Effective System Grounding

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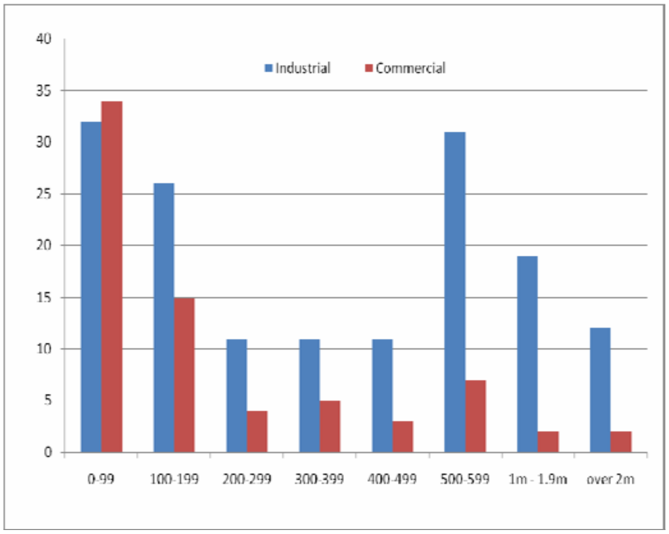
The costs associated with losses stemming from ground faults are staggering. For example, over a seven year period, the clients of a leading U.S. based insurance company submitted 228 claims of losses attributed to ground faults, resulting in payments of $180 million by the insurer. Seventy two of these claims came from the commercial and institutional sectors (hotels, shopping malls, universities, and hospitals), with an average cost of $830,000. One hundred fifty six claims were from the manufacturing sector, with an average cost of $769,000.



There are direct and indirect costs associated with ground fault generated losses. On the direct side are the costs resulting from equipment repair and replacement as well as the direct medical costs associated with injuries. On the indirect side is the cost of business interruption, in terms of unscheduled delays, employee training and redeployment, accident investigation, legal costs and possible fines, etc.

Quite often, the impact on business interruptions and other indirect costs significantly outweighs that of the direct costs. The National Fire Prevention Association (NFPA)notes that “during the five-year period of 1994 through 1998, an estimated average of 16,900 reported industrial and manufacturing structure fires caused 18 civilian deaths, 556 civilian injuries, and $789.6 million in direct property damage per year,” with electricity a major source of ignition. From this we can estimate that the average equipment and property damage from an electrical fire is almost $47,000.

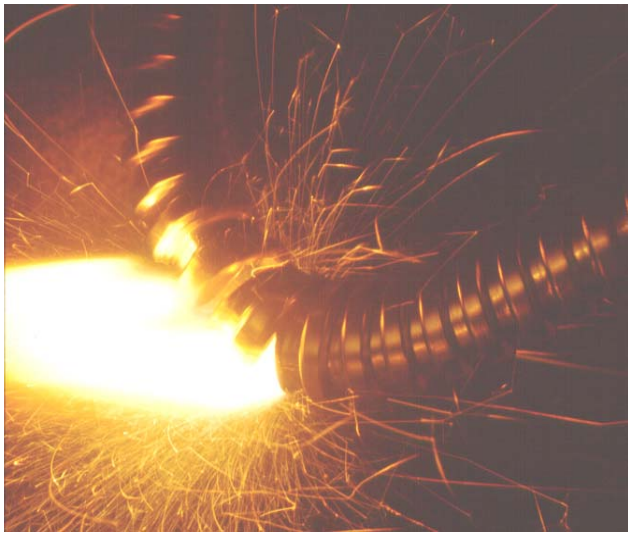
Injuries from arc flashes are a part of these losses as well. Cap Schell, a Chicago based research and consulting firm specializing in preventing workplace injuries and deaths, suggests that there are five to seven arc flash incidents per day in North America that require hospitalization.

