History

Edward L. Owen

The Historical Development of Neutral-Grounding Practices

John Dunki-Jacobs is guest author this month, recounting his views on the history of neutral-grounding practices. Dunki, as he is widely known, is eminently qualified for this task. He is a Fellow in the IEEE and recipient of the Richard Harold Kaufmann Field Award and the IEEE Medal for Engineering Excellence. Dunki continues an active career devoted to the development of and contributions to the engineering and implementation of industrial power systems. His career encompasses most of the important developments in industrial power systems occurring in the time following World War II. -ELO

Looking back on 40 years as an observer of and contributor to the changes that have taken place in the technology of industrial-system neutral grounding, this author realizes that developments in this discipline that have become accepted current practices were not always distinctly identified as significant when they first made their appearances. This may be attributed in some degree to the welter of ideas and propositions for methods of neutral-grounding that occurred over this time interval. Today, however, the technology of system grounding has stabilized and has coalesced into a limited number of neutral-grounding methods that reflect clearly on the major technical developments along the way. In retrospect it is true, as John W. Gardner has said in *No Easy Victories*, that "history never looks like history when you are living through it. It always looks confusing and messy, and it always feels uncomfortable." Mindful of both the turbulent past of the subject matter and author Gardner's maxim, I have undertaken to unfold the history of system neutral-grounding practices in a more placid manner than was characteristic, at the time, of the events described here.

The historical review given here is limited to system neutral-grounding while excluding other distinct grounding modes, such as equipment grounding, surge-arrester grounding, human safety grounding, electronic-equipment grounding, and mine-system grounding.

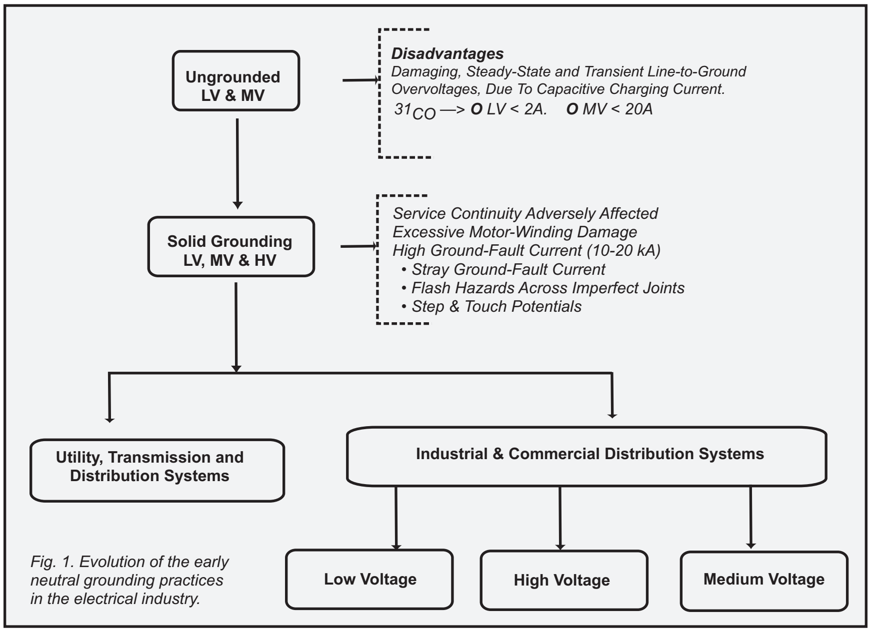

Fig. 1. Evolution of the early neutral grounding practices in the electrical industry.

The evolution of neutral-grounding practices will be described using four flow diagrams (Figs. 1 through 4), respectively depicting:

1. the early neutral grounding practices in the electrical industry (Fig. 1)
2. the low-voltage neutral grounding practices in industry (Fig. 2)
3. the medium-voltage neutral grounding practices in industry (Fig. 3)
4. the integration of these figures, with complementary notations, into a composite flow diagram (Fig. 4), showing the evolution of neutral grounding practices in the electrical industry. The heavy solid lines indicate the general progression to currently accepted grounding practices: the lighter dotted lines

indicate those practices that have been tried but generally proved unsuccessful or severely limited in their applicability. Italicized text attached to dashed call-outs associated with specific text boxes summarize pertinent experiences, elaborated on in the following text.

