INSULATION COORDINATION OF MEDIUM VOLTAGE POWERLINES: SOUTH AFRICAN EXPERIENCES

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ABSTRACT

The design of medium voltage overhead distribution lines is affected by many considerations. For example, their insulation coordination philosophy addresses the insulation strength, comprising the primary insulation (insulators), the secondary insulation (in some cases wood) and the stresses (predominantly the normal power frequency voltage and lightning transient overvoltages). The insulation coordination philosophy adopted also affects other aspects of distribution line performance, such as quality of supply, structural reliability, safety of people and animals, ease of maintenance and cost. This paper evaluates the structure (pole and cross-arm) bonding options that result from adopting three different insulation coordination philosophies by comparing the above aspects of their performance. The comparison provides a holistic picture of the insulation coordination experiences in South Africa.

INTRODUCTION

The design of medium voltage (MV) overhead distribution lines is affected by many considerations. For example, their insulation coordination philosophy is centered round their insulation strength and their expected voltage stresses. The former comprises primary insulation (usually insulators and bushings) and also in some cases secondary insulation in the form of a series wood path. The stresses consist predominantly of the normal power frequency voltage and lightning transient overvoltages. Additional insulation stresses result from environmental conditions such as rain and insulator pollution. The problem is that the insulation coordination philosophy adopted also affects other aspects of the distribution line performance, such as quality of supply (e.g. voltage dips caused by lightning-induced flashovers), structural reliability (i.e. ability to withstand mechanical damage due to insulation failure), safety of the public and animals (including large birds that may perch on the structures), ease of maintenance, protection performance and cost (across the entire life of a line). There are therefore trade-offs that need to be made when designing the insulation of an overhead MV distribution line, and effects beyond insulation performance should also be considered when performing such a design.

This paper evaluates three different structure (pole and cross-arm) bonding options resulting from three different insulation coordination philosophies against the above aspects of distribution line performance using intuition and real-life network experience from South Africa. The structure bonding options are then compared and the advantages, disadvantages and implications of each are determined.

INSULATION COORDINATION PHILOSOPHIES EVALUATED

The three basic structure bonding options evaluated are illustrated in Fig 1, with wooden poles and wooden cross-arms assumed throughout. The primary insulation (phase insulators) is assumed to be the same for each of the structure bonding options, with the difference being in terms of their secondary insulation, which is dictated by the presence and extent of bonding and earthing. The fully insulated option (a) has no bonding or earthing whatsoever, resulting in a large secondary insulation level (a long series wood path), the fully bonded and earthed option (b) has all unenergised metal hardware connected together and earthed so that there is substantially no secondary insulation (no series wood path) and option (c), similar to (a), has some secondary insulation (a short series wood path) by virtue of a gap inserted in series with the earth downwire (termed a partially bonded and earthed structure in this paper). There is also an option where the hardware is bonded but not earthed. This is not covered here for simplicity.

The situation is complicated somewhat in the presence of stay wires, which are added for mechanical strength, and shield wires, for improving the lightning performance. The former is illustrated in Fig 2, and is similar in principle to the partially bonded and earthed option of Fig 1c), in that there is some secondary insulation, with the value dictated by the insulation level of the stay insulator and the length of any wood path in series with this.

When shield wires are used, the resistance to earth is theoretically reduced due to the presence of multiple paths to earth for fault or lightning current. If there is a connection to earth on each pole then only partial and full bonding and earthing is possible, due to the presence of the earth downwire.

