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DESIGN AND TESTING OF A 400 KV INSULATING CROSS-ARM

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INTRODUCTION

Electrical power transmission across developed countries relies upon the existing infrastructure of overhead lines and high voltage cables. These arterials of the energy system have historically provided a robust and sufficient network. In the immediate future and looking further forward, new challenges are being presented to the capacity of the existing infrastructure. The response to these challenges is an economic imperative for all such countries.

A major issue, particularly in the present economic situation is that building new infrastructure is very expensive. In addition, many countries have restrictive planning laws which prevent or slow down new development. Nonetheless the need to connect renewable low carbon electricity sources is immediate and necessary to achieve governments' low carbon emission commitments. This puts new load requirements on previously lightly-loaded parts of the network and increases loads on heavily committed routes. In the UK for example, generation changes will increase the required transmission from north to south. In the longer term, if electricity replaces gas as a prime space heating fuel and if electric vehicles replace hydrocarbon powered vehicles, the demands for electrical power to be moved from source to load will be even greater.

A number of low cost, incremental measures can increase capacity on existing overhead lines. These include re-tensioning existing conductors, re-conductoring with higher performance conductors and use of flexible AC transmission systems (FACTS) [1]. These are now routine upgrade activities as network operators optimize their assets. However, more radical steps are needed to get the greater increase of power transmission required. Up-rating the line in terms of voltage is an option, although this requires major spend and upgrade in associated substations and is limited by tower clearance. Clearly rebuilding lines with larger structures is also possible. In addition entirely new lines can be built to reinforce the network. Whilst the latter two solutions are attractive, they are both very costly and incur severe planning delays and uncertainty in many countries [2].

One step, which is now proposed and is potentially much lower in cost and quicker (in terms of planning and implementation) than rebuilding overhead systems, is to replace existing cross-arms and insulation sets on lattice towers with insulating cross-arms (ICAs). Insulating cross-arms provide an opportunity to upgrade existing lattice towers in both ampacity and voltage. This may be achieved using existing tower bodies, thereby reducing time to build and reducing planning issues. Such a technology has the potential to meet increased demand for connection of wind farms to networks and additional future needs arising from increased electrification of heating and transportation.

Previous insulating cross-arm technologies are reviewed and their limitations considered in this paper, which focuses on electrical issues. Then the design and testing of a new ICA system is reviewed. This includes a two-year trial in extreme weather conditions and a fully instrumented 400 kV system voltage installation in Scotland.

THE ROLE OF THE TRADITIONAL CROSS-ARM

Before considering the new cross-arm, the requirements of existing designs need to be considered. Structures holding overhead conductors need to be strong and inherently large to maintain the separations required by the voltages carried. In addition to the weight and tension of the conductors, ice-loading and wind-loading add to the mechanical forces the structure must support. Separation of conductors from the ground, each other and the towers must be designed for electrical over-voltages, caused by lightning and switching events in the circuits, in addition to power frequency over-voltages. Finally, in the rare case of a conductor failing, the structures must be capable of supporting the resulting asymmetric loadings.

The essential electrical and mechanical considerations lead to some generic tower geometries, the detailed engineering of which varies from territory to territory. Lattice towers are found as a universal solution because they have competitive capital costs, are readily designed with appropriate foundations and body strength, can be maintained and so give long asset lives, are easy to climb and are reasonably transparent from the visual perspective. Equally important, lattice towers are now accepted, albeit reluctantly by some, as part of the countryside.

Given the metallic lattice tower is at earth potential and it is strong enough to support the cables mechanically, there are additional requirements for:

- cross-arms to separate the conductor bundles from the tower
- insulators to carry the conductors but keep them electrically isolated from the cross-arm.