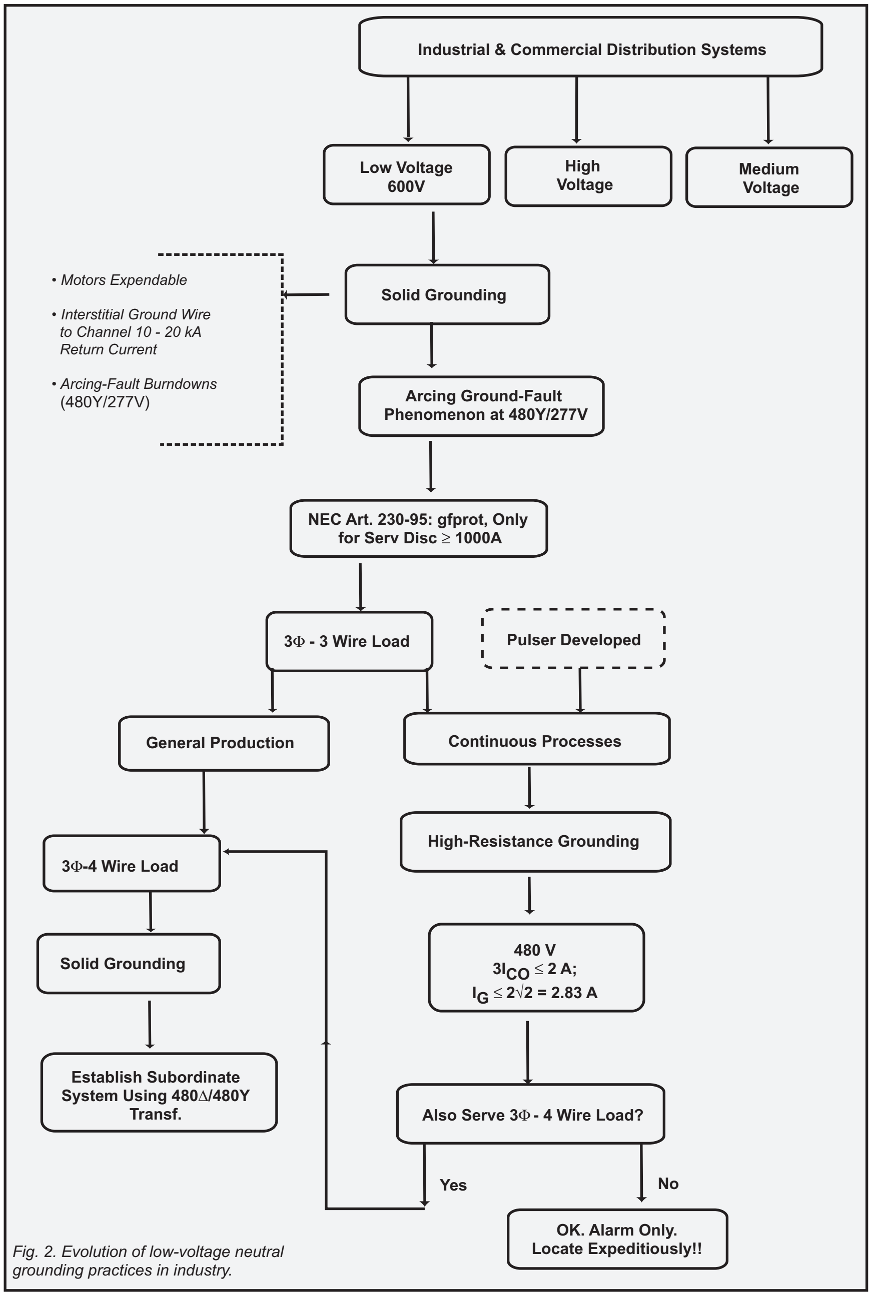

Fig. 2. Evolution of low-voltage neutral grounding practices in industry.

