Electrical Safety Practices in Utilities and Personal Protective Grounding: An Update

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Abstract - Electric utilities place high priorities on providing their workers with a safe worksite environment for power line construction and maintenance. In addition, regulatory agencies such as Occupational Safety and Health Administrations and the Institute of Electrical and Electronics Engineers, National Electrical Safety Code provide fundamental rules and guidelines to create a safe working environment for workers.

This presentation will cover the foundations of key electric safety issues for transmission line maintenance for de-energized lines. Different standards and codes will be discussed at length in conjunction with a variety of topics including engineering justifications (modeling, analysis and results) of the standards and the safety codes.

Index Terms — Safety, Personal Protective Grounding, De-energized Line Maintenance, Transmission Line Maintenance

I. INTRODUCTION

The personal protective grounding (PPG) practices is used to prevent injury from electric shock and arc hazards and to meet the standards set by the Occupational Safety and Health Administration (OSHA) for workmen maintaining these lines under de-energized condition.

OSHA has three requirements[1] when a transmission line is taken out of service for maintenance and personal protective grounds are applied (Section 1910.269 of CFR):

1. "Temporary protective grounds shall be placed at such locations and arranged in such a manner as to prevent each employee from being exposed to hazardous differences in electrical potential."
2. "Protective grounding equipment shall be capable of conducting the maximum fault current that could flow at the point of grounding for the time necessary to clear the fault. This equipment shall have an ampacity greater than or equal to that of No. 2 AWG copper."
3. "Protective grounds shall have an impedance low enough to cause immediate operation of protective devices in case of accidental energizing of the lines or equipment."

There are four basic classes of line types covering the most common design and construction practices in utility system for which safe grounding techniques are examined.

1. Isolated line using wood construction.
2. Isolated line using steel construction.
3. Non-isolated line on wood construction.
4. Non-isolated line on steel construction.

Each of these cases is divided into two sub-cases: (a) where shield wires are available and (b) where shield wires are not available, making a total of eight (8) different grounding situations as shown in Fig. 1.

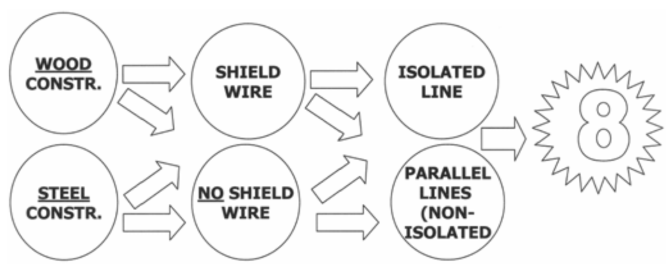

Fig. 1 Eight Different Scenarios

There are two classes of workers at the maintenance location which must be considered since the requirements for their safety are different. These are:

1. Workers working above the ground, such as in a bucket truck, ladder, or climbing a pole.
2. Workers working in direct contact with the ground.

The present investigation addresses analysis and methods utilized to accomplish these three objectives. The recommendations given are applicable to all transmission voltage levels between 115kV and 500kV. Special attention is given to the effects of high ground resistivities and the effects of paralleled and multiple circuit lines in a single right-of-way.

II. ANALYSES, METHODOLOGY AND DESIGN

There are several types of situations that may result in safety problems for workmen. These are:

1. Accidental energization of a line grounded for maintenance by closing the end of line breakers or switches.
2. Accidental energization of a line grounded for maintenance due to a fault caused by a line either in the same right-of-way or crossing the grounded line.
3. Voltage differences that may exist between the de-energized line and ground due to electrostatic induction from a nearby line running in parallel (same right-of-way).
4. Voltage differences that may exist between the de-energized line and ground due to electromagnetic induction from a nearby current carrying line in parallel.
5. Step and touch potentials that can exist near ground rods and ground bed, trucks, and other grounded parts.

