance Grounding.

A. Deep Sea Drill Ship

This covers a case of six on board generators providing power to the propulsion system and the drilling load. Two, 11 KV, 8000 KVA, 6500 KW generators connected to each generator bus of the three generator buses.

Generator zero sequence impedance was low and this required an impedance ground. Grounding was applied to each generator bus using a Grounding Transformer with the LV secondary in open delta connected to a resistor. The propulsion load on each bus is 2X4000 KW, 12 pulse drives feeding thrusters and 5000 KVA drilling load supplied through a mutli-winding Delta-Wye-Delta transformer feeding a rectifier to the DC bus. Instead of grounding each generator, the generator bus was grounded. This kept the ground let through current through the grounding transformer constant and independent of number of generators connected. Ground let through of 10 A was selected based on an estimate of 7 A of capacitance contributed current[17]. Using a 240 V secondary on the neutral grounding transformer (NGT) the secondary resistor was rated 153 A. A 10 sec rated resistor was chosen. A Zig-Zag connected transformer with full voltage resistor could have been used just as effectively. Selective first fault tripping was applied using zero sequence sensor and GF relay set for 5 A. Fig. 8 shows the arrangement.

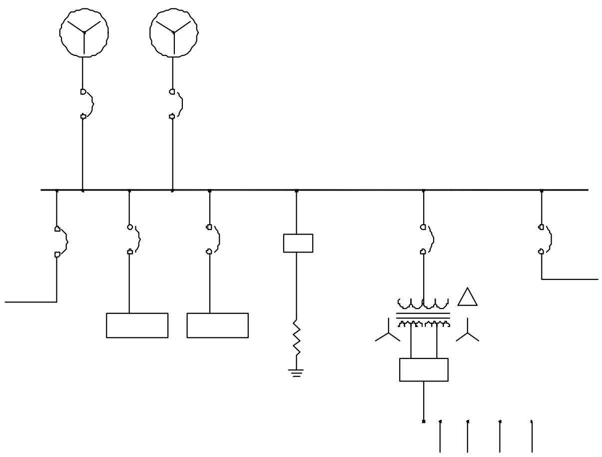

Fig. 8 Deep sea drilling electrical service

B. *Resistance Grounding MV Distribution at Mass Transit Facility*

For the 4800 V star connected transformer feeding the loads at the substation, the (NGR) rating was 2771 V (L-N), 5A. A continuously rated resistor was applied and another 5 A let through current was added to assist in fault location after the ground fault alarm was acknowledged and the faulted feeder was identified. The additional pulsing current was contributed through a MV/LV transformer with LV secondary resistor which was cycled on and off. Fig. 9 shows the arrangement.

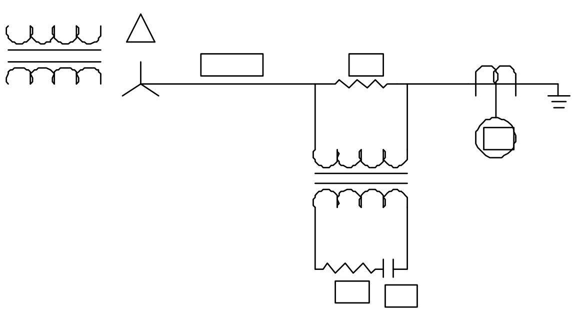

Fig. 9 Mass transit MV HRG system

VI MODELS

The current through the resistor of a NGR must conduct current that is equal to or greater than the capacitive charging current of the system. There are generally no difficulties if the ground fault is a solid ground fault.

If, however, the ground fault is a high impedance fault, the ground fault current is limited not only be the resistor, but also by the impedance of the fault. This graph shows the amount of current flowing through the fault as well as through the NGR from 0% resistor current, or 100% arcing current, to 100 % resistor current, or ~0% arcing current.

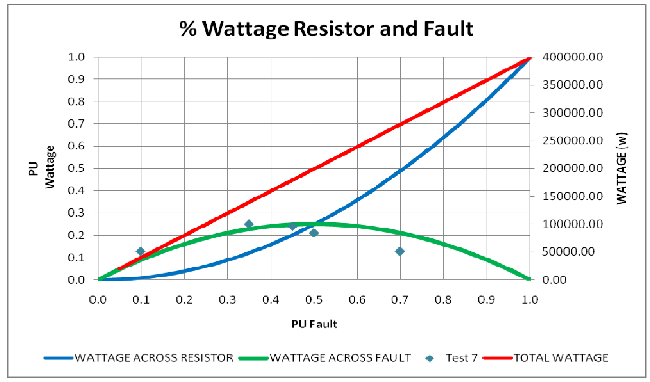

Fig. 10 Comparison of neutral and ground fault current

This figure shows the results of a 13.8kV system with a 50 A neutral grounding resistor. The rating of the resistor is approximately 400 kW. The maximum energy in the fault occurs when the fault through the resistor is 50% of rated current and the fault is a high impedance fault. This means that 100 kW is dissipated through the fault itself and 100 kW is dissipated through the resistor. This seems to coincide with the results from test 7 [10].

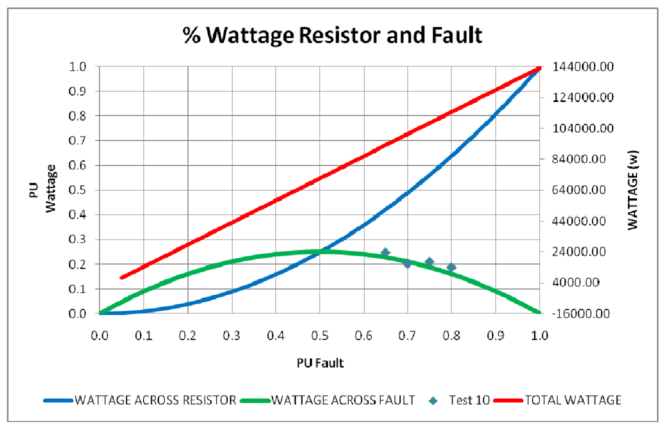

Fig. 11 Comparison of neutral and ground fault current

Fig, 11 shows the results of test 10 superimposed onto the graph. It is evident that the results closely match the model.

This test reduced the NGR current to from 50 A to 18 A. it was very difficult to sustain an arc and the arc repeatedly extinguished. 50 A proved to be too high for this system and 18 A proved to be too low to sustain an arc. At 18 A of resistive current the maximum heat produced would be at 50% or at 36 kW resistive and 36 kW arcing energy.

The capacitive charging current in this example was 13.4 A. So realistically, the resistor could have been lower to 13.4 A with no adverse affect.

VII CONCLUSION

On low voltage systems high resistance grounding provides a safer and more reliable distribution system. The arc flash hazard on line ground fault can be eliminated. The power continuity can be maintained in the event of a ground fault. The performance of the distribution system can be enhanced by using high reliability neutral grounding resistors with low temperature coefficients, by monitoring the NGR continuously, by using pulsing system to find ground faults and by using coordinated selective second fault tripping. In many applications, it is more beneficial to apply the neutral grounding resistor at the main bus and in such a case the incoming supply feeders can be monitored for ground fault very cost effectively by applying multi circuit relays.

On MV systems, the ground resistor let through current is selected to be higher than the net capacitive current. The decision whether or not to trip on a ground fault can be addressed by considering both the current level and the application voltage. It is recommended that distribution systems with multiple sources be resistance grounded at the main bus. Distribution systems with multiple generators can be hybrid grounded using HRG at the generators and additional LRG on the main bus. Older low resistance grounded generators can be retrofitted with hybrid grounding.

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