In addition to the monetary aspect of workplace injuries resulting from electrical accidents, there is also a significant human cost, with arc flash victims suffering from chronic pain and scarring. Workers may also have difficulty re-integrating into the community, and may experience anxiety, depression, or other psychological symptoms. The social and economic costs may also be high. Workers' compensation pays only a portion of lost wages. Some workers may not be able to return to their pre-injury job. Employers bear the costs associated with lost productivity, reduced competitiveness, employee rehiring and retraining, as well being subject to increases in workers' compensation premiums.

Published data from the state of Washington notes that from September 2000 through December 2005, 350 of the state's workers were hospitalized for serious burn injuries occurring at work. Of these, 30 (9%) were due to arc flash/blast explosions. Total Workers' Compensation costs associated with these 30 claims exceeded $1.3 million, including reimbursement for almost 1800 days of lost work time. From this we can estimate that the indirect impact in terms of personnel costs for an electrical incident average over $43,000.

Business interruptions due to unscheduled downtime, repair, and spoilage varies by industry, with per hour costs ranging from $15,000 for automotive companies, to $24,000 for mining and metal companies, to $90,000 for airline reservation companies. When we add the equipment and property damage estimates to the personnel costs and business interruption costs, and then add possible OSHA fines and other indirect costs, it is quite easy to total in excess of $500,000 per incident, in line with the experience of the major insurance company previously detailed.

The common cause of the losses and injuries noted above are undetected arcing faults occurring within a facility's electrical distribution system. IEEE Std. 242-2001, *IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems*, (The Buff Book) states that "the majority of electrical faults involve ground" and that "even those that are initiated phase-to-phase will spread quickly to any adjacent metallic housing, conduit, or tray that provides a return path to the system grounding point."



When an electrical system is grounded, there is an intentional connection of a phase or neutral conductor to earth for the purpose of controlling the voltage to earth, or ground, within predictable limits. It also provides for a flow of current that will allow detection of an unwanted connection between system conductors and ground [a ground fault]. The root cause of this unwanted connection is often the result of insulation breakdown.

Unless specifically required by the National Electrical Code, the majority of industrial facilities that experience arcing ground faults continue to operate without adequate Ground Fault Protection (GFP). They typically use an ungrounded or solidly grounded electrical distribution system, both of which have inherent disadvantages.

An ungrounded system is one in which there is no intentional connection between the conductors and earth ground. However, in any system, a capacitive coupling exists between the system conductors and the adjacent grounded surfaces. Consequently, the “ungrounded system” is, in reality, a “capacitively grounded system” by virtue of the distributed capacitance.

The reasoning behind the prevalence of ungrounded systems in many industrial facilities appears to be historical. Prior to the emergence of High Resistance Grounding in the late 1980’s, the only choice when process continuity was required was an ungrounded system that allowed for the controlled shutdown for fault repairs at a convenient time. This was of tremendous value to continuous manufacturing processes because it reduced production losses, equipment damage and outages.

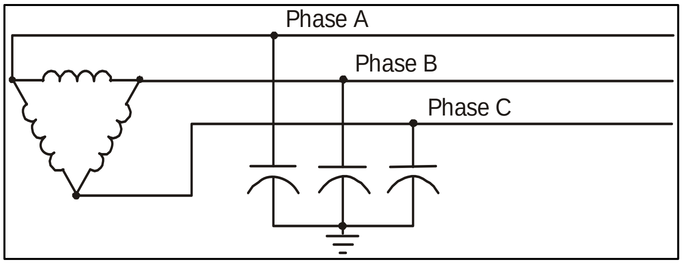
However experiences with multiple failures due to arcing ground faults has resulted in a change in philosophy over the use of ungrounded systems. This change is supported by the IEEE, specifically in The Buff Book. Section 7.2.5 of this standard offers the following perspective:

“Ungrounded systems offer no advantage over high-resistance grounded systems in terms of continuity of service and have the disadvantages of transient overvoltages, locating the first fault and burndowns from a second ground fault. For these reasons, they are being used less frequently today than high-resistance grounded systems”