A. Limit of Tolerable Body Current

One commonly used formula, Equation (1), is used to determine the maximum allowable current the human body (110lb body weight) can conduct before an injury (without ventricular fibrillation) or death occurs[3].

$$I_B = \frac{0.116}{\sqrt{t_s}} \qquad (1)$$

Where: I_B= Body Current
t_s = Duration of Current Exposure in seconds

Typically the fastest an accidental energization can be cleared is assumed to be approximately 6 cycles (0.1 seconds) including the relaying and the breaker operating time. Using this value of 0.1s, the maximum current the body could be exposed is 367mA. In many actual cases it may take far longer to clear a fault. If a 1.5 second clearing time is assuemd the body can tolerate approximately 95mA.

B. Use and Purpose of Ground Rods

The first step in placing a line for a safe maintenance procedure consists of connecting the de-energized line to the earth (ground), either through the rebar of the concrete foundation of a steel pole, or by connecting the line directly to a ground rod bed near the tower. The purpose of this earth connection is often misunderstood. Even for very low resistance values to ground the connection to earth does not insure the safety of a lineman in contact with the line if it is accidentally energized.

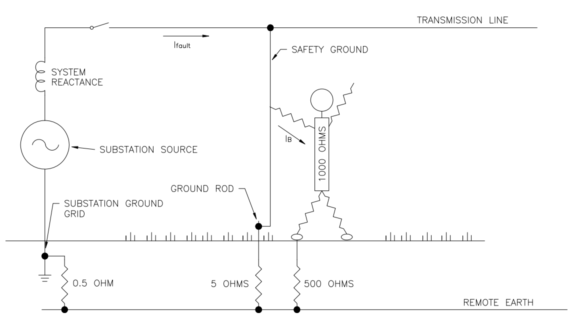

Fig. 2. Touching a Grounded Line During Accidental Energization

As shown in Fig. 2, the main purpose of a connection to earth is to provide a path for current (for a line-to-ground-fault) to flow back to the source. The substation (source) will have a grounding grid (mat) which usually presents a low resistance to remote earth, often less than 1Ω. Also shown are the typical body resistance and the resistance between foot and earth and between the ground and remote earth. This body and foot resistance can be high, but typically not high enough to reduce the current flow if the body touches an energized source.

A worker on a grounded, non-insulated truck is shown in Fig. 3. PPG is applied so that it parallels the body. A #2 50ft. PPG has an impedance of approx. 0.0095Ω. If the line is accidentally energized, the current flowing through the body is reduced to a safe limit. To be effective, PPG must have two requirements:

1. It must be low enough in resistance to divert sufficient current to prevent the death of the worker.
2. It must be of sufficient size to allow it to pass the available current for a sufficient length of time without melting.

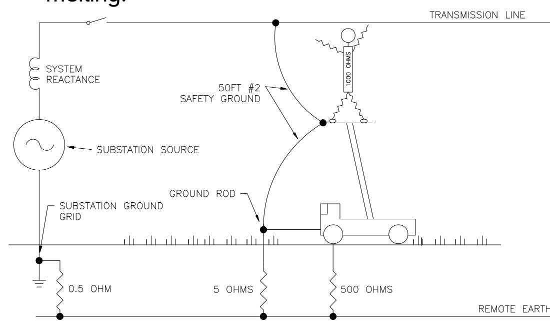

Fig. 3. Worker Touching a Grounded Line During Accidental Energization with PPG Installed

Equation (2) can be used to determine approx. the maximum resistance permitted for a PPG.

$$R = \frac{I_B}{I} \qquad (2)$$

Where: I=Available Fault Current (A)
I_B=Allowable Current through the Body (mA)
R=Maximum Resistance of PPG (Ω)

There are two ways to rate personal protective cables to prevent melting: (a) rated to be re-used after conducting faultr current, and (b) one-time use only. Since the accidental energization of a line under maintenance is a rare event, it is recommended for economical and practical reasons to use cables sized for conducting fault current only one-time.