The Early Neutral-Grounding Experience in Industry

The time frame illustrated in Fig. 1 represents, at the topmost, the inception of three-phase ac systems, just prior to the turn of the 20th century when Edison's initial infatuation with dc systems was redirected toward ac systems, initially above all for lighting purposes. It was not until 1886 when William Stanley developed his commercially practical transformer that the first 4000-foot lighting installation at Great Barrington, Mass., ushered in the era of ac lighting. Nicola Tesla, a Yugoslav-born immigrant entering the United States in 1884, disclosed his radical concept of a rotating magnetic field leading to the first practical induction motor four years later, to provide the world with the workhorse of the industry. One year later, the first long-distance power transmission system for lighting of some 13 miles was placed in operation between Portland and Willamette Falls, Ore., while George Westinghouse introduced 60 Hz frequency in 1891, which became the standard in the U.S. In this banner year, his company not only installed the first electrical equipment for a steel mill in Bessemer Pa., for the Carnegie Steel Company, but also the first ac power transmission installation for industrial use at Telluride, Colo. In 1894, the first industrial power system, powered by two local 500 kW waterwheel generators, was inaugurated to serve a textile plant a Columbia Mills, S.C. In 1908, five 6000 HP motors (the largest ever built) produced 166 tons of rails per hour (the fastest rate in the world) at the Gary Works of the Indiana Steel Co.

These breathtaking achievements of the electrical pioneering giants came fast and furious with scant indication of the grounding mode being employed. But there is reason to believe that the early three-phase industrial power systems were operated delta-ungrounded for the practical reason that only three power conductors were required to supply the three-phase loads.

The Ungrounded-Neutral System, LV and MV

Ungrounded systems offered the obvious advantage that no unscheduled service interruption was required at the first incident of a phase-to-ground fault. The most senior of power system engineers will recall the former widespread use, on ungrounded systems, of three star-connected and neutral-grounded incandescent lamps used as ground-fault detectors. The three lamps, each glowing equally and dimly under normal conditions, would signal the occurrence of a ground fault by changing to one dark and two bright lights. Only in rare instances today is the ungrounded-neutral system still used.

In the 1940s, however, a pattern of widespread multiple insulation failures in these systems began to occur under certain operating conditions. Investigations revealed that when specific types of ground faults occurred on one phase, the unfaulted phases experienced steady-state or transient phase-to-ground overvoltages; these resulted in the observed insulation failures. Motor winding insulations were particularly vulnerable and their failure often escalated to extensive motor-core damage, resulting in expensive repairs. These overvoltages also proved to be hazardous to personnel.

The investigations established that all so-called ungrounded systems in fact are weakly and reactively grounded through the capacitive impedances to ground attributable to the insulation of the system's energized phase conductors. The studies led to representing this grounding effect, for analysis purposes, as a neutral-grounding capacitive reactance $X_{CO}/3$, where X_{CO} is the essentially balanced capacitive reactance to ground of each phase. Using Thevenin's theorem to convert a balanced three-phase system to a single-phase equivalent of the ungrounded system, it can be shown that the neutral-grounding reactance $X_{CO}/3$ forms a classic series LC (inductive-capacitive) circuit in the presence of an inductive ground-fault impedance X1. This series LC circuit may be resonant, or nearly so. If the fault inductance X1 is approximately equal to the effective grounding capacitive reactance $X_{CO}/3$. Such a fault circuit would set up excessively high *steady-state* line-to-ground overvoltages on the unfaulted phases of the actual system. Practically, these overvoltages would be at least twice normal line-to-neutral voltage E_{LN} (and possibly be much higher) for all values of X1 that are in the range from 2/3 to 2 times $X_{CO}/3$.

In addition to the foregoing, it was found that a repetitive (i.e. restriking) arcing ground fault of just the right cadence could generate *transient* line-to-ground overvoltages of up to six times $E_{LN.}$ The simple and effective solution that researchers recommended for the above problems was to ground the system neutral, thus initiating a distinct movement toward the solid grounding of electrical power systems.

As the technical explanation of the generation of these line-to-ground overvoltages is outside the scope of this article, it is helpful to take notice that the quantity $3I_{CO}$ is identified as the "total charging current" of an ungrounded system. This is a convenient quantity and label that has relevance in the technology of high-resistance grounding; it is based on the capacitive current per phase I_{CO} normally flowing to ground through the reactances X_{CO} of the insulation on the system's energized phase conductors.

Solidly Grounded Neutral Systems LV, MV, and HV

On existing *ungrounded* systems, the physical neutral point being absent therein, the principal recourse was to ground a corner of the delta. In a relatively few cases, where there was an accessible "mid-phase" connection in the delta, this was used to ground the early delta systems. As a more effectual alternative, sometimes a neutral-deriving transformer (NDT) was used to furnish a neutral point for solid grounding, or occasionally to permit applying a neutral resistor to reduce the ground-fault current to a minimum, since this would reduce considerably the physical size and investment otherwise required for an NDT if it is solidly grounded.

