Bonding Requirements for Conductive Poles

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Abstract -- **Increasing load density at electric utilities has driven the trend toward larger distribution conductors and higher settings on overcurrent protective equipment. Not only are pickup values of feeder breakers and reclosers increasing, the protective curves are often slower to achieve coordination with downstream devices. Where there are larger conductors and slower protective settings you will often find more application of conductive distribution poles to carry the structural loads imposed by larger conductors.**

The potential problem arises with the possibility of the distribution pole becoming electrically detached from the distribution neutral. If a conductor makes direct contact with an unbonded pole the fault current is limited to a much lower value. Proper tripping of the faulted line section may not take place due to the combination of limited fault current and high pickup levels on the feeder protection equipment.

This paper will examine typical feeder ground trip settings and the effect these will have on the sizing of bonding jumpers for conductive distribution poles. The effect of loss of bonding jumpers on contact voltage is addressed.

Index Terms -- **Fault Currents, Fault Tolerance, Grounding, Grounding Electrodes, Overcurrent Protection and Short Circuit Currents.**

I. INTRODUCTION

Bonding of steel distribution poles has assumed more importance as increasing load density at many electric utilities has driven the trend toward larger distribution conductors and higher settings on protective equipment. Not only are the overcurrent pickup values of feeder breakers and reclosers increasing, the protective curves are often slower in order to achieve coordination with larger downstream devices. Where there are larger conductors and slower protective settings you will often find more extensive application of steel or concrete distribution poles. Let us consider the importance of proper bonding of these poles to the distribution system neutral. This paper will develop a rational method to properly size bonding connections so that they will function effectively and reliably.

It should be noted that the situation on distribution systems is markedly different from that existing on transmission systems where conductive poles were initially applied. Transmission systems with large continuous currents typically have high-speed relaying to quickly clear faults, even those faults with relatively high impedance. This is attributable in part to the lack of load between sectionalizing points and the economic feasibility of installing protective systems that do not depend on achieving selective coordination through the selection of compatible time-current curves. Also, the feasibility of high-speed communication between sectionalizing points allows for greater selectivity. Given these advantages, transmission system faults typically exist for much shorter times than distribution faults. Typical transmission fault clearing times are usually about three to six cycles (0.05 to 0.1 sec.) for a cumulative line deenergization time on the order of 0.15 to 0.3 seconds. Distribution system line deenergization times can be on the order of 0.6 to 3 seconds. The faster fault clearing times on typical transmission systems reduce the heating of any conductors in the path of the fault current. Pole bonding practices that have served well on transmission systems may be found wanting on heavy distribution circuits.

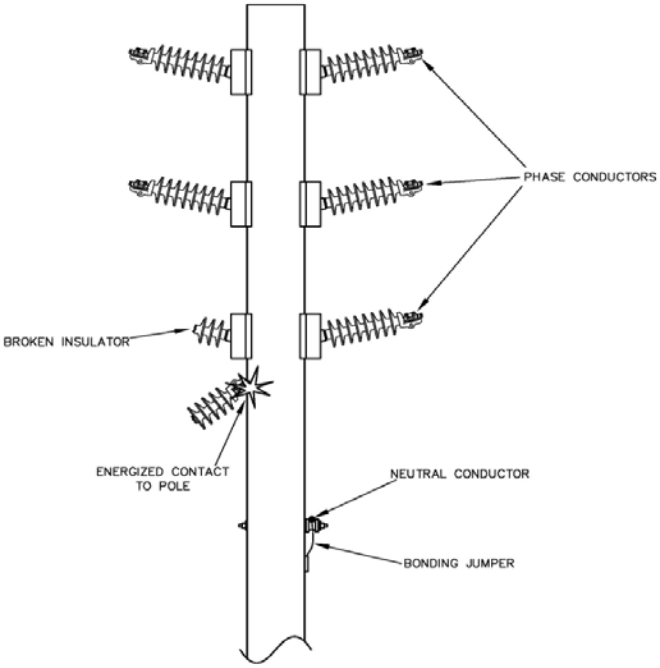
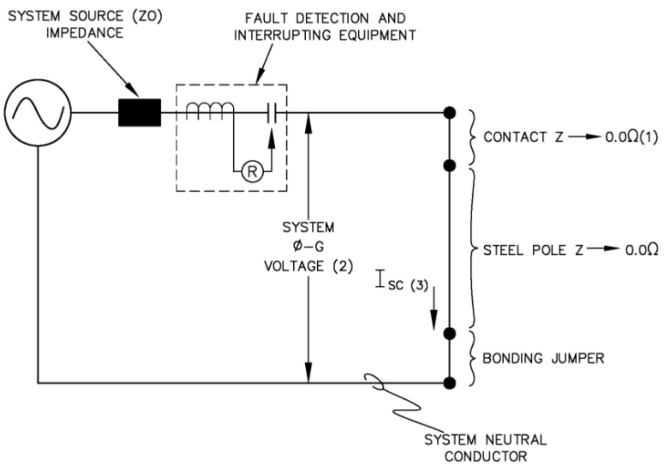


