ANALYSIS OF GROUNDED AND UNGROUNDED PHOTOVOLTAIC SYSTEMS

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ABSTRACT

Grounding has always been a subject of controversy during discussions of electrical systems. Grounding techniques and requirements, like language, vary from region to region and country to country. Optimized grounding for personnel protection does not optimize the fire safety of a system and grounding for fire safety does not optimize personnel safety. Grounding to provide protection for equipment requires a third set of requirements. Photovoltaic (PV) systems are current sources and require different grounding techniques than conventional voltage sources. Distributed leakage paths, multiple fault paths, and new roles for fuses and circuit breakers are among a few of the new issues that need careful consideration. This paper presents and analyzes the grounding issues associated with PV energy sources. Grounding configurations, faults, personnel safety, fire safety, and surge protection are addressed.

INTRODUCTION AND BACKGROUND

When early power generation and electrical distribution systems were being developed in the late 1890's to the early 1900's, grounding issues were the subject of many debates. The requirements were not agreed upon at that time and the result has been different requirements and codes in different countries throughout the world [1]. In the United States, the *National Electrical Code* (NEC) was first published in 1897. Most countries independently developed their own version of an electrical code that addressed the installation and grounding issues for electrical power systems.

The first grounding requirement in the NEC was a mandatory earth-grounding requirement to minimize lightning damage. The grounding debate began a few years later when it was suggested that the secondary distribution circuit of ac utility grids be grounded. It was immediately argued that grounding secondary circuits carrying hazardous voltages increased the probability of shocks. Counter-arguments cited the added safety features that limited the maximum voltage imparted on the secondary distribution circuits should a primary circuit be accidentally connected to a secondary circuit. The discussions and arguments have continued, and international standards have never been written. The PV industry is now poised to further complicate the issue of grounding electrical systems throughout the world.

PV codes and PV system grounding requirements have followed the codes for electrical power systems. In the USA, Article 690 on PV systems was added to the NEC in 1984, but NEC grounding practices were used before 1984. European codes have also followed the national practice of the individual countries for ac power, but the PV codes are being developed as stand-alone documents rather than being integrated in existing codes.

PV systems range in size from single-module, 12-volt systems through hundreds-of-watt systems with storage batteries, to multi-megawatt systems operating at thousands of volts connected to the electrical utility grid. System and equipment grounding practice and legal requirements vary widely between countries and sometimes within a particular country. Codes in the USA require equipment grounding of all systems, and system grounding for systems with voltages over 50 volts (open circuit module voltage) [2]. European codes require equipment grounding, but do not require systems grounding, and most European PV systems do not have a grounded current-carrying conductor [3].

GROUNDING ISSUES

General: Grounding or "earthing" various metal parts and conductors of an electrical system is intended to reduce the effect of faults by minimizing electric shock and fire hazards, to reduce damage to equipment from induced surges, and to reduce the incidence of electromagnetic interference [4]. System grounds provide grounding paths for the current-carrying conductors, whereas equipment grounds provide grounding paths for the metallic surfaces that may be unintentionally energized. Equipment grounds ensure that those surfaces remain at or near ground potential.

Systems are solidly grounded to limit the magnitude of the voltage to ground during normal operations and to reduce induced voltages due to lightning, switching transients, or line surges. Grounding of electrical systems stabilizes the system voltage during surges and also provides a path to trip protection devices if there is unintentional contact with higher voltage lines.

PV Systems: PV system electrical schematics rarely show all of the electrical parameters. Stray inductance, capacitance, and resistance abound and are distributed throughout the system. Leakage currents associated with the array, wiring, surge protection, and conduits often make fault detection difficult. The leakage currents associated with all of the system elements pose unseen and unfamiliar hazards to personnel, and may contribute to fault currents and fires. Improperly selected or improperly installed cables, diodes, PV modules, and other components have failed in PV systems.

PV systems are frequently connected to other sources of

First WCPEC; Dec. 5–9, 1994; Hawaii

power or energy storage devices such as battery banks, standby generators, hydo generators, wind turbines, and the utility grid. The grounding of the PV system must be consistent with the grounding used on the connected power system.

