Dealing with copper theft in the distribution of electricity

by Mike Rycroft, features editor, and Gavin Strelec, Eskom

Theft of earthing conductors has become a major problem in the electricity distribution industry. In addition to theft of feed conductors, theft of earthing conductors at substations and other installations places the safety of the whole network at risk.

One of the solutions is to replace copper conductors with other materials that are difficult to remove and have no scrap value. It is strange that, despite the existence of commercially available solutions to copper theft for over 100 years, particularly for earthing, the problem has never been addressed in a widespread manner.

The first thing that needs consideration are the prices of scrap metal. Copper is roughly R60/kg, whereas steel is somewhere between R2 and R3/kg. It is obvious from this that theft of copper is extremely lucrative and is driven by the market for scrap copper in South Africa. This situation does not exist in African countries where there is no market and no buyers, and most countries do not experience copper theft. Substations in other parts of Africa use protected copper, and people building new substations still install highly exposed pure copper.

The information in this article is based on the documents being prepared by the NRS working group looking at theft deterrent earthing materials (NRS 012) The NRS Project Management Agency produces NRS specifications for the electricity supply industry in collaboration with the South African Bureau of Standards (SABS) on behalf of the Electricity Suppliers Liaison Committee. The purpose of this working group is to promote local standardisation, such as the size of conductors used, to avoid having a miscellany of conductors that need to be manufactured or imported. Another very important aspect is local manufacture of material to support local industry. There are many examples of poor installations and challenges, which are not specific to any end user but occur across the industry. We are all affected by this, and can learn from these examples, some of which are really preposterous. Many of the current practices in use are based on personal preference and opinion, and are based on experience. There is also a lot drawn from international standards and prices in other countries. The NRS working group welcomes opinions and the views and preferences of people working in the industry, as these could contribute substantially to the development of the standard.

**Basic technical requirements**

In order to develop a solution it is necessary to know what the basic technical requirements are. How is an earthing system rated? If we are to adopt a standard we need to make sure that it is a functional alternative to what we do presently, and there are many examples of different materials and connection options which could be considered. One of the prime requirements of earthing is a coordinated system, where the connections need to be coordinated with the conductors. There is no point in using very expensive conductors with poor connections that give 20% conductor utilisation.

The starting point then is a coordinated earthing system, and for a holistic solution an earthing system that is theft deterrent is needed. Earthing systems also need to be effective from a power frequency point of view, which involves large magnitude currents with a duration of possibly seconds. At the same time they need to be effective from a high frequency point of view, which involves lightning impulses associated with frequencies of several hundred kHz, which are generally covered by NRS 083 which covers electromagnetic compatibility. The NRS 083 is a good standard to read and in general it will only reinforce the performance of the earthing system. In addressing EMC there are benefits in other aspects of earthing.

One of the things that have really held development back is the practical aspect of some of these options. Corrosion is one of them. Some of the solutions that have been implemented internationally utilise large sections of steel which are difficult to work with. Another point is the maintenance aspect. This is part of what could be called a hierarchy of risks. At the top of the hierarchy we have the biggest risk which is theft, but there are other levels of risks. The second level is unreliable earthing systems because of corrosion, poor connections or inadequate earthing, which could also be due to theft. We cannot look at theft in isolation but should also consider the maintenance and practical aspects in order to improve the reliability of the system. It’s obvious that even if there is an inadequate earth, 99% of the time it’s going to work in a functional manner to initiate protection operation. If the design calls for a substantial copper conductor that can handle 30 kA for a specified period, in most cases a much smaller conductor will cause protection operation. Most of the time instantaneous operation will occur. The second risk is that of poor connections.

**Connections**

Bolted connections limit usage. Crimped connections can take a much higher temperature. Some very good crimp connections exist but there is again a quality issue – was the proper tool used? Conductor utilisation is improved if a crimped connection is used. Brazing also provides a better form of connection, as there is no connection interface from a corrosion point of view. Utilisation is only 100% with an exothermic connection. Temperature rise affects the conductor utilisation and determines the amount of material required for a particular connection. Bolted connections are also unacceptable because of maintenance required and factors such as relaxation deformation and bimetallic connection problems. They also require that torque specifications be adhered to, and need routine inspections.

**Examples**

765 kV substations in India make use of substantial cross sections of steel, either flat bar or rebar. The problems are that conductors of substantial cross section like this cannot be bent, are difficult to work with and installation becomes difficult as joining requires welding which calls for a high skill level. Contractors doing substation work in Africa prefer to use exothermic welding.
because they can’t find people who can weld and braze properly. Substantial cross sectional areas are required because of high resistivity of steel, which is somewhat offset by the higher fusing temperature, but this is limited by bolted connections, which limit temperature rise. Concealed earthing buried in concrete is another example where utilities are getting good results. The disadvantage is that earthing is not visible, also quite tricky because of severe limitation in temperature rise, which could damage foundations. This is also not an economical solution as conductor utilisation is very poor.