Fig. 1A.



NOTES:

1. TYPICAL CONTACT IS BARE CONDUCTOR TO METAL POLE SHAFT
2. TYPICALLY 7.2KV TO 14.4KV FOR DISTRIBUTION SYSTEMS.
3. FAULT CURRENT TYPICALLY 5KA TO 15KA

Fig. 1B.

II. NESC REQUIREMENTS

Bonding is defined in Section 2 of the National Electrical Safety Code [1] as "The electrical interconnecting of conductive parts, *designed to maintain* a common electrical potential." (Emphasis added). The Code recognizes the need for not only establishing a method of bonding, but doing so in a manner that the effectiveness of the bond will be maintained during reasonably anticipated operating conditions.

Beginning in the 2007 Edition, the NESC [2] added a new Rule 094B7 which stipulates the conditions under which the metal pole can be considered to be an effective grounding electrode. Rule 094B7 stated that:

Directly embedded steel poles shall constitute an acceptable electrode, if all of the following requirements are met:

a. Backfill around the pole is native earth, concrete, or conductive grout (not gravel).
b. Not less than 1.5 m (5.0 ft) of the embedded length is exposed directly to the earth, without nonconductive covering.
c. The pole diameter is not less than 125 mm (5 in), and
d. The metal thickness is not less than 6 mm (1/4 in).

NOTE 1: Directly embedded steel poles having a nonconductive covering below ground that limits the length of direct exposure to earth to less than 1.5 m (5.0 ft) are not considered as an acceptable electrode. Aluminum installed below ground is not considered as an acceptable electrode. Weathering steel may not be an acceptable material for this application.

NOTE 2: There are structural and corrosion concerns that should be investigated prior to using metal poles as grounding electrodes.

EXCEPTION: Other lengths or configurations may be used if their suitability is supported by a qualified engineering study.

This is in recognition that under most conditions metal poles require some form of protection against corrosion. This always involves insulation between the pole and the surrounding earth. Therefore, effective corrosion protection can be a detrimental to use of the pole shaft as an effective grounding electrode. It is also significant that Note 1 in Rule 094B7 includes the statement that "weathering steel may not be an acceptable material for this application".

During the 2012 NESC revision [1] cycle Rule 094B7 was modified by deleting the requirements for a minimum embedment length and minimum thickness of the metal used in the pole. This allowed latitude for a "qualified engineering study" to support other embedded pole configurations.

III. POLE RESISTANCE TO REMOTE EARTH

The embedded portion of a bare conductive pole has significantly less resistance to remote earth than a normal ground rod in similar soil. While not a usual installation, a bare (non-coated) pole in "good" 100 ohm-meter (Ω-m) soil will have a resistance to remote earth of approximately 23 ohms. A similar steel pole with a non-conductive coating - except for a 1 ft length at the butt - below ground would have a resistance of approximately 39 ohms to remote earth in 100 ohm-meter (Ω-m) soil. These values can be favorably compared to the 40 ohms resistance of a normal 5/8-inch x 8 ft ground rod under similar soil conditions. Therefore, even a bare conductive pole is far from a "perfect" ground.

The values above are for hypothetical soil with a volume resistivity of 100 ohm-meter (Ω-m). Be aware that common soil resitivities in the field can vary over a range of 25 to 1500 ohm-meters. A sandy soil with a 1000 ohm-meter (Ω-m) resistivity will produce a pole-to-earth resistance of 230 ohms for a bare pole and 390 ohms for a coated pole with a 12" area exposed at the butt.

IV. FAULT CURRENT LIMITATIONS FOR ISOLATED POLE

The potential problem arises when you consider the possibility of the conductive distribution pole becoming electrically detached from the distribution system neutral.

