Power transfer capacity improvements of existing overhead line systems

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***Abstract*— The increased demand for power transfer in combination with environmental and economic issues which set constraints to building new lines, force the implementation of new technologies into the existing system in order to improve its power capability. Such methods involve re-tensioning, re-conductoring, or modifying the tower design to utilize composite cross-arms. It is hypothesized that a composite cross-arm and a novel conductor together provide an insulating significant opportunity to increase the overhead line voltage. The paper explores the range of options that could be implemented on an L3 overhead line tower typically used at 275kV in the United Kingdom, and demonstrates clear improvement in power capacitiy through the implementation of new technologies.**

***Keywords*- ampacity; composite insulating; cross-arms; insulation co-ordination; power uprating; reconductoring; sag.**

I. INTRODUCTION

The steel towers used in transmission lines within the UK may be as old as 50 years. Recent changes to the power system structure as well as the continuous demand for load growth would ideally see the building of new overhead lines. However, environmental and economical issues pose barriers to building new lines and lead to the accommodation of new technologies into the existing Overhead Power Line (OHL) systems to improve their power capacity. This usually involves methods such as re-tensioning and re-conductoring.

Re-tensioning is usually applied in old lines for which the conductor sag is the limiting factor for increasing thermal rating or on surveyed lines which experienced unpredicted severe weather and electrical loading conditions. Re-conductoring involves replacing the existing conductors with conductors of larger sizes or alternative materials and technologies. In this way the conductor resistance and/or sag are reduced, increasing the system's power transfer capacity. Different conductor types can be used when elevated conductor operating temperatures are required allowing further increase in a conductor's thermal rating without loosing mechanical strength. Such conductors are usually described as High-Temperature Low-Sag (HTLS) conductors and have opened the horizons to new conductor designs applying new composite materials and technologies [1, 2].

Another possible solution involves modification of the tower design so as to incorporate composite cross-arms. Such solutions could also reduce the need for tower painting, reduce electromagnetic fields or improve pollution performance of a system. Composite cross-arms are as strong as conventional ones and usually lighter. The idea of having an insulated cross-arm on an OHL system is not new and relevant work dates back to the 1960s. Kimoto et al (1971) had successfully developed and tested a prototype of insulator cross-arm for a 345 kV transmission line [3]. Other groups also reported findings and developments in this area [4, 6] as well as some patented designs [7, 8]. Previous work seems to support potential benefits of composite insulator cross-arms such as the compaction of the tower structure for aesthetical purposes, the ability to erect the line in smaller rights-of-way, the reduction of electric and magnetic fields at ground level and the ability to carry higher voltages/currents.

This paper investigates the potential improvements in power transfer capacity that can result from the use of alternative conductors and composite cross-arms on an existing lattice tower OHL system. The paper builds on previous work that showed how novel composite conductors perform better than the conventional ones in a 33 kV wood pole structure and 275 kV lattice tower OHL systems [9, 10]. In particular, an insulation co-ordination study indicates the potential of voltage uprating for the tower modified with composite cross-arms system, and this is followed by re-conductoring scenarios with two conductor case studies.

II. METHODOLOGY

A. *Current Uprating*

In order to evaluate the potential benefits of re-conductoring an OHL system, a holistic computational methodology is used. This allows sag, ampacity and tension calculations to be carried out while considering the electromechanical properties of the system [10, 12]. The implementation of this methodology allows a comparative analysis of the performance of the chosen conductors, under the current specifications and with the hypothetical application of composite cross-arms.

Conductor sag and its clearance to the ground depend on the OHL system structure, the conductor electrical and mechanical properties, the environment, and operating conditions [11]. The critical operating conditions that develop the maximum sag are the maximum mechanical and electrical loading, one of which influences the designed minimum clearance to the ground and consequently, the power rating of the system. The maximum mechanical loading occurs at the designed maximum weather loading of the structure (i.e. when ice is attached to, or wind is incident on the conductor) and

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defines the development of the maximum conductor tension (MCT). At maximum electrical loading, the tension is at a minimum because of the thermal elongation resulting from the current flow. Usually, during these loading conditions, the worse sag and minimum clearance to ground occur and they limit further allowable increase in current flow.

The methodology summarized in the flowchart of Fig. 1 emphases the key electromechanical elements that influence a conductor's sag and ampacity calculations. A holistic perspective of the system performance is taken by considering four different groups of data together for the calculations: Overhead line data (i.e. structure type and dimensions, tensile loading strength, latitude, azimuth, elevation), weather data (i.e. ambient temperature, wind speed, ice, pollution level), conductor data (i.e. materials, number and shape of strands, diameter of strand, grease pattern) and operational data (i.e. frequency, maximum conductor temperature) [11-13].