The reason for limiting the current by resistance grounding may be one or more of the following, as indicated in IEEE Std. 142-2007, *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems* (The Green Book), in Section 1.4.3:

- To reduce burning and melting effects in faulted electric equipment, such as switchgear, transformers, cables, and rotating machines.
- To reduce mechanical stresses in circuits and apparatus carrying fault currents.
- To reduce electric-shock hazards to personnel caused by stray ground-fault currents in the ground return path.
- To reduce arc blast or flash hazard to personnel who may have accidentally caused or who happen to be in close proximity to the ground fault.
- To reduce the momentary line-voltage dip occasioned by the occurrence and clearing of a ground fault.
- To secure control of transient overvoltages while at the same time avoiding the shutdown of a faulty circuit on the occurrence of the first ground fault.

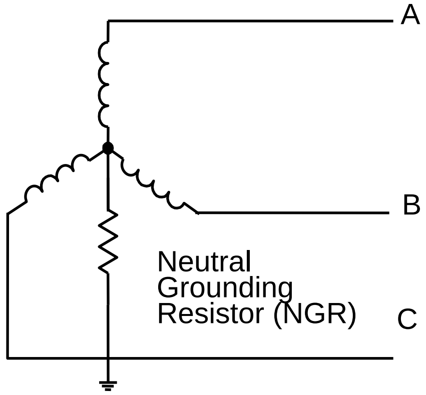
The two major questions facing the contractor or engineer when a customer wishes to upgrade and receive the benefits of resistance grounding are “How do I size the grounding resistor?” and “Where do I make the connection?” The resistor must be sized to ensure that the ground fault current limit is greater than the system's total capacitance-to-ground charging current. If not, then transient over-voltages can occur. 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. When it is impractical to measure the system charging current, the "Rule of Thumb" method may be used, as per the Table below.



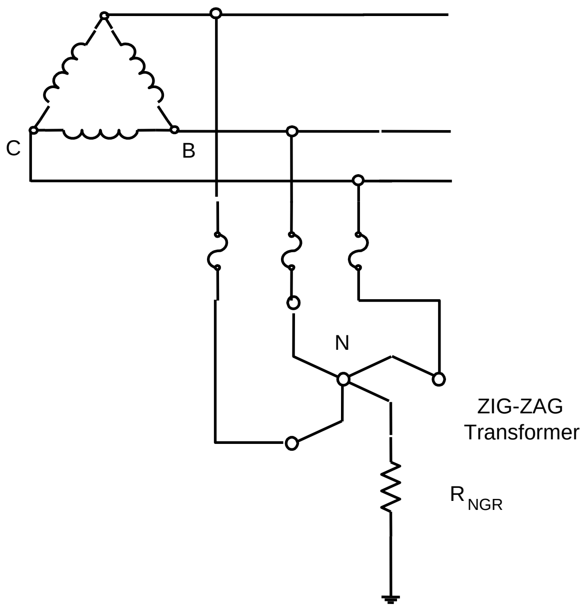
SYSTEM PHASE-TO-PHASE VOLTAGE	ESTIMATED LET-THROUGH CURRENT VS. SYSTEM KVA CAPACITY WITHOUT SUPPRESSORS	ADDITIONAL CURRENT FOR EACH SET OF SUPPRESSORS
600	1A/2000 KVA	0.5A
2400	1A/1500 KVA	1.0A
4160	1A/1000 KVA	1.5A

There is no performance downside to having ground let-through current of 5A, even on smaller 480V system with only 0.5A charging current. It is critical to have the charging current more than 0.5A and it can be up to 5A. It is unlikely that a 480V system would have a charging current larger than 5A. This would only occur if a customer has added line-to-ground capacitance for surge suppression, etc. Once the size requirement for the resistor has been determined, the next step typically would be to connect the current limiting resistor into the system. It should be noted that converting the system will not affect the metering or relaying already in place.