C. Ground Rod Sizing and Number of Rods

Ground rods have a limited ability to conduct current. To determine the number of ground rods for a given fault current, a measurement of the soil resistivity is necessary. The maximum current per foot of rod length[2] for a total rod system should not exceed the value calculated using Equation (3).

$$I = \frac{34{,}800(d)(L)}{\sqrt{\rho\, t}} \qquad (3)$$

Where: d = Rod Diameter in meters
L = Total Rod Length in meters
ρ = Soil Resistivity in ohm-meters
t = Time in seconds

Equation (4) can be used to determine the resistance of a bed of ground rods[3], assuming that the rods are arranged in an approx. square configuration with one rod length spacing.

$$R = \frac{\rho}{2\pi\, n_R L_R}\left[\ln\left(\frac{8L_R}{d}\right) - 1 + \frac{2.16(L_R)}{\sqrt{A}}\left(\sqrt{n_R} - 1\right)^2\right] \qquad (4)$$

Where:
d = rod diameter in meters
L_R = length of each rod meters
ρ = soil resistivity in ohm-meters
A = Area in which rods are placed meter^2
n_R = number of rods in area A

D. Risks to Workers on the Ground

As long as a worker is not in contact with the ground and the body is paralleled by a properly sized PPG, the worker is safe.

Workers in contact with the ground, however, have additional concerns: step and touch potential. Most of the resistance to earth occurs close to the rod. Over 50% occurs within 6 inches, and nearly 100% occurs within 25 feet. This means that as a worker nears a rod the voltage will increase from 25 ft. and the increase will become more pronounced very close to the rod[2].

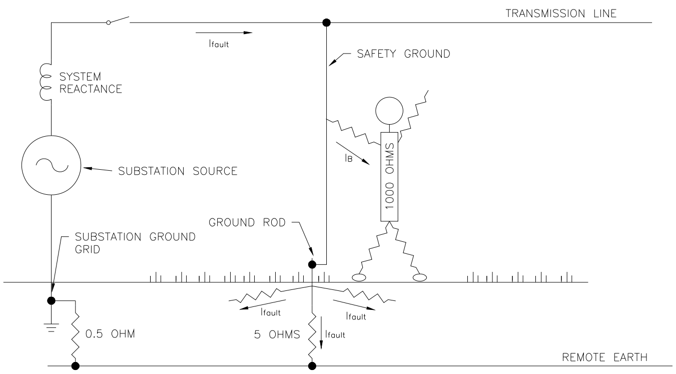

Fig. 4. Touch Potential

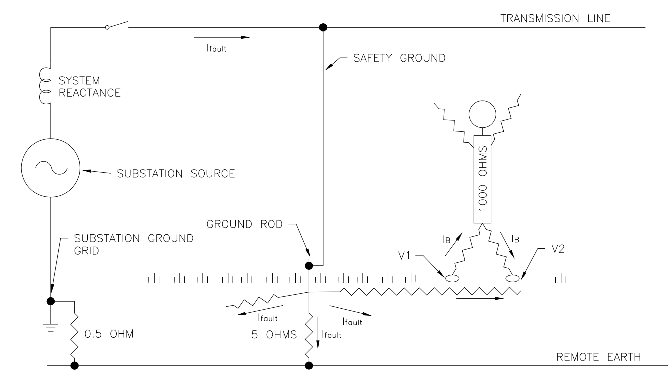

Fig. 5. Step Potential

Other considerations in the design of PPG and safety ground that will be addressed during the presentation includes:

1. Tower Foundations as Ground Connections
2. Grounding of Steel Structures, and
3. Use of Personal Ground Mat (PGM) (shown in Fig. 6)

Fig. 6. Personal Ground Mat

E. End-of-Line Grounding Switches

Grounding switches are used in substations to provide a low resistance to ground fault current. Applications of these switches are not universally accepted and it is often left up to the line crews to determine if and when they are used. End-of-Line switches do have some advantages. Their use does not remove the necessity of PPG and using PGM at the site.