In *new installations*, the simple specification of a delta-wye rather than a delta-delta connection of transformer windings gradually resulted in wye-connected neutral-grounded systems superseding delta systems. For ground-fault protection purposes, the transformer specification also required that the neutral of the wye winding be brought out through an insulating bushing.

The consequences of grounding the neutral were distinctly different in utility systems than in industrial power systems for the reasons described under the following heading, that compelled the individual evolution of separate grounding practices.

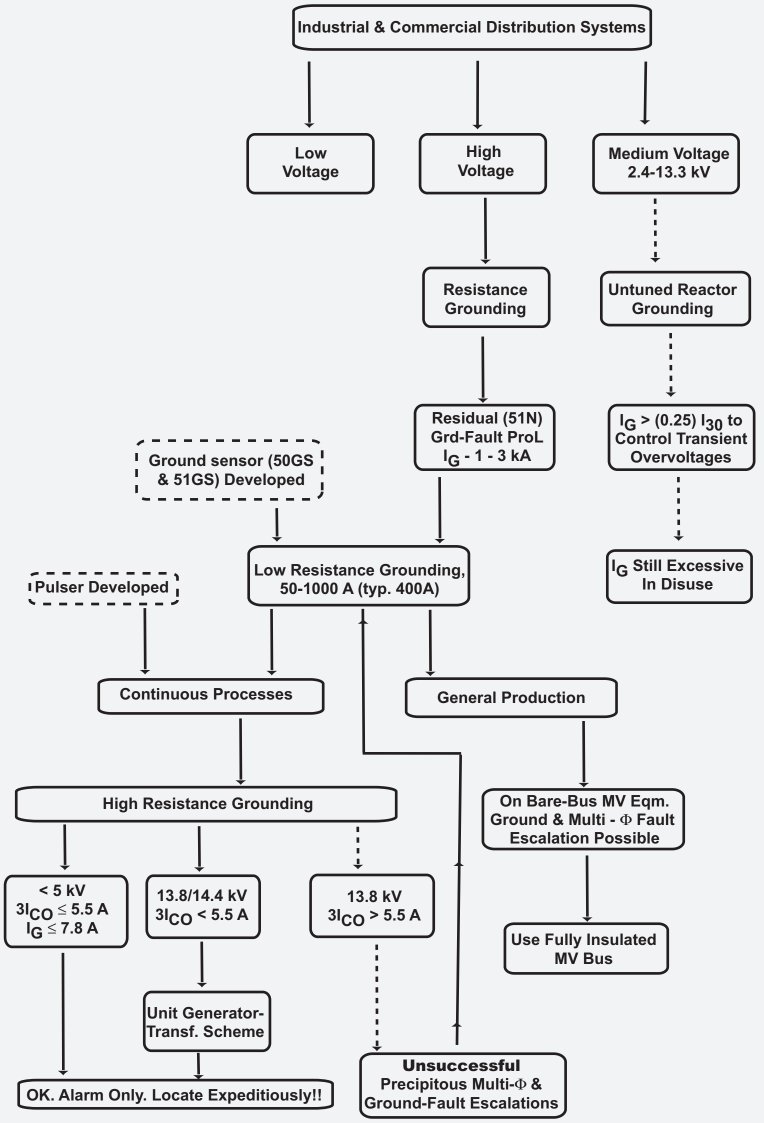

Fig. 3. Evolution of medium voltage neutral grounding practices in industry.