The interface between connected power systems may allow unanticipated currents to flow in the PV system. These fault conditions must be accounted for in the design of the PV grounding system [4]. Utility interconnected PV systems are often installed in close proximity to utility power lines, and accidental cross connection is a possibility that must be addressed.

There has been only one well documented electrical shock case relating to PV systems in the USA [5], and there have been several fires resulting in substantial damage [6]. General grounding practices were followed in all cases, but the uniqueness of the PV energy source contributed to conditions that allowed fire dangers to exist.

PV SYSTEM GROUNDING CONFIGURATIONS

General: In this paper, grounding is defined as connecting a conductor or piece of equipment to earth or ground potential with a low-resistance and low-impedance conductor. The grounding conductor must be sized to carry the same fault current that any other conductor in the system is sized to carry. System grounding with single-point grounding, and equipment grounding with solid, low impedance bonding of multiple grounds, provides an equipotential ground for surge protection and minimizes circulating ground currents that can lead to corrosion and ground-fault detection problems. The grounding configurations for PV systems may differ greatly [7]. Figure 1 shows a PV system with single-point system and equipment grounding.

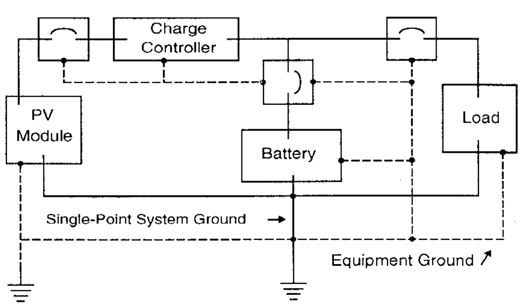

Figure 1. Equipment and System Grounding

IEEE JW 12/94

Ungrounded: A totally floating or double insulated system (Type II insulation) has none of the current-carrying conductors grounded, and any exposed metal conducting surfaces are effectively double insulated from the current-carrying conductors. There is no requirement for the exposed conducting surfaces to be grounded.

An ungrounded PV system with only equipment grounding has all of the exposed metal surfaces grounded that could possibly come into contact with energized sources. These surfaces typically include the module frames, metal enclosures, distribution panels, inverter housings, and the chassis of end-use appliances. Most codes require equipment grounding in all PV systems [3].

Grounded: A PV installation with system grounding has one of the current-carrying conductors grounded. System grounding almost always is used with equipment grounding since the two systems complement each other in interrupting fault currents.

FAULTS IN PHOTOVOLTAIC SYSTEMS

General: Faults are defined as currents flowing in other than the normally designated current-carrying conductors. The magnitude of fault currents depends on the impedance of the fault path. Faults are generally localized and not distributed. Fault currents may pose fire and electrical shock hazards. Leakage currents are small in magnitude, are distributed throughout the PV array and system components, and are associated with high voltages (>100V). The leakage currents in an ungrounded PV system create a distributed high-resistance ground connection, and can allow sufficient ground fault current to injure personnel.

PV modules can develop leakage currents as they age, especially in wet conditions. The leakage comes from module currents flowing to the outside frame or surface of the module through the edge seal or through other deteriorated insulating membranes. Faults can evolve from continuous leakage when carbon or metal is released or deposited by the minute leakage current. Module junction boxes can accumulate water, either from condensation or rain, and this water, when coupled with airborne debris or corrosion products, creates leakage paths within or external to the junction box. Leakage currents also occur as the insulation on conductors ages or is damaged due to abrasion [6].

Insulation failures between current-carrying conductors of opposite polarity cause bolted, line-to-line faults. The current flow into bolted faults can be from PV modules in the faulted circuit, from modules connected in parallel with the faulted circuit where blocking diodes are absent or shorted, or from external sources such as batteries or inverters. Blocking diodes have failed frequently in PV installations and have allowed multiple PV strings to contribute to the fault current [6]. Inverters even under normal operating conditions can feed ac utility currents into faults in the dc array wiring.