F. Shield Wires

Shield wires are used to minimize outages from lightning. They may or may not be continuous and sometimes insulated from the structures. Incorporating shield wires in PPG results in most cases a low impedance path and must be included in the safety grounding system. The main consideration is the current carrying capacity.

G. Protective Relaying Considerations

There are two major issues to deal with in protection requirements: (1) reclosing, and (2) tripping time. Reclosing poses a number of maintenance problems, safety and over-sizing the PPG. It is recommended that reclosing be disabled on all lines in the same right-of-way with the line under maintenance. This will reduce the reliability of the other lines in the same right-of-way, however personnel safety is a much bigger issue. Regarding the tripping time, ideally lines should be tripped in 6 cycles or less, however this is often impossible. If PPGs are sized for 1.5 seconds, then it is suggested that protection engineers set the ground fault relays to trip the line in less than 1.5 secs. This is quite intriguing and will be discussed in the presentation.

H. Line Construction and Coupling

As mentioned in the beginning of this paper that type of line construction makes a big difference in designing the PPG. Eight different scenarios have been studied. The biggest threat to the lineman comes from the number of lines in the same right-of-way as shown in Fig. 7, which causes both electrostatic (ES) (capacitance and voltage) and electromagnetic (EM) (current flowing through conductor) coupling. Depending on the operating conditions, PPG must be designed to meet specific requirements. With ES coupling, there are two problems:

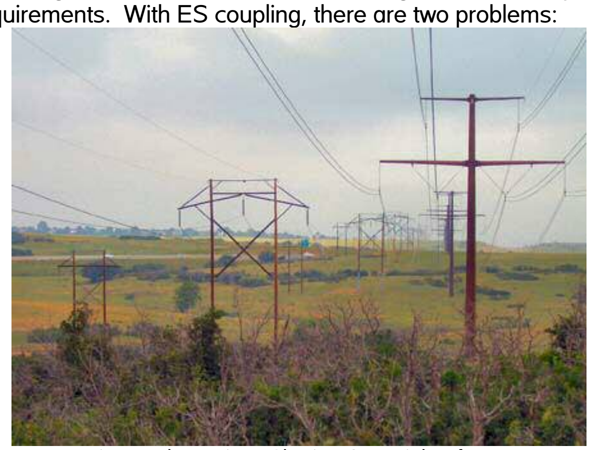

Fig. 7. Three Lines Sharing One Right-of-Way

(i) slow drying out of the soil near the grounding electrode, and (ii) when the line is un-grounded after the maintenance, an arc will occur that must be safely interrupted. The length of the arc can become long enough to cause numerous additional safety requirements.

Danger assessment due to EM coupling is very complex and unpredictable. Any technique that minimizes the effects of ES coupling may make the EM coupling worse. Safety procedure and PPG varies with the line construction and will be addressed at length at the presentation.

II. CONCLUSIONS

Current PPG practices for de-energized line maintenance have been studied. It depends on the type of line construction, wood vs. steel pole, shielded vs. un-shielded line and whether there are multiple lines in the same right-of-way. The presentation will address the specific recommendations in detail based on analytical models and analyses.

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VI. VITA

Keith Malmedal, (M' IEEE) received his MSEE (Power) and MSCE (Structures) degrees from the Univ. of Colo. at Denver in '98 and '02, respectively. He has over ten yrs. experience in electrical power design and is presently a principal engineer at NEI Electric Power Engineering, Arvada, CO, specializing in all aspects of power system design. Mr. Malmedal is a Registered Professional Engineer in 14 states.

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John P. Nelson (Fellow IEEE '98) received his BSEE from the Univ. of Illinois, Urbana, IL in '70 and MSEE from the University of Colorado, Boulder, CO in '75, respectively. He spent 10 yrs. in the electric utility industry and the last 27 yrs. as an electrical power consultant. Mr. Nelson has been active with IEEE IAS/PCIC for 25 years, and has authored numerous papers (over thirty) involving electric power systems, grounding and protection, and protection of electrical equipment and personnel safety. John is a registered professional engineer.