Differentiating Between Industrial and Utility Practices

Through the last 50 years, industrial-system design engineers have developed a rationale for having specific neutral-grounding practices that differ from those of their utility colleagues (see the lower portion of Fig. 1). Their primary reasoning is that *industrial systems* serve as dynamic load characterized by a multitude of transformers, motors, and switching- and control-centers. These power distribution and utilization equipments are interconnected by cable circuits at medium- and low-voltage levels and operate in a confined, high-investment area in which personnel generally are present and where hazardous or explosive atmospheres may be present. Also, sensitive electronic equipment scattered throughout the industrial plant must operate without fail in the presence of harmonics, and in conjunction with high-power equipment and circuits. In contrast, *utility systems* employ high- and medium-voltage, open-wire transmission and distribution circuits covering a broad area, and generally terminate these in widely dispersed step-down transformers serving residential-area low-voltage loads consisting largely of lighting, resistance-type heaters, and numerous small

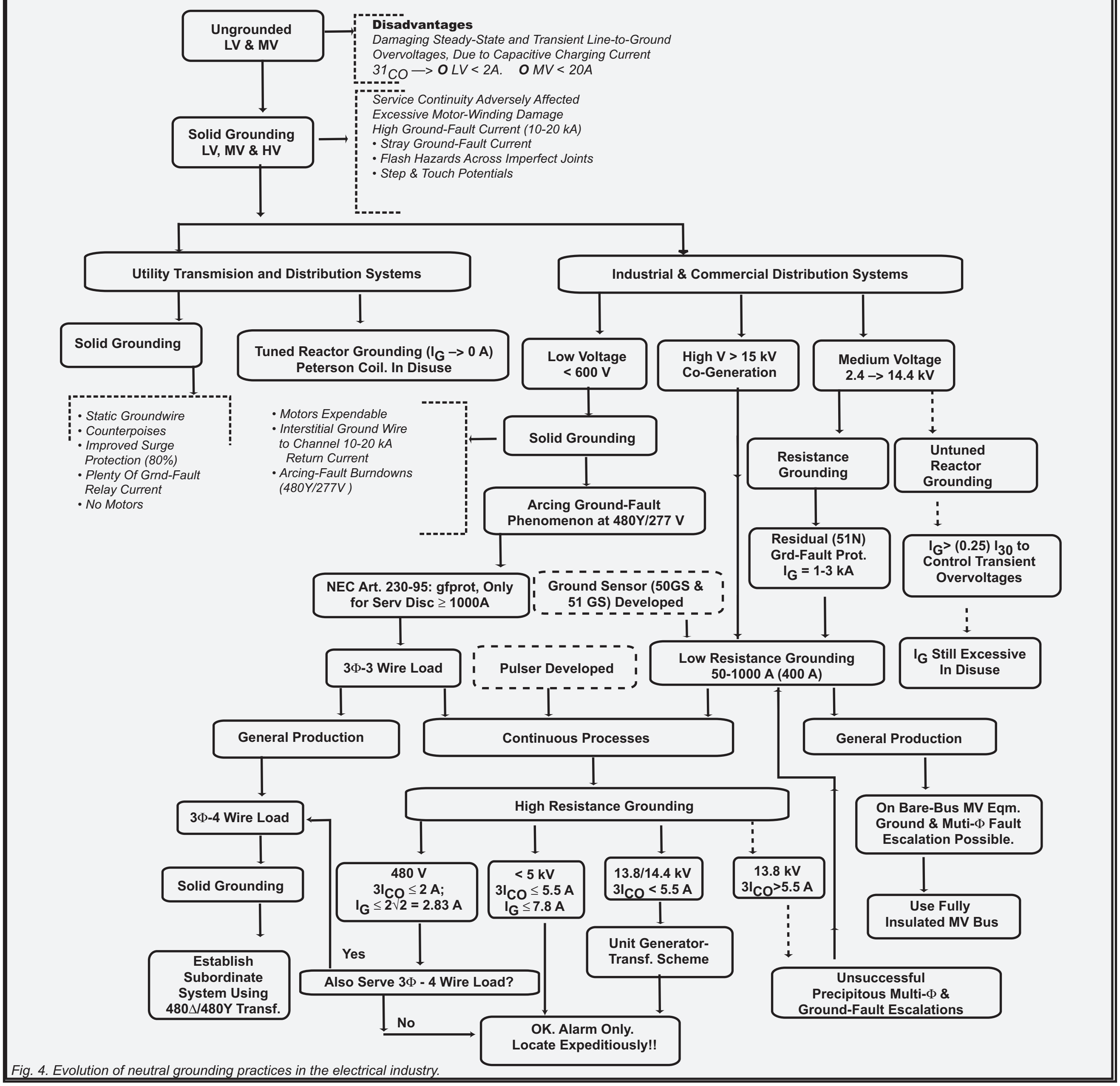

Fig. 4. Evolution of neutral grounding practices in the electrical industry.

motors. Only in the utility substations serving industrial plants or co-generation plants do the industrial and utility power systems have a common interface.