Under these circumstances if a conductor makes direct contact with the pole the fault current is limited to a value that is a function of the system phase-to-ground voltage and the impedance of fault current path. Since the fault current must not only pass into the earth through the pole ground resistance but it must also return to the distribution system neutral source through either the distributed resistance of the distribution system grounding (including the substation ground mat) the total return path impedance will be approximately 5 ohms greater than the resistance of the pole involved in the fault [7]. This means that for a 7.2/12.5 kV distribution system in 100 ohm-meter (Ω-m) soil the resulting fault current will be approximately 250 amperes for the uncoated pole and 190 amperes for the steel pole with a non-conductive coating immediately below the groundline.

An even greater concern is generated when higher resistivity soils are considered. For example, areas with the sandy 1000 ohm-meter (Ω-m) soil the isolated bare pole will only produce a ground fault current flow of about 25 amperes and current through the partially coated pole will be on the order of 19 amperes.

The preceding examples are admittedly an optimistic simplification that ignores the impedance of the phase conductors between the source transformer and the fault location. Therefore, it is apparent that heavy distribution circuits having ground trip pickup values of 140-200 amperes may not effectively trip if the conductive distribution pole does not remain effectively connected to the distribution system neutral conductor.

V. TOUCH POTENTIAL

Since the pole ground resistance constitutes the majority of the impedance in the path of the fault current the conductive pole that is isolated from the system neutral will have a very high touch potential when subjected to contact by medium voltage conductors - particularly if the supply system has relatively low source impedance. Step potentials will also be elevated in the vicinity of the pole. Both of these hazards will exist until the circuit is deenergized. This is of special concern since the poles are highly accessible to the public.

VI. CONNECTORS

Since the bond between the system neutral and the steel pole must carry full fault current for the duration of all recloser operations, it is important that the connectors used at each end of the bonding jumper be evaluated to determine the capacity of the bonding conductor. An example of a questionable connector is the single-bolt transformer tank ground connector (aka "transformer lug") (Figure 2) that is often used to ground apparatus. The most common application of these devices is on the distribution transformer tank. While lugs of this type are adequate for most applications on distribution equipment where there are multiple ground connection points and a redundant ground path, a superior connection can be made with a two-hole bolted terminal lug. Also, the fault current duration through a transformer grounding lug is usually limited by the size of the fuse on the primary of the distribution transformer. The two-hole NEMA standard type of bolted terminal connector (See Figure 3) has much greater durability and is designed to carry the full current rating of the conductor. The greater thermal mass of the NEMA standard connector also provides an additional margin of reliability. It is also apparent that the current transfer surfaces of the two connector types are vastly different. The 'transformer lug' connector depends significantly on current transfer through threads. A properly installed two-hole terminal connector transfers current through machined surfaces. This provides inherently greater conductivity and higher reliability.

Fig. 2. Transformer Grounding Lug

Fig. 3. Bolted 2-Hole Terminal Connector

If it is accepted that connections to the pole will be bolted at one or both ends, the limit on maximum conductor temperature will be established at a level that will not impair the integrity of the connector. This is usually accepted as 250ºC for mechanical connections. [4] [5] Of course, if exothermic connections are used at both ends of the jumper, a maximum conductor temperature of 450°C (or more) might be acceptable. However, this is not a situation that is normally encountered since there is almost always a mechanical connection of some type where the jumper attaches to the neutral conductor.

VII. THERMAL PERFORMANCE OF BONDING JUMPERS

The thermal performance of the bonding jumper conductor is a function of the fault current through the conductor, the duration of the fault, the jumper material, and the cross-sectional area of the conductor. Analysis of the short-time phenomenon is simplified by treating this as an adiabatic event where there is no heat transfer to the surrounding environment. One classical equation for determination of conductor temperature is shown as Equation 1. [3] [4] [6]

$$\left(\frac{I}{1000A}\right)^2 t = K\log_{10}\left(\frac{T_2+\lambda}{T_1+\lambda}\right) \qquad (1)$$

I = fault current, A
t = fault duration, sec
A = cross-sectional area of the conductor, kcmil
T2 = conductor temperature from the fault, °C
T1 = conductor temperature before the fault, °C
K = constant depending on the conductor, which includes the conductor’s resistivity, density, and specific heat (see Table 1)
λ = inferred temperature of zero resistance, °C below zero (see Table 1)