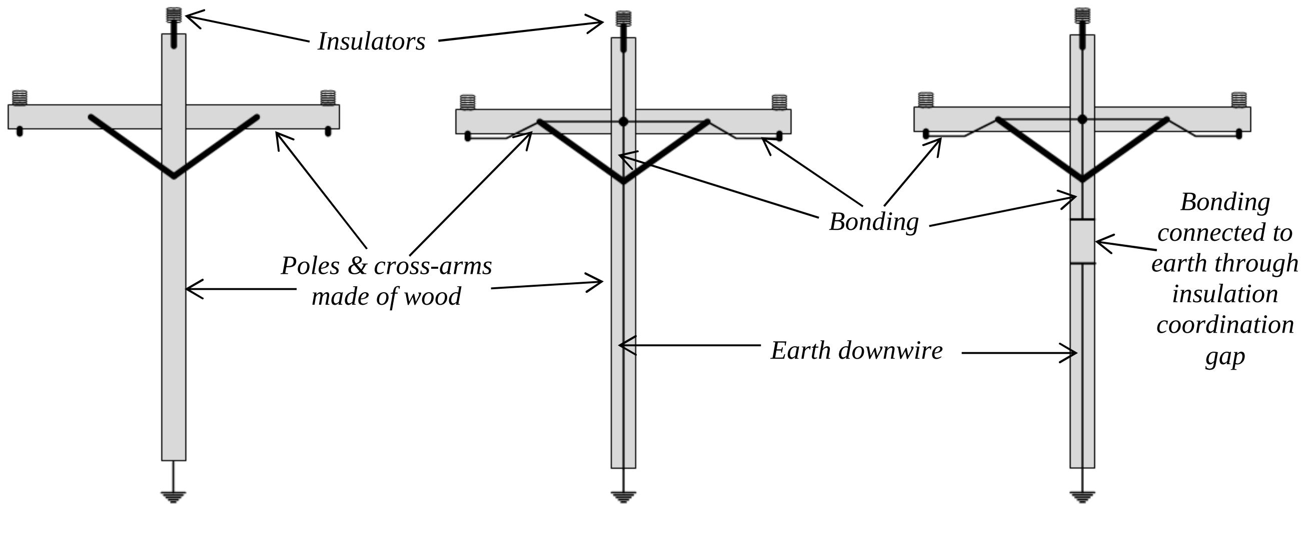

Fig 1: Basic phase-to-earth structure bondingoptions considered: a) fully insulated (no bonding), b) fully bonded and earthed (all unenergised metal hardware bonded together and earthed), c) partially bonded and earthed – as for b) but with a 500 mm wood path (gap) inserted in series with the earth downwire

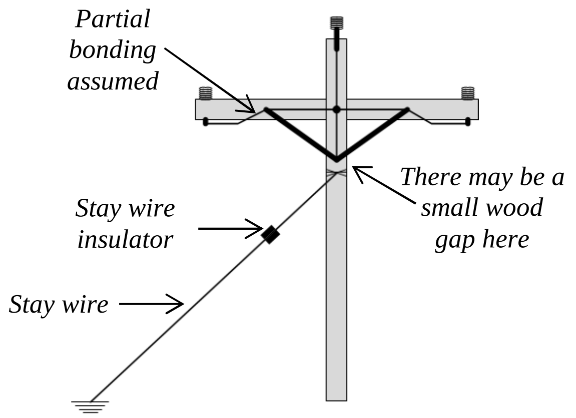

Fig 2: Phase-to-earth insulation when stay wires are present

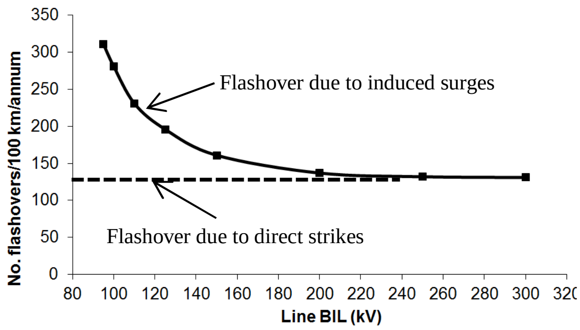

Fig 3: Number of lightning flashovers per 100 km per annum for 10 m high line and ground flash density (N_g) of 10 flashes/km^2/annum [1], [2]

COMPARISON

Table 1 compares the structure bonding options illustrated in Fig 1 and Fig 2 and the options where shield wires are included. Table 1 shows the following:

- There is no significant difference in the theoretical number of earth faults due to lightning strikes between the fully insulated and the partially bonded and earthed configurations, due to the fact that indirect strikes are not expected to result in earth faults for lines with a BIL of greater than 300 kV. The fully bonded and earthed option is expected to result in more frequent earth faults due to indirect strikes, but the increase is relatively small. This is illustrated in Fig 3.
- Lightning-induced earth faults, which may be followed by power frequency follow-through currents, are more likely to damage structures of certain configurations than others. Three examples of partially bonded and earthed structures damaged in such a way are illustrated in Fig 4. The two upper photographs show structures damaged slightly in their wood path gaps and the centre photograph shows an extreme (and relatively rare) case. It is not known how deep such damage should be before the pole should be replaced. A mitigation measure, which involves a spark gap to move the arc away from the pole wood surface, is shown at the bottom of Fig 4, and has been successfully implemented within Eskom [4].
- Risk to human safety is expected to be acceptable for all configurations, except for fully bonded and earthed structures (Fig 1c), where further precautions may be necessary. In this case, the footing resistance of the downwire needs to be specified and maintained in much the same way as for conductive (metal) structures, so that step and touch potentials are limited should the downwire become live, e.g. if one or more

Table 1: Comparison of structure bonding options

Option	Lightning insulation level[1]	Transient faults due to lightning	Pollution performance[2]	Structural reliability[3]	Human safety[4]	Bird safety[5]	Workmanship & maintenance[6]	Cost[7]
Fully insulated (Fig 1a)	High[8] (BIL > 1 MV)	Fewest (< 130 flashovers/ 100 km/ annum for N_g = 10)	Poor	Not recommended for areas with high lightning activity	Acceptable	Acceptable	Errors least likely (simplest structure)	Inexpensive, little maintenance required
Fully bonded & earthed (Fig 1b)	Acceptable (BIL = that of the insulators, ≈ 170 kV)	Most (≈ 150 flashovers/ 100 km/ annum for N_g = 10)	Best	Acceptable	May require additional precautions	Problem for some configurations	Errors more likely (greater complexity), incomplete connections may result in substandard performance	More expensive, more maintenance required
Partially bonded & earthed (Fig 1c)	Good (BIL ≈ 300 kV for 170 kV BIL insulators)	≈ 130 flashovers/ 100 km/ annum for N_g = 10	Acceptable	Better in areas with low lightning activity	Acceptable	Acceptable	Similar to Fig 1b), but effect of incomplete connections may be less severe	Similar to Fig 1b) to build, but less maintenance required
Partially bonded + stay wire (Fig 2)	Similar to Fig 1c)	Similar to Fig 1c)	Similar to Fig 1c)	Better in areas with low lightning activity	Similar to Fig 1c)	Problem for some configurations	Similar to Fig 1c), but more complex	More expensive than Fig 1c)
Shielded line – used with Fig 1b) or Fig 1c)	Similar to Fig 1b) or Fig 1c)	Fewer faults expected than Fig 1b) or Fig 1c)	Similar to Fig 1b) or Fig 1c)	Better in areas with low lightning activity	Similar to Fig 1b) or Fig 1c)	Problem for some configurations	Similar to Fig 1b) or Fig 1c), but more complex	More expensive than Fig 1b) or Fig 1c) to build, similar maintenance

[1] BIL is the Basic Insulation Level (lightning impulse 10% withstand voltage) of a structure in phase-to-earth mode.
[2] Refer to [3] for further details.
[3] Likelihood of damage due to lightning flashover, whether followed by power frequency follow current or not.
[4] Safety of humans (and animals) at ground level with respect to power frequency electrocution.
[5] Phase-to-earth mode only. Phase-to-phase mode also needs to be considered, but this is mostly a function of air clearance.
[6] Likelihood of incorrect construction or incomplete bonding or earthing occurring. Severity of effect of errors occurring are also included.
[7] Cost refers to the amount of material and labour needed for construction and planned maintenance required across the line's life; this is a qualitative and relative estimate and may additionally be affected by the frequency of unplanned maintenance.
[8] This configuration is most likely to be damaged in high lightning or high pollution areas. Also, the stress imposed on terminal equipment is expected to be the most severe, as this equipment will likely have the lowest BIL on a line.

of the phase insulators flashes over. This would likely add additional design specifications and maintenance requirements, and so requires careful consideration.