It should be clear from the foregoing that the dissimilar characteristics, loads, and operating requirements of industrial and utility power systems resulted in different neutral-grounding practices. Therefore it is appropriate that the evolution of these practices be discussed separately, beginning around a half-century ago with the movement, in industrial plants, away from the almost universal use of (ostensibly) ungrounded delta power systems and toward various and expectedly more advantageous modes of grounding. Primarily due to economics in investments in electrical power equipment and protective devices, diverse design practices emerged that obviated the need to select unique grounding modes for low-voltage and medium-voltage systems.

The early users of solid-neutral grounding were averse to accepting service interruptions in the event of the first ground fault. Also, solid grounding required that they become proficient in designing and handling power systems which produced large magnitudes of ground-fault current, approximating three-phase fault currents of about 10-20 kA at all voltage levels. Their cumulative experiences soon pointed to additional drawbacks associated with solid grounding, such as stray ground-fault currents which created step-and-touch potentials, or flash hazards created at imperfect joints and bonds as returning ground-fault currents traversed conduits and raceways. In the early ’60s, tests were made and techniques developed to analyze the behavior of ground-return circuits These measures resulted in the identification of acceptable Z_O/Z_1 ratios for ground-return circuits, to assure their adequate performance. Also in the early ’60s the interstitial ground wire became an essential component of interlocked armor cable, while three-conductor cable with a bare ground-return (fourth) conductor became standard in conduit and aerial cable installations.

Damage inflicted on motors by winding ground faults was particularly distressing since such faults generally involved burning of core iron, requiring its expensive restacking. Industrial operators resolved their plight by retaining, at low-voltage only, solid grounding’s advantages (i.e., simplified protection mostly), while accepting the probability of destructive loss of low-voltage motors for internal ground faults, essentially designating these motors as expendable. The increasing use of larger, and thus more costly, motors requiring operation at 2.4 and 4.16 kV, however, created an industry demand for some form of resistance-limited grounding mode for medium-voltage systems.

Arcing Ground-Fault Phenomenon

In the ’60s too, a number of devastating electrical burndowns of motor control centers and switchboards in solidly grounded 480-V wye systems became headline stories. Generally, the affected equipment had been property protected for assumed maximum bolted-fault currents. Subsequent research and tests determined that the burndowns were caused by *arcing* faults to ground (as distinct from *bolted* ground faults); the explosive and eruptive behavior of these arcing faults often was characterized by greatly reduced short-circuit currents, compared to bolted faults (which, remarkably, at the point of fault are quiescent). For an arcing ground fault at 480 V, for example, a reduction to a probable minimum of about 38 percent of the three-phase bolted-fault current value was representative. Direct-acting trip devices, properly set, were generally slow or, if not optimally set, unable to respond to these low short-circuit current levels, and thus failed to provide protection. The 1972 NEC introduced Article 230-95 requiring that the service disconnecting means (read: transformer main secondary breaker) for these solidly grounded systems, if rated 1000 A or more, be provided with ground-fault protection. Coordination with downstream protectors was beyond consideration.

Ever since, solidly grounded three-phase, three-wire systems have been used to serve general production loads. Subordinate line-to-neutral loads, requiring more expensive three-phase, four-wire systems, can be served more effectively from the three-wire 480-V system using one or more smaller sub-system three-phase transformer(s) rated 48OΔ-480Y V, solidly grounded on the secondary.

Continuous Process Plants

The loss of service due to the first ground fault, inherent in solidly grounded systems, was of great concern to the designers and operators of continuous-process plants, who desired a reduction in the ground-fault current to a level that would allow the system to operate with one, unremoved ground fault. Additional research and experimental system operations aimed at limiting the ground-fault current to that normally commensurate with an ungrounded system–a level that only a decade earlier had been identified in ungrounded systems as being responsible for transient phase-to-ground overvoltages. Researchers now determined that these overvoltages could be controlled by inserting, between the system neutral and ground a high resistance that, under ground-fault conditions, would allow a resistor current I_R to flow at least equal to the total charging current of the system, previously identified as 31_{CO}. This new grounding technology, known as the high-resistance-grounded concept [1], became practical and its acceptance assured by the further development of portable ground-fault detectors employing the “pulsing” scheme of detection.