On a wye-connected system, the neutral grounding resistor is connected between the wye-point of the transformer and ground as shown below.



On a delta-connected system, an artificial neutral is required, since no star point exists. This can be achieved by use of a zig-zag transformer as shown below.



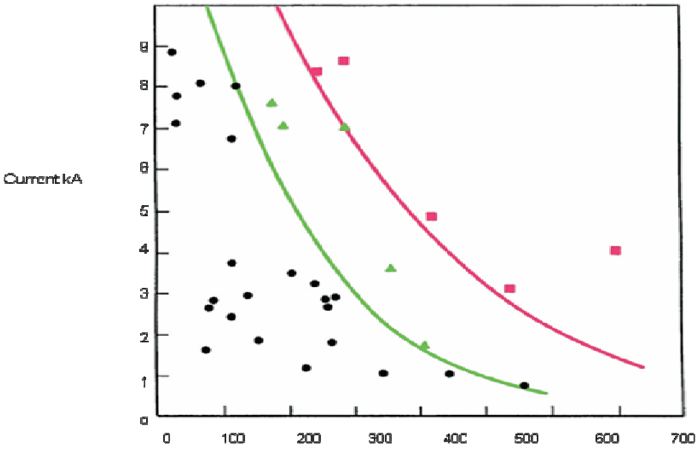
The most common grounding method in use in North America for both commercial and industrial facilities is called solidly grounding and in this method the neutral points have been intentionally connected to earth ground with a conductor having no intentional impedance. This partially reduces the problem of transient over-voltages associated with ungrounded systems, as was the primary reason for the growth of this option from the 1970’s onwards. However, this grounding method has the highest incident level of arc flash events and electrical fires.

While solidly grounded systems are an improvement over ungrounded systems, speeding up the location of faults, they lack the current limiting ability of resistance grounding and the extra protection this provides. The destructive nature of arcing ground faults in solidly grounded systems is well known and documented and is caused by the energy dissipated in the fault.

The Green Book states that “a solidly grounded system has the highest probability of escalating into a phase-to-phase or three-phase arcing fault, particularly for the 480V and 600V systems. A safety hazard exists for solidly grounded systems from the severe flash, arc burning, and blast hazard from any phase-to-ground fault.”

An arc is developed in milliseconds and leads to the discharge of enormous amounts of energy. The energy discharged in the arc is directly proportional to the square of the short circuit current and the time the arc takes to develop, i.e. energy = i^2t.

The damage resulting from the arc depends on the arcing current and time. Of these two factors, time is the most easily controlled and managed. Rules of thumb for different arc burning times are as follows:



- **35 ms or less**: No significant damage to persons or switchgear which can often be returned to use after checking for insulation resistance
- **100 ms**: Small damage to switchgear that requires cleaning and possibly some minor repair. Personnel are could be at risk of injuries.
- **500 ms**: Catastrophic damage to equipment and personnel are likely to suffering serious injuries.

The key to mitigating the arc hazard is to address the primary factors of time and fault current available. The latter can be addressed through the installation of a Neutral Grounding Resistor (NGR) into the circuit, thereby limiting the fault current anywhere from a 500A to 2000A, depending on the system.

NGRs are similar to fuses in that they do nothing until something in the system goes wrong. Then, like fuses, they protect personnel and equipment from damage.

Damage comes from two factors: the duration and magnitude of the fault. Ground fault relays trip breakers and limit how long a fault lasts based on current. NGRs limit the fault magnitude.

To improve coordination between resistors and relays and to avoid loss of protection, many NGRs are now being designed with integral combination ground fault and monitoring relays. In distribution systems employing resistance grounding, the relay protects against ground faults and abnormal conditions in the path between system and ground possibly caused by loose or improper connections, corrosion, foreign objects or missing or compromised ground wires.