Figure 1 shows the electrical clearance requirements schematically. The clearances required at the tower are phase-to-phase between conductors and phase-to-ground between the conductors and the tower structure. In addition, there is a statutory requirement for phase-to-ground clearance. One feature of the suspension insulators shown is the sideways movement that results from winds with a component perpendicular to the conductors' length. This is known as blow-out and reduces the clearance between the tower body and conductors as shown in Figure 2. Cross-arms, towers and insulators must be sized accordingly.

INSULATING CROSS-ARMS

The opportunity

The opportunity presented by insulating composite cross-arms is that by integrating the cross-arm function (suspension and horizontal separation of the conductors from the tower body) and the electrical function (retaining electrical integrity) two distinct benefits arise. Firstly, there is no vertical insulator and so the position of the conductor is raised by a distance roughly equal to the insulator length. Secondly there is no issue of blow-out, potentially allowing the location of the conductor to be designed to be closer to the tower.

Raising the point of attachment on an existing tower enables a network operator to allow an existing or new conductor to sag more whilst retaining the statutory clearance to ground. This can be used to allow a higher current to flow because the additional thermal expansion of the cable becomes acceptable. It also allows a wider choice of conductor, if re-conductoring is being considered [2], providing potential cost and power transmission benefits. In addition the greater clearance can be used for voltage uprating.

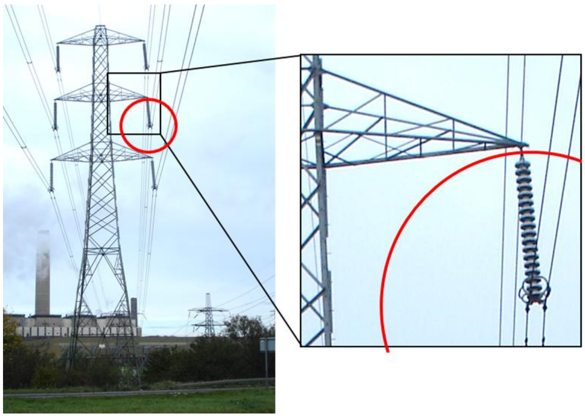

Figure 1 A steel lattice tower with conventional steel cross-arms and a suspension insulator. Phase-to-ground clearance requirements of one conductor bundle are shown by the red line.

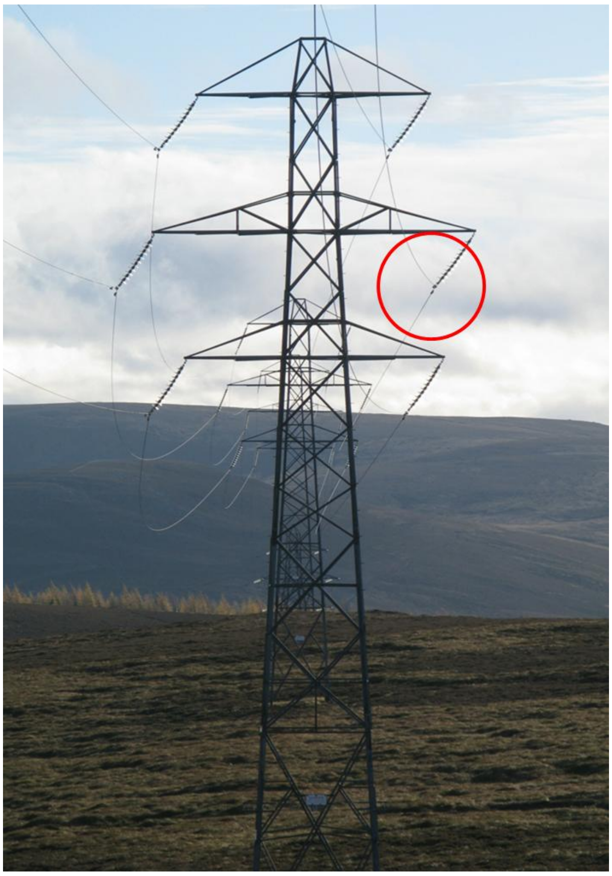

Figure 2 Blow-out of a conductor in high winds. The red circle shows phase-to-ground clearance requirements of one conductor bundle.