TABLE 1

Conductor Material	λ, °C	K
Copper (97%)	234.0	0.0289
Aluminum (61.2%)	228.1	0.0126
6201 (52.5%)	228.1	0.0107
Steel	180.0	0.00327

Source: Southwire Company, *Overhead Conductor Manual, 1994.*

If the initial conductor temperature is considered to be 40ºC and the maximum temperature of 250ºC is used for copper conductors, Equation 1 can be reduced to:

$$t = \frac{7141\,A^2}{I^2} \qquad (2A)$$

$$A = 0.01183It^{0.5} \qquad (2B)$$

Much work has been done in verifying the basic assumptions for Equation 1. This has included laboratory testing of both new and artificially aged connections [5]. In recognition of the importance of the bonding connection, it is judged appropriate to include either redundancy or a factor of safety when designing jumper conductors. While true redundancy would provide more insurance against gross workmanship defects, oversizing of jumper conductors is a more normal approach. A factor of safety of two (2.0) can be incorporated by simply doubling the area of the conductor as calculated using Equation 2B.

Results of calculations for three common conductor sizes are shown in Figures 4 and 5. These were plotted for the cases of 10 kA (Figure 4) and 14.5 kA (Figure 5). While these fault current levels might seem extraordinary for rural circuits, the circuits being considered are near large substations that would normally be required to feed heavy circuits to concentrated loads. The installation that caused consideration of this situation has 600-ampere class 12.5 / 7.2 kV circuits from substations with low-impedance 30 MVA transformers.

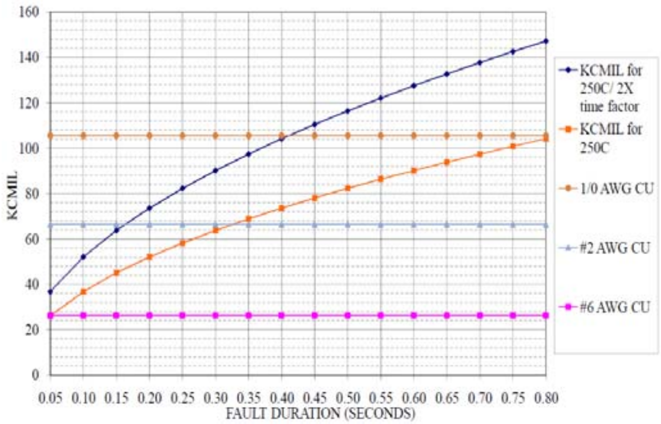


Fig. 4. Conductor Size Required for 10,000 AMP Fault
Soft Drawn CU - Start Temp 40ºC

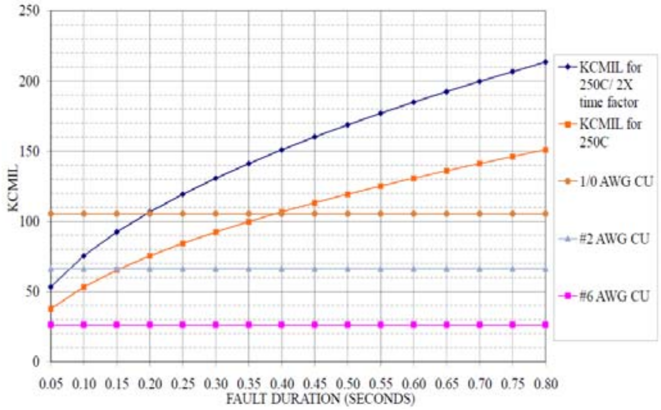


Fig. 5. Conductor Size Required for 14,500 AMP Fault
Soft Drawn CU - Start Temp 40ºC

Figures 4 and 5 show how the safety factor can be applied by doubling the time for damage of the jumper conductors. For example, it can be seen that the 250ºC damage point for a 1/0 AWG jumper is reached in approximately 0.40 seconds. Similarly, if a safety factor of 2.0 is applied by allowing the fault to only exist for one-half of the time required to reach 250ºC, that time limit is approximately 0.20 seconds for a 14.5 kA fault. The accompanying figure for the 10.0 kA fault level shows the 1/0 AWG jumper requires 0.80 seconds to reach the basic 250ºC limit. It can be seen from this comparison that the results are not directly proportional to the fault current level; so it is important to evaluate the expected fault current levels that might exist during the life of the project.

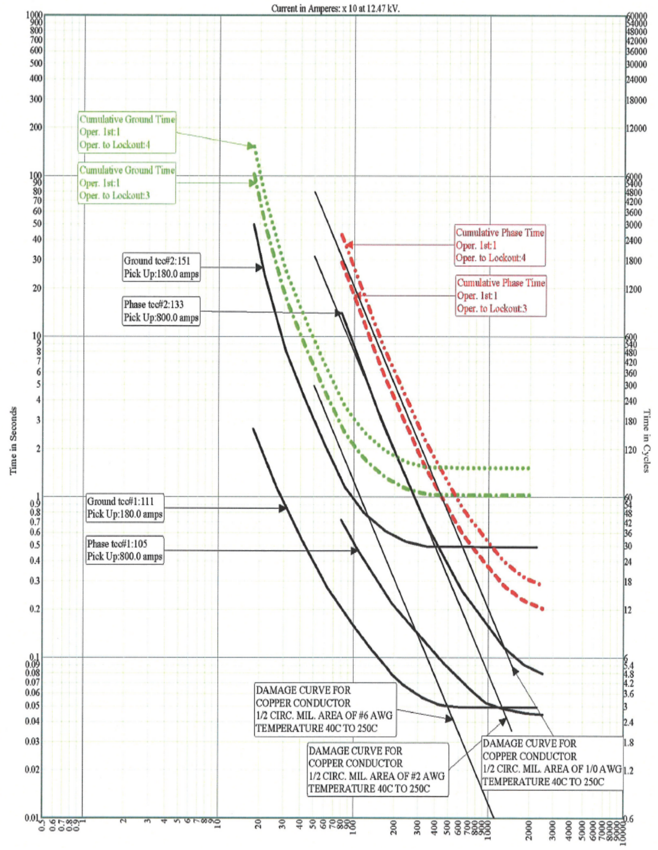


Fig. 6. Feeder TCC vs Jumper Damage

Another approach to applying a factor of safety is exhibited in Figure 6. Here the 250ºC conductor limit is compared with typical time-current curves that might be found on heavy feeders. The feeders considered are 600-ampere class and are expected to carry loads approaching 600 amperes. The phase and ground pickup levels are respectively 800 and 180 amperes. Here the jumper 250ºC damage limits are compared with the cumulative clearing times for the feeder breaker. The safety factor of 2.0 is applied by using the damage curve for a conductor with a cross-sectional area of one-half of the actual jumper.

Another feature of Figure 6 is plotting of cumulative clearing times for operational sequences of both three and four shots to lockout. All sequences use only one "fast" curve since it was judged that heavy feeders with settings in this range cannot have fuse-save operation; therefore, the second "fast" operation is of limited value. Comparison of these two scenarios demonstrates the advisability of considering limiting the total number of operations to lockout to three.

VIII. CONCRETE POLES

It is recognized that concrete poles are conductive and pose the same problems with conductor contact as steel poles. While the contact impedance may be higher in the initial stages of the fault, dielectric breakdown of the thin layer of concrete over the internal steel may occur. This leaves the reinforcing steel or the prestressing strand carrying fault current and energizing the entire pole at phase potential until the circuit is deenergized. Since there is not an immediate solid contact between the phase conductor and the internal conductive elements, this is a more complex problem.

Another complicating factor is that the internal steel is not exposed at the level of the distribution neutral; thus special arrangements have to be made for electrical continuity between the distribution system neutral and the reinforcing. This is easily accomplished during the specification process. However, normal connection provisions involve bolted internal connection to one of the internal prestressing strands. These strands are extremely high strength steel that is subject to loss of strength by annealing at arcing sites or when they are forced to carry fault currents. Examination of the damage susceptibility of prestressing strand is beyond the scope of this paper. However, the same basic principles apply. Contact of phase conductors to the pole surface will carry the same risk of exposure of the public to injurious voltages and even more risk of concealed damage to the pole structure. Consideration should be given to this phenomenon during the design and operation of high-capacity distribution circuits on concrete poles.

IX. CONCLUSIONS

- Proper sizing of bonding jumpers is important to maintain public safety by avoidance of contact voltages on metal poles.
- Reasonable factors of safety are advisable in determining the minimum jumper size.
- The appropriate jumper size is highly dependent on overcurrent setting of circuit protective equipment. This includes the number of operations to lockout.

- Concrete poles are also conductive. Proper bonding is also important on these poles and pole design should be reviewed to minimize loss of structural integrity during the passage of fault currents.

X. ACKNOWLEDGEMENTS

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XI. REFERENCES

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