High-resistance grounding.

Presently, high-resistance grounding is in common use in plants where process continuity is an overriding consideration. To successfully apply this mode of grounding there must be a management commitment to locate and remove the first ground fault at once to preclude its potential escalation to a phase-to-phase fault, especially for faults occurring in motor and generator windings. The probability of such escalation is to a large extent influenced by the so-called I^2t energy (in amperes^2-seconds) released at the point of fault. Thus, the determining co-factor is the value of the total enduring ground-fault current, $I_G = \sqrt{I_R^2 + (3I_{CO})^2}$. At 48OV, high resistance grounding has become widely accepted because the $3I_{co}$ value of a typical 1000-kva system is less than 2A. If the neutral resistor then is selected to make its current I_R to exceed slightly the value of $3I_{co}$, the ground-fault current I_g will not be more than 3 A. Operational experience has proved that this small total ground-fault current almost assures fault escalation will nor occur within the time needed to expeditiously locate a ground fault and isolate its circuit.

The Medium-Voltage Neutral Grounding Practices in Industrial and Commercial Distribution Systems

Low-resistance grounding.

In the early resistance-grounded systems, limiting bolted ground-fault current to a low value was inhibited by the relative insensitivity of the only available ground fault protective devices, namely, residually connected (time-overcurrent 51N, or a unique instantaneous 50N) relays. As the ratio of its phase CTs essentially determined the 51N relay’s sensitivity, 1000/5-amp CTs serving a relay with a minimum cap of 0.5 A would provide pickup at 100 primary A. Based on the general rule that the available fault current should be at least10 times the relay’s sensitivity, the neutral resistor then had to be selected to limit bolted ground-fault currents to not less than 1000A, a level well beyond the nominal range (50-400 A) of low-resistance grounding. The amount of burning damage at 1000 A or more was considerable, considering the delayed operation of the time-overcurrent 51N relays. Not until the introduction of “ground sensor”-type relays, with a sensitivity of 5 primary A and an operating time of two cycles, was it feasible to apply neutral resistors limiting bolted ground-fault currents to not less than 50 A? This would be an appropriate current level for the simplest of “ground-fault islands”[1], such as a unit-transformer-motor scheme, which requires only one ground-fault relay. A more typical single-source (radial) ground-fault island, consisting of only one neutral resistor, but requiring two or more coordinated series-steps of ground-fault relays—possibly including a bus-differential relay—may require 400 A. In an extensive multi-source ground-fault island (a double-ended substation with a normally-closed tie) with multiple coordinated ground relays in series, may result in a total ground-fault current value of up to 1,000 A. Today, the low-resistance grounding mode has become the universal preference for medium-voltage systems serving most industrial production operations, which typically comprise a

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[1] A *ground-fault island* is defined as “a neutral-grounded system within which a ground-fault (zero-sequence) current flows as an outgoing unbalanced phase current, and returns in a ground-return path to its source neutral and therefore can be detected by ground-current-responsive devices. External to the ground-fault island, its ground-fault current is converted (by specific transformer connections) into equal outgoing and return *phase* currents, and thus not detectable by ground-fault protective devices.

large number of motors.

High-Resistance Grounding

Operators of medium-voltage continuous process operators, as in the case of low-voltage plants, prefer high-resistance grounding for their medium-voltage systems. Operating experience and limited research indicate, however, that high-resistance grounding can be successfully applied to systems operating at 2.4 and 4.16 kV, only when the total charging current, $3I_{co}$, does not exceed about 5.5 A. Thus, the ground-fault current is limited to about 8 A In assessing the $3I_{co}$ value, include any 0. 5 uF/pole machine surge-capacitors, each adding 0.78 A at 2.4 kV and 1.35 A at 4.16 kV, but exclude power-factor capacitors.

At 13.8 kV, the total charging current is much higher (than 5.5 A) if only for the reason that typically such systems are much more expansive. Known references suggest that there are no successful 13.8-kV high-resistance grounded systems, relying strictly on an alarm to reveal the occurrence of a ground fault. Such a single line-to-ground fault tends to escalate to massive multi-phase and ground faults, before the initial fault can be located and its circuit de-energized. The notable exception is the 13.8 or 14.4 kV unit-generator/transformer scheme, in which a large generator is direct-connected to a transformer stepping up the voltage to 69 kV or higher. In this bounded ground-fault island operating at generator voltage, the 0.25 uf/pole surge capacitor contributes 2.25 A, which may be most of the total charging current.