NGRs limit the maximum fault current to a value that will not damage generating, distribution, or other associated equipment in the power system, yet allow the sufficient flow of fault current to operate protective relays so that the fault can be cleared.

To ensure that sufficient fault current is available to positively actuate the over-current relay and that the fault current does not decrease by more than 20% between ambient and the full operating temperature, it is recommended that the NGR element material to be specified have a temperature coefficient not greater than 0.0002 ohms / C.

The element material is critical in ensuring high operating performance of the NGR and must be a special grade of electrical alloy with a low temperature coefficient of resistance. This prevents the resistance value from increasing significantly as the resistor operates through a wide temperature range. It also ensures a stable value of the fault current for proper metering and relaying.

Low resistance grounding of the neutral limits the fault current to a high level (typically 50A or more) in order to operate protective fault clearing relays. These devices are then able to quickly clear the fault, usually within a few seconds.

The second option is to control the time component, since the arc flash hazard is quantified by the incident energy released in an arc flash and is proportional to the length of time the arcing fault persists. Therefore, arc flash hazard can be reduced by lowering time delay settings of the ground fault overcurrent protective devices.

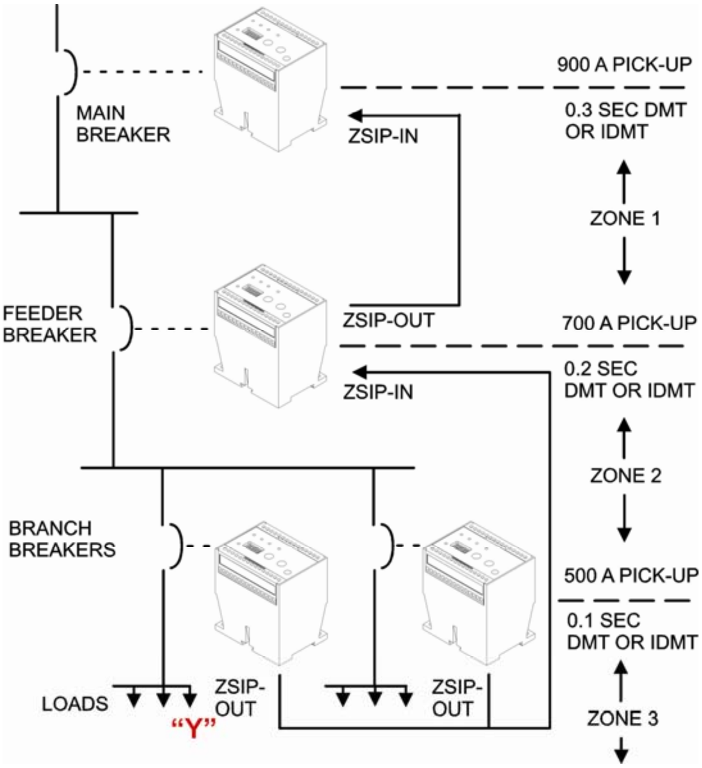
Continuity of service is important in many plants, and is maximized by time-current coordination of the ground fault devices. The drawback of time-current coordination is that extra time delay is required on upstream protection devices

Arc flash safety now overrides service continuity on switchboards that require inspection while energized.

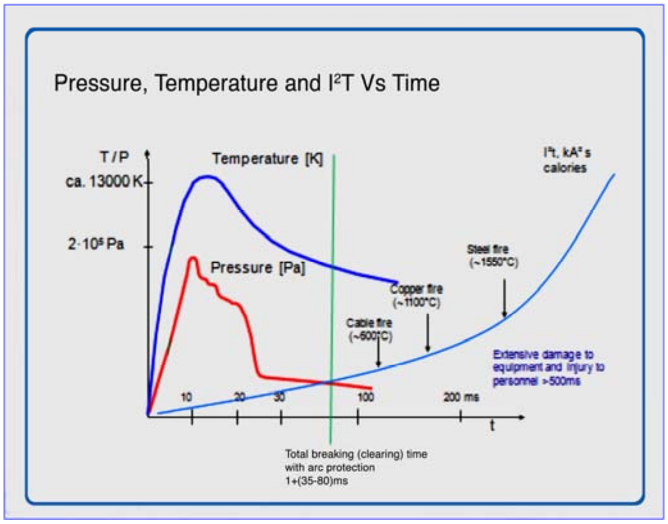
Zone Selective Interlocking (ZSI), also known as Zone Selective Instantaneous Protection (ZSIP), offers an excellent solution to this problem. It improves arc flash safety upstream in the plant distribution system without affecting service continuity. ZSI is applied both to phase overcurrent devices (on the short-time protection function), and to ground fault protective devices. It is available on electronic trip units and relays of circuit breakers.