Lifecycle costing
The next point is lifecycle costing. The first focus is on a technical solution and then the economic factors come into play. It is the opinion of this article that far too much money is invested in the conductors used in solutions, an opinion which will be substantiated later. Cost of theft forms an important component of lifecycle costing. Although it is a substantial amount no exact figures are available. The new systems defined in the proposed standard should have much lower maintenance requirements. That is related to the reliability aspects, and should reduce lifecycle costs tremendously. A lot of time is spent doing continuity tests, at great risks to people doing the tests. A lot of risk and cost are associated with things that could be done away with. Maybe it is ambitious to talk eradication of copper theft but this is a possible target. Mitigation of a great many things has been discussed for a long time. Concrete encasement of earthing is a mitigation point. But some thieves are so determined they will break the concrete. Mechanical barriers are not impenetrable and the only solution is to use a material which has virtually no market value. This has been proven in other countries.

Substation earthing
The focus of this article is transformer and transmission earthing, with transmission being the limiting case because of high currents involved. If we consider 50 kA fault current for example, that would be the most difficult solution to develop, and anything below that would be easy, so the principles which will be developed apply to any electrical or utility environment and even plant environments where copper is used for earthing. One of the big problems with transformers is that there is no convenient way to conceal the earthing, which uses mostly copper, so there is a tremendous amount of copper that is exposed. This is regularly harvested with the result that because there is no earthing, large transformers are lost when protection systems fail to operate.

There are many examples of copper or aluminium strip running down the side of steel structures. Existing standards suggest using the structure as part of the earth path as this structure provides a substantial cross section of steel, with low impedance, and copper conductors are completely superfluous in this case.

In developing the design requirements for an earthing system, we need to look at the amplitude and duration of the fault currents that the system must handle. Typical information about the mean and peak amplitudes of the neutral current that will be dealt with and the duration of the fault will determine the sizing. The heating effect will depend on the duration of the fault and good protection systems will affect the sizing of the conductor. However there is a need to design conservatively and design of earthing systems will involve a probabilistic approach.

If we consider the amplitude of neutral current associated with faults, we see that the mean of the normal distribution is somewhere very much lower than design value, so if the design value is 25 kA, this is a minimal risk and the mean of this current might be 5 kA. Then, in terms of the duration, the design may be 1 or 3 s, in the US most of the utilities are using 0.5 s. Europe is more conservative using 1 s.
Some people in the past used 5 s which possibly originates from the equipment’s short time rating, which is 2 s locally. Earthing should be more conservatively rated at 5 s. It is quite difficult to design a system for 25 or 50 kA for 5 s as it requires an enormous amount of copper or whatever material you are using.

In terms of the fault duration there is also an international requirement to design for the backup protection operating time, which is normally somewhere around 500 ms, but somehow 1 or 2 s are being used which has a very small probability. The overall probability of 25 kA for 3 s is something of the order of 10^-6. As a concept for the future, the probabilistic way of rating might be something reasonable.

The solution
Do we need to install copper? It appears not to be the case. The preferred solution is to use steel that is plated with copper or clad with copper. The SANS 623 standard specifies earthing rods consisting of high tensile steel with a 250 μm minimum copper outer layer. These are not intended as the main earthing system, but have been adapted as earthing connections. The limitation is that they are only available in 3.6 m lengths. The electroplating process has a limitation that it cannot do continuous coils, so in big substations it is necessary to join many sections together. Also the rods have 20% of the conductivity of equivalent copper cross-sectional area.

This is an immediate solution that has been done and is extremely effective in eradicating copper theft. What the working group is looking at is the development of this product to make it more practical and something that can be used in a more widespread fashion. Copper clad steel appears to be that solution. It is favoured in the NRS working group because it has been available commercially for a very long time and has been tested in America and proven internationally. There is a lot of value add in the manufacture of these conductors but the component’s material is substantially cheaper so we should expect it to be cheaper than pure copper, and should save capital costs. The real savings come from the non-technical losses over the lifespan of the substation installation. With the use of maintenance free connections, lifecycle costs could be 20% or less of that using conventional copper with bolted connection.

Copper clad steel conductor is available in standard sizes with 20%, 30% and 40% conductivity, for this application to be practical smaller diameter rods, that have thicker layers of copper should be chosen in order to meet the electrical requirements. The product is manufactured by induction heating steel and rolling on copper foil, giving a bonding between steel and copper with no connection interface for corrosion. Different shapes of conductor are required to provide a comprehensive set of solutions, including flat bar.

Industry has been approached to see if they could manufacture a steel conductor that is plated, coated or clad with copper and the response has been positive. Sample electroplated flat bar has been produced, but copper clad flat bar seems to be beyond the capability of the industry. If the industry requires flat bar this can be pursued. Flat bar is favoured because thin wide conductors can be stacked for higher current ratings. Because it contains steel it would be difficult to work with. Thin bar could be stacked, or better still placed side by side to give better utilisation because of the skin effect.

Conclusion
Eradication of copper theft needs a change of the entire earthing system to a theft deterrent conductor. The working group proposes that even the main buried grid should be copper clad, not only the earth tails or earth connections which are superficial. It is also the intention to engage the metal recyclers associations.

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