When considering tower designs for new lines, insulating composite cross-arms allow a choice or balance to be struck between towers with reduced heights and increased transmission capability. The former course may reduce planning/consenting times which would reduce time and cost, whereas the latter would give increased capacity on the same right of way.

Previous Work

The key feature of any high voltage composite cross-arm structure is having insulating elements which also have sufficient mechanical strength, particularly in compression. Such considerations are an extension of composite insulation on lower voltage systems and their use as tension members at all voltages. The main challenge is one of providing compressive strength to the lower elements of the cross-arm structure. The 'trident', design for single circuits on wood-pole structures might be regarded as an intermediate technology [3]. This design initially required significant mechanical properties offered by robust, heavy ceramic insulators but now uses lighter composite insulators.

Developing the concept of using glass-reinforced polymers as a strength member in tension to create an insulating cross-arm is well established. In 1964 BICC suggested tackling the underlying problem of insulators buckling under compression in an insulating cross-arm by using resin-bonded rods rigidly bonded by cross members, thereby enabling composite technology to fabricate a cross-arm for large towers as shown in Figure 3 [4]. The practicality of this system was, and is limited by its physical construction. Also, at that time, the polymeric materials were not available to provide high performance sheds, required to prevent surface tracking at high voltages. In the intervening period the use of silicone rubber composites for high voltage insulation surfaces has become standard technology.

NGK addressing the same opportunities published a seminal paper in 1971 [5]. The same needs and restrictions commented upon above were identified. Efficient use of right-of-ways, the need for unobtrusive designs and up-rating of lines are all described in this paper written over 30 years ago. This design was heavily tested. As with all cross-arms, the most basic design issue is that of providing tensile strength to the top elements which are under tension and compressive or buckling strength to those at the bottom which are in compression. Clearly, there are many other salient features of design such as vibration, response to transients and abnormal asymmetrical loads created by conductor failure but the key issue restricting implementation was acknowledged then to be the buckling characteristics of the structures.

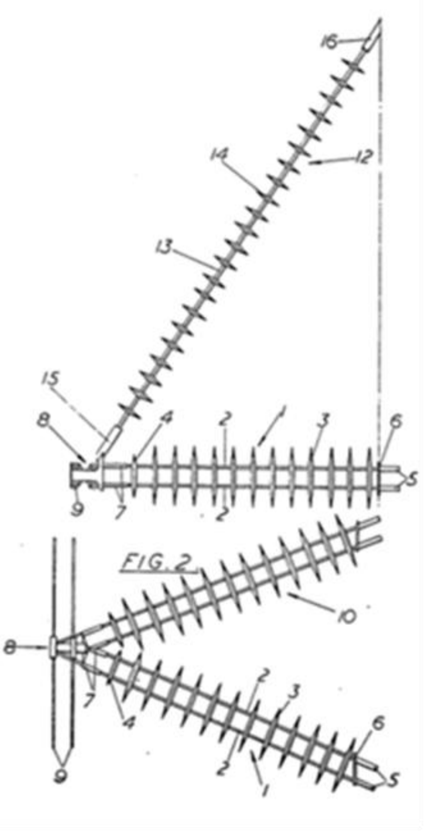

Figure 3 The three-dimensional cross-arm (side view above, plan below), fabricated from composite insulators with high tensile strength. Proposed in 1964 [4].

In the NGK design of 1971, wide-bodied ceramic insulators were used for the compressive elements. This construction is too heavy for practical implementation. Ceramic solutions are limited because tower bodies and increased foundation costs become too expensive to build if excessive extra loads have to be carried.