Fault Escalation on Bare Bus Medium-Voltage Equipment

Long after the industry had come to grips with arcing burn-downs occurring on solidly-grounded 480-V systems, there were reports in the late ‘70s of a few isolated instances of devastating escalation of an arcing-fault in resistance-grounded medium-voltage systems, this despite the presence of the normal complement of properly-set ground-fault relays. It is reassuring to report, fortunately. chat such incidences appear to have been limited to equipments with bare buses operating at 2.4 or 4.16 kV. Prevention of such devastating events requires fully-insulated buses and their connections (to PTs, arresters, etc.), which is a standard feature of all 5 kV and 15 kV switchgear equipments.

Untuned-Reactance Grounding

In the early attempts to minimize the ground-fault current in solidly grounded medium-voltage systems, copying the utility practice of using neutral reactors was found to be impractical since, in order to control the transient-overvoltage problem inherent in ungrounded systems, the untuned grounding reactor had to limit the ground-fault current to not less than 25% of the prevailing three-phase short-circuit current. For example, in systems with a typical available three-phase fault current of 20,000 A, reactance grounding would require the minimum ground-fault current to be 5,000 A, an unacceptable value for industrial grounding purposes.

The Grounding of High-Voltage Systems Inside an Industrial Plant

In the more recent decades, 34.5-kV and 69-kV systems have made their appearance in large industrial plants for the reason that their power systems had outgrown the usefulness of 13.8 kV as a synchronizing voltage level. In other cases, co-generation facilities were to be superimposed on an existing medium-voltage in-plant power system. Such high-voltage intrusions are typically the consequence of tying into a utility company system, which neutrals are invariably solidly grounded, as explained under the next heading. However, to the extent that these high-voltage circuits are routed as overhead or cable circuits inside the industrial plant perimeter, it is essential to secure the long-established features and characteristics of industrial-plant grounding (viz. low-resistance-neutral grounding) by extending this preferred grounding mode to these intruding high-voltage systems. Thus, a utility inter-tie consisting of a 230-34.5 kV transformer to establish, or interconnect to, a 34.5-kV industrial synchronizing bus, should employ a delta-wye connection (or its equivalent), with the 34.5-kV winding neutral grounded through a single phase “neutral grounding transformer” or NGT. By connecting the secondary wiring of the NGT to an appropriate standard medium-voltage grounding resistor package, the 34.5-kV system could be caused to be low-resistance grounded; possibly as low as 100 A per neutral. Protective systems, incorporating primary and back-up relays, can be designed to perform adequately under these low-level ground-fault currents. The most effective location of inter-tie transformers is at the plant perimeter, to assure that a large ground-fault current due to a fault on the inter-tie transformer’s primary system will not be experienced within the plant’s perimeter.

The Grounding Practices in Utility Transmission and Distribution Systems

Unlike those of industrial systems, utility substations and circuits generally are located and operated in restricted areas and rights-of-way. Not surprisingly, then, the grounding practices of utility transmission and distribution (T&D) systems (but not of their generating plants) differ from industrial procedures. T&D systems generally are operated with solidly grounded neutrals, to secure the unique advantages of this mode of system operation as well as its distinct surge- and overcurrent-protection suitability. The characteristically high ground-fault current magnitudes of solid grounding require overhead static wires and/or buried counterpoises to safely carry about 20,000 A of ground current from the point of fault to the source neutral. The early attempts of utility engineers to reduce these ground-fault current magnitudes included experimentation with “tuned reactor” grounding, in which a variable-inductance neutral reactor XL was tuned to the capacitive reactance co ground of the system, $X_{co}/3$. On the occurrence of a ground fault the combination of these capacitive and inductive reactances then appeared to the system as a tuned parallel circuit of high impedance, limiting the ground-fault current to a value approaching zero amperes Also known as the “Petersen coil” [2] or “ground-fault neutralizer,” this grounding mode gained popularity for a time in Europe but gradually fell into disuse, due in part to the complexity of the equipment required and to the eventual improvements made in ground-fault protection technology.

Acknowledgement

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-*J.R. Dunki-Jacobs*