Insulation failures between current-carrying conductors and the ground are known as ground faults. Ground faults can develop within the PV array, in circuits that have electrically combined the array, or in switches and inverters. Ground fault detectors must be used to sense ground faults in both grounded and ungrounded PV systems. The sensitivity of ground-fault detectors for ungrounded systems should be higher than for grounded systems. The practical limit for ground-fault sensitivity is limited by wet-weather leakage currents. More than one ampere has been measured in a 300-kW system in the USA. Single-point grounds are necessary to minimize circulating ground currents that may interfere with ground fault detectors and pose hazards.

Ungrounded: On ungrounded systems, a single ground fault will not cause fault currents, but a second ground fault in conductors of a different voltage will allow fault currents that circulate through circuits associated with the two faults [6]. PV array modules and conductor capacitance to ground can contribute significant shock hazards in the form of a capacitive discharge on ungrounded systems. Resistance grounding can eliminate the charge on these distributed capacitances.

Grounded: On grounded systems, the first ground fault will cause currents to flow. The location of the fault and the source and magnitude of these currents may cause overcurrent devices to function and interrupt the fault currents. Distributed capacitances are a lesser problem because they are already ground referenced and act in the same manner as the other grounded current sources.

PERSONNEL SAFETY

General: The requirement for the safety of users and maintainers of electrical power systems has been the basic impetus for the study and application of grounding to electrical power systems. Much of the research on electrical shock has been derived from studies on human volunteers and animals [8].

Research has defined the term "let-go" as the current level, either ac or dc, where the subject in contact with the electrical circuit experiences involuntary muscle contractions to the point where he or she is unable to disengage from the circuit. The effect of currents through the body are a function of the applied voltage, the resistance of the body, and the path through the body. Although varying greatly, the average body resistance is assumed to be about 1000 ohms. Biological and situation variations can cause this value to vary over a ten-to-one range [9]. While the "let-go" level of current may not be fatal, higher levels of current can cause the heart to go into a rapid useless beating called ventricular fibrillation.

The values of "let-go" and ventricular fibrillation currents are higher for dc circuits than for ac circuits. Men are less susceptible to these currents than are women. DC "let-go" currents are in the range of 90 milliamps (dc) for men and 60 ma. for women. Ventricular fibrillation currents are between 500 and 1300 ma. for men and women [9].

Ungrounded: It is thought that a floated, ungrounded, electrical system is safer to work on and service than is a system in which one of the current-carrying conductors is grounded [4]. With an ideal ungrounded system, contact between one of the conductors and the earth, or a grounded conductor, cannot result in a current path. This is true only of theoretically ideal systems with no leakage and no capacitance to ground. However, the average PV installation has many leakage resistance paths to ground and distributed capacitance between module wiring and ground.

With resistive leakage paths to ground, accidental contact with the conductors of the ungrounded system results in a closed circuit for shock currents. Even with no leakage to ground, the ungrounded system, with its distributed capacitance to ground, can impose a shock experience during the capacitive discharge which can cause involuntary muscle contractions that result in other injuries.

Leakage paths and capacitance generally result in ungrounded systems that have the voltages referenced to ground and leakage currents to ground The Class II systems proposed in parts of Europe will minimize these factors by ensuring a more ideal ungrounded system. If Class II guidelines and hardware are not used in ungrounded systems, both conductors can have voltages that are theoretically higher than the normal operating system voltage. For example, a 300-V system would typically have balanced line voltages that are approximately 150 volts to ground. If one conductor develops a leakage to ground, the second conductor will have 300 volts to ground. Additionally, static charge may build up in an ungrounded system and the resulting conductor voltage to ground may be greater than the operating voltage of the system.

Grounded: In a grounded system, in which one current-carrying conductor is grounded, or the system is center-tap grounded, the system voltage is stable, and the highest voltage appearing on the ungrounded conductors, except when large surge currents are induced into circuits, is the normal system operating voltage. During nearby lightning strikes, the conductor voltages may rise to a clamped voltage determined by the surge protection devices for a short time during the surge pulse.