Composite insulators, being lighter than ceramics, have been used successfully in two dimensional structures. These structures are designed to collapse to the side if over strained asymmetrically by a conductor break. This has become a standard technology. Figure 4 illustrates a 275 kV installation from 1967 [6] and a contemporary 420 kV composite cross-arm [7]. In the latter case, compressive strength is added by using parallel wide bodied composite insulators but the need for high strength is reduced by accepting that the cross-arm will swing in broken wire situation. The use of parallel insulators to build up the compressive strength of the lower arm can improve the performance of the structure but is limited by the fundamental shape of the individual elements and doubles the number of ‘compressive’ elements, increasing cost and complexity.

A new approach is required if direct replacements for rigid metallic lattice cross-arms are to be found. This has been achieved using a combination of modern technologies and is described in the following section.

THE INSULATING CROSS-ARM

The design developed addresses the fundamental issue of the balance of compressive strength, weight and cost of fabrication [8]. The installation in the highlands of Scotland (Figure 5) and discussed later illustrates the key features. The tension members are industry standard composite suspension type insulators. The key feature is the compressive elements which have brought together well-proven material and processing know-how and innovative design. The mechanical strength comes from glass pultrusion. However, the obvious approach of making a very large diameter insulator would not work

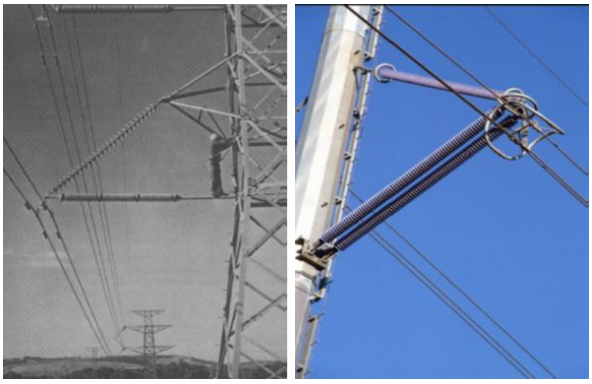

Figure 4 Two-dimension implementations of composite cross-arms in 1967 using ceramics on a 275 kV line [6] and a contemporary line using parallel post composite insulators [7].

Figure 5 Insulation cross-arm installed on a redundant line in Scotland for two years' load testing.

for two reasons. Firstly, the weight of the element would become prohibitive and, secondly, the manufacturing process would become extremely slow and thus costly. The use therefore of a cross-section shape which provides high compressive strength, resistance to buckling and low weight facilitates fabrication. The use of conventional material processing technology and industry standard liquid silicone rubber for the sheath and sheds also enables years of industry experience to provide confidence in the products' durability.

Finite element analysis (FEA) has been used extensively to design the product and particularly the end fittings which are an integral feature of the design [9]. The FEA modeling has been verified by standard laboratory testing, using power frequency and impulse testing in wet and dry conditions. However, new technologies such as this require field testing to gain confidence in the applicability of laboratory testing and modeling.

THE FIELD TESTING REGIME

Two key sites have been used in Scotland to verify the product design. Firstly, insulating cross-arms were installed on a de-energised line in the Scottish highlands (Figure 5) [10]. The lines were not energized and this allowed full mechanical monitoring of the cross-arms. In addition, the opportunity was taken to refine installation and operational techniques. Extensive real time recordings of snow and ice accretion have also given a unique set of records providing added confidence in the product. That trial has now been terminated since the line has been taken down. No degradation to the cross-arms has been identified after the two years exposure during which time the cross-arms regularly experienced sub-zero temperatures and winds of over 100 mph.

The second test site, detailed in [11] and shown in Figure 6, has been specially erected in a coastal location to provide an onerous environment for long-term measurements. A tower has been built, allowing two cross-arms to be erected at 90° orientation to each other. The cross-arms are energized at ~245 kV to give a 400 kV system stress. The physical orientation is designed to provide an understanding of how prevailing winds may effect performance. Weather is being extensively monitored at the site, including solar radiation, wind speed and direction, temperature, visibility, relative humidity and rainfall. As in the other installation, real-time video images are also being captured. This information is recorded locally but also relayed in real time to the University of Manchester for analysis. After six months, the cross-arms are both behaving as expected. A detailed physical inspection showed no damage and the silicone rubber surface is retaining its hydrophobicity. As a result, leakage currents are not showing any anomalous behaviour, although affected by the weather. An example of the data stream obtained is shown in Figure 7. This graph shows the current at the tower taken from each of the four insulating elements of one cross-arm. Each current is different because in this trial the elements are different and they are in different geometric situations with respect to each other and the bus-bar. Their relative behaviour is also as predicted from theoretical models.