- The risk of phase-to-earth bird electrocution is lower for the fully insulated and partially bonded and earthed structures than for the fully bonded and earthed structure due to the presence of secondary insulation (wood path) to earth, which limits the potential difference between energised and unenergised parts of the structure at the pole top. On the fully bonded and earthed structure, earth potential is transferred to the pole top via the earth downwire and bonding, resulting in full phase-to-earth voltage appearing across the short length of the insulator. This is, however, only a problem on structures where a large bird could breach the clearance between a phase conductor and a bonding conductor. Mitigation measures include mounting the bonding conductor where it is not exposed and covering one or more phase conductors (the latter also mitigates against phase-to-phase electrocutions). An example of a conductor cover is shown in Fig 5.
- With regard to workmanship and maintenance, a structure should be as simple as possible to construct and to maintain, as this reduces costs and reduces the chances of errors being made. The consequences of an error being made should also be taken into account. For example, if any error is made with the earthing on the configuration shown in Fig 1b), a potentially lethal power frequency voltage could be transferred to ground level.

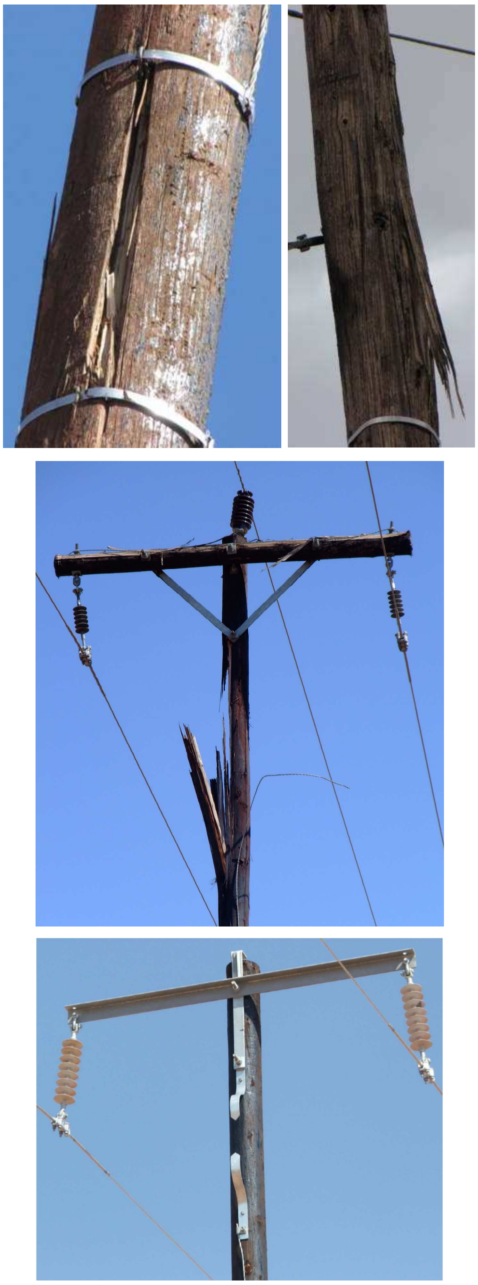

Fig 4: Partially bonded and earthed structures damaged by lightning (above and centre) and mitigation measure (below)

- Total lifecycle cost is the sum of construction costs (materials and labour) and maintenance costs (materials, labour and cost of unserved energy). The most significant difference in costs between the options listed in Table 1 is likely to be maintenance cost, because the fully bonded and earthed configuration likely requires more planned maintenance than the other pole bonding configurations, due to the fact that the quality of the earth connection needs to be maintained. Stay and shield wires also add additional construction and maintenance costs. Unserved energy refers to where maintenance cannot be performed live and the line therefore needs to switched off.

Fig 5: Centre phase conductor covered to increase bird safety

- Another implication is protection performance – this is not expected to be significantly affected by the structure bonding and earthing arrangement in isolation (the network neutral earthing philosophy would, however, affect this, but that is outside of the scope of this paper).

DISCUSSION

The comparison of Table 1 shows that each bonding configuration has advantages and disadvantages. For example, fully insulated structures (Fig 1a) are the simplest structures in principle and require the fewest precautions to ensure the safety of large birds, but perform poorly in high lightning or high pollution conditions (which may impact the amount of unplanned maintenance). Fully bonded and earthed structures (Fig 1b) offer the best pollution performance, but may require additional precautions to ensure acceptable human and bird safety. Partially bonded and earthed structures (Fig 1c) offer the most reasonable compromise, in that they offer acceptable pollution and safety performance, with a similar number of lightning flashovers as the fully insulated option expected.