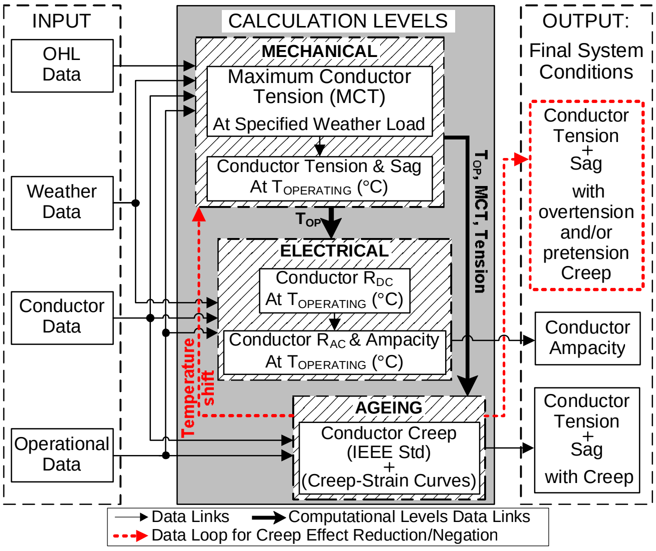

Figure 1. Flowchart of power rating computations of OHL [13]

The computations involved in this process are divided into three different levels which are performed separately and then linked together to compute the final conditions. The mechanical computation section is performed first for the calculation of conductor sag at maximum operating temperature, hence MCT is required [14]. Computations are then performed within the electrical level to determine the conductor AC resistance. As a final step, the ageing computation deals with the long term plastic elongation (creep-strain effect) at the system everyday temperature and the shorter term influence of working at elevated temperatures and the maximum tensile load. Once this level of calculations is performed the final system conditions of a particular conductor on a given structure are known: conductor ampacity, conductor sag with creep, and conductor sag when creep is negated.

B. *Voltage Uprating*

Any voltage uprating case study requires determining the new voltage level which the circuit will reliably sustain. This voltage level may be limited by one or more of the following factors, which guide the feasibility of each case: (a) clearance to the ground (b) insulation at the tower (both the clearance to the tower and the insulator length), (c) electrical gradient on the conductor surface, and (d) electrical gradient on the earth's surface. In this paper we report a preliminary analysis based on (a) and (b).

Insulation coordination is required to ensure an adequate and balanced line design. Data needed to assess insulation coordination are collected with reference to expected voltage stresses, the voltage withstand level of each component, and the characteristics of surge protectors. These values and necessary equations are derived from relevant standards [15-17]. Using the formulas below the electrical distances for switching (D_{el}^{sf}) and lightning (D_{el}^{ff}) impulses can be determined.

$$D_{el}^{sf} = \frac{e^{\frac{K_{cs}U_{sf}}{1080K_aK_z^{sf}K_g^{sf}}} - 1}{0.46}, \quad D_{el}^{ff} = \frac{U_{ff}}{530K_aK_z^{ff}K_g^{ff}} \tag{1}$$

with: U : Withstand Voltage cs : coordination factor
K_a : altitude factor K_g : gap factor K_z : deviation factor
ff : fast front sf : slow front

The clearances at the tower during maximum wind load are reduced by a factor k_1 because the low probability of simultaneous occurrence of an overvoltage whilst the conductor is moved by wind load is very small [15].

III. SYSTEM DESCRIPTION

According to the methodology [11], it is important to specify the variables that define the OHL structure and the weather loading in order to initiate the computations.

A. *The 275 kV Lattice tower System: Existing and Modified*

The 275 kV lattice tower studied here is a typical L3 type standard suspension tower. The diagram of the L3 lattice tower with the key dimensions for this study is illustrated in Fig. 2. A span length of 366 m is used with a weight span of 720 m. The maximum loading tension permitted by the strength of the structure is 72 kN and the maximum weight that can be supported by each cross-arm is 30 kN. The tower was designed in 1953 for an insulator string set with a maximum length of 3.46 m and a 30° swing angle. This includes all additional steel work for the twin bundle configuration [18]. However, a total of 3.32 m for the insulator set is employed here with a 35° swing angle according to current common practice [19].

The insulator string examined for this system is composed of 20 U120BP designation dishes with 120 kN