With ZSI, a breaker that senses a fault will trip with no intentional time delay unless it receives a restraint signal from the breaker immediately downstream. If so restrained, the breaker will wait to time out before tripping. The downstream breaker only sends a restraint signal upstream if it also senses the fault, i.e. only for faults located downstream of both breakers. For the fault at point Y, the Sub-Feeder breaker will restrain the Feeder breaker; and the Feeder breaker will restrain the Main breaker. Hence the Main and Feeder will wait to time out. In the meantime, the Sub-Feeder breaker will clear the fault.

Zone selective interlocking has been available for decades, but has not been widely used because time-current coordination was deemed safe enough; damage upstream in the distribution system was a tolerable trade-off. However, the push today for increased arc flash safety means that shorter trip times will be used. The cost of the ZSI twisted pair control wiring between switchboards, panelboards, and motor control centers will now be considered a worthwhile investment because it improves arc flash safety without compromising service continuity.



The final option for solidly grounded systems is to employ optical arc detection technology.



An arc is accompanied by radiation in the form of light, sound, and heat. Therefore, the presence of an arc can be detected by analyzing visible light, sound waves, and temperature change.

To avoid erroneous trips, it is normal to use a short-circuit current detector along with one of the aforementioned arc indicators. The most common pairing in North America is current and light.

The burning of the arc heats up the ambient air, causing it to expand and create a measurable increase in pressure inside the switchgear. In Europe, it has become common practice to use the combination of light and pressure as positive indicators of an arc. The pressure sensor has an operating time between 8ms and 18ms and when combined with a circuit breaker with an operating time between 35ms and 50ms, we have achieved our goal of 100ms or less.

However, many older circuit breakers operate closer to 80ms, so these must be paired with a faster acting arc detection device. Arcs produce light at intensity levels that excess 20,000 lux. This can be detected through special optical sensors connected to a relay system that has a typical operating time under 1ms and is the fastest arc flash detection technology currently available. The operating time is independent of the fault current magnitude, since any current detector elements are used only to supervise the optical system.

With optical arc protection technology installed, the relay operating time is essentially negligible compared to the circuit breaker's operating time. Also, the cost is fairly low since current transformers are only needed on the main breakers. Again, if we sum up the circuit breaker operating time and the optical arc detection time, we are well below the goal of 100ms, regardless of the age and speed of the circuit breaker. More importantly, we have mitigated the damage to a more reasonable level.

One concern often discussed is the possibility of nuisance tripping caused by light sources that may not be an arc or may be a simple switching load. The safeguard approach is to utilize a second measurement criterion before providing a trip signal, which can be thermal, current, or pressure.

Pressure and temperature increase rapidly at the start of the arc. Also, there is a definable and measurable change in current. The combination of any two metrics provides positive indication of an arc.

The combined use of high resistance grounding for protection from ground faults and its ability to prohibit the escalation of the fault, the use ZSIP to eliminate the delays associated with time and current coordination, and arc mitigation technology including pressure sensors and optical arc detection for phase-to-phase and three-phase arcing faults is an effective engineering approach to minimizing the impact of ground faults and the arc-flash hazard and to establish an effective and safe electrical grounding system.