It is a challenge to understand fully the behaviour of any such out-door test site, since all sites tend to vary from each other due to their environment. To gain a deeper understanding of the live test facility, a set of traditional insulators was set up in an identical arrangement to the composite cross-arms for three months before the formal trial started. This arrangement would not have the structural capability for a mechanically loaded trial but was robust enough to install and carry its own weight.

Figure 6 The live test site: fully instrumented and energized to 400 kV system voltages.

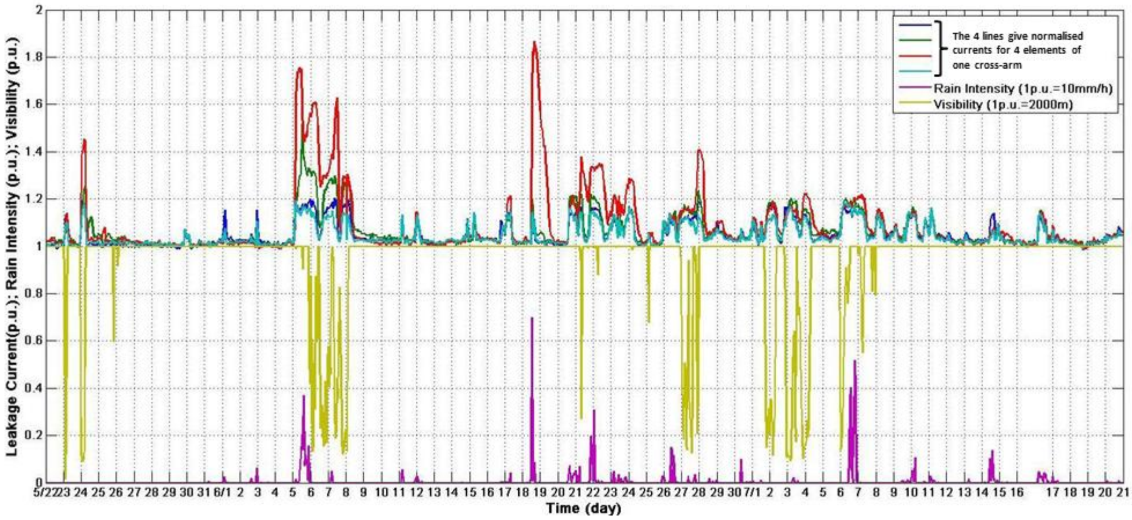

Figure 7 The purple bottom line shows rainfall patterns, the yellow line shows visibility (reducing from a normalised value of unity) and the four uppermost lines show the variation in current on each member of one cross-arm. The bottom axis gives time in days.

In this earlier trial, both new insulators, which had previous been in service for a long period as standard tension insulators, were used to identify comparative performance. Data from this trial on 'standard insulators' is still being analysed, but will be used to support interpretation of the cross-arms' behaviour.

To date no signs of ageing have been observed on the insulating cross-arms live trials and the currents measured have been in line with models developed and experience with traditional insulation systems.

CONCLUSION

A robust insulating composite cross-arm has been developed which will create an opportunity to increase the power flow through existing lattice tower power lines and reduce the visual impact and size of new lines built. The cross-arm uses a novel compression member design, employing traditional composite materials and processes, giving excellent compressive strength-to-weight ratios.

The insulating cross-arm is performing to design expectations after a two-year environmental trial, and six-months in an energized field trial.

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