With grounded systems using grounded equipment enclosures, there is a greater possibility of a service person completing a fault path when working within the enclosure. The grounded system presents energized conductors in close proximity with substantial amounts of grounded exposed metal in the enclosures. Non-conductive enclosures can minimize this problem.

FIRE SAFETY

General: The fault currents supplied by the PV array are determined and limited by the array size and the incident irradiance. A properly designed system uses cables and overcurrent devices sized to carry the highest short-circuit in each protected circuit. The current limited PV source normally will not supply enough current to open protection devices on faults. In cases where more current was supplied from a second source or PV string, the blocking diodes had failed. Other sources of current that may cause the fuses or circuit breakers in PV circuits to blow or trip include inverters connected to the utility grid or batteries [10]. Even bolted faults (line-to-line) in PV array conductors may create arcs that will burn insulation at current levels that will not trip an overcurrent device. Multiple faults in grounded or ungrounded systems result in circulating currents that may not be detected, but can result in loss of power and create fire hazards.

Ungrounded: Ungrounded systems offer clear advantages for avoiding fire hazards. The ungrounded system must develop two ground faults before a ground-fault fire hazard exists. Ground-fault detectors, which are easier to install on ungrounded systems than on grounded systems, can detect the first ground fault and disable the system before dangerous multiple ground faults develop. Disabling an ungrounded system can be achieved by short-circuiting the array. Although the fault is not eliminated, the voltage on the conductors is substantially reduced. Excessive leakage to ground may, however, cause ground-fault detection sensitivity problems.

Grounded: A single fault or leakage to ground results in circulating ground current whenever the PV array is illuminated in a grounded system. This is a dc current and can result in corrosion of dissimilar metal connections and, if sufficiently high, can pose fire hazards. Grounded systems are very difficult to disable because of the division of currents. Short circuiting a faulted array will not eliminate the fault current. The disabling circuit may include many meters of wire, several disconnect devices, fuses or circuit breakers, and blocking diodes between the fault and the disabling device. The current division between the fault resistance and the array disable circuit can approach a value that allows enough current to flow through the fault with enough power dissipated to cause a fire [6]. The fault current, voltage, and power can actually increase unless the fault current is interrupted by ungrounding the system. If all of the conductors are open circuited, the fault path is opened. The ungrounded array then can be disabled by short circuiting.

SURGE SUPPRESSION

Surge suppression devices may be added to either of the grounding configurations and are independent from the grounding system used. Suppression devices are used to control surges induced by nearby lightning strikes and any other inductively or capacitively coupled surges that might be introduced to the system. Surge suppression devices are connected between each of the current-carrying conductors for line-to-line (differential mode) surge reduction. They are connected between each current-carrying conductor and earth for line-to-ground (common mode) protection.

SUMMARY

The grounding of systems is complicated by the introduction of current-limited PV systems interconnected with batteries and conventional voltage-source electro-mechanical generators. There is still no international agreement for grounding PV systems, and there is little likelihood of agreement. The USA requires system grounding of all electrical systems with voltages greater than 50 volts. Many other countries require ungrounded PV systems. Two universal rules for grounding are a) most codes and standards require equipment grounds for all metal surfaces that might become energized, and b) when system grounds are used, single-point grounds are required.

The ungrounded system provides the best fire hazard reduction because multiple faults are needed to create a fire hazard. The ungrounded system might also provide the best protection for preventing shock if the system were ideal, with reliable, sensitive ground-fault detection and no leakage. The proposed Class II European systems operating at voltages below 120 volts will increase fire and personnel safety in PV systems.

The grounded PV system provides the best personnel protection from electrical shock because voltages to ground are well defined. Since PV systems inherently have leakage to ground, they are not solidly grounded or ungrounded. The system ground ensures a solid or known PV array ground through properly sized conductors. With proper design, both grounded and ungrounded PV systems can achieve personnel, fire, and equipment safety.

ACKNOWLEDGMENTS

This work was sponsored by the U. S. Department of Energy under Contract DE-AC04-94AL85000.

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