Adding a stay wire with stay insulator (Fig 2) results in similar performance to a partially bonded and earthed structure (Fig 1c). However, actual flashover values may vary, depending on the electrical properties of the stay insulator and the length of the wood gap in series with the stay wire. If a stay wire is added to a structure with no bonding or earthing (fully insulated), the insulation level is reduced in line with the difference between the insulation level of the pole (and cross-arm) and the stay insulator. Adding a stay wire to a fully bonded and earthed structure theoretically makes no difference to the insulation performance if the stay wire is electrically connected to the bonding.

If a steel (or other conductive) cross-arm is used with a wooden pole, such as that shown in the lowest photograph in Fig 4, the structure either behaves as a fully insulated structure (if no earth downwire is present), a partially earthed structure (if an earth downwire is present with a wood gap) and a fully bonded and earthed structure (if the earth downwire is electrically connected to the cross-arm and it has no wood gap). If both the cross-arm and pole are made of conductive material, then the structure behaves as a fully bonded and earthed structure, with the properties and implications listed in Table 1.

More complex structures than those shown here for illustration, an examples of which is shown in Fig 6, require more care to ensure that the design meets the insulation requirements, e.g. that there are not inadvertent wood gaps, and that the structures are constructed in accordance with the design. This is particularly important in areas with a high risk of pole-top fires, where all unenergised metal hardware should be bonded together (refer to [3] for further details).

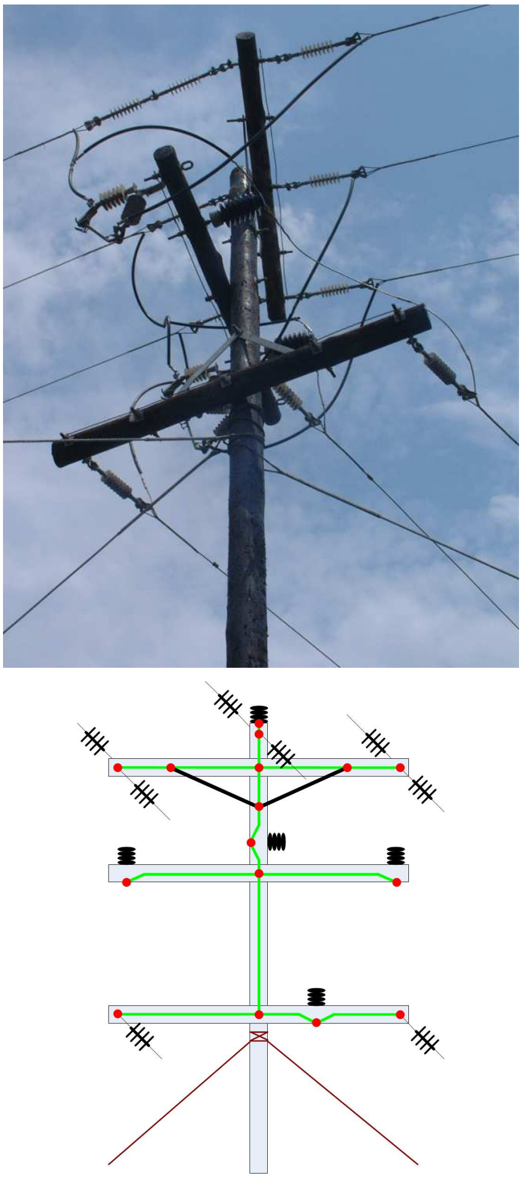

Fig 6: Example of complex structures and a diagram illustrating bonding of a complex structure for mitigation against pole-top fires

CONCLUSIONS AND RECOMMENDATIONS

South African experiences with respect to insulation coordination of medium voltage overhead powerlines have been shared and the implications of available structure bonding options discussed, including complicating factors such as the presence of stay and shield wires. In doing so, insulation design has been expanded to include all considerations. It is clear that each option has advantages and disadvantages. A trade-off between different aspects would therefore likely be required in many cases. Some aspects are still being researched further and hence the understanding of this topic is still evolving. Examples of areas of further research are practical aspects associated with fully bonded and earthed structures and the effect of changes in wood impedance on its insulation properties.

ACKNOWLEDGEMENTS

Manie Kotzé, of Eskom Holdings SOC Limited, is thanked for providing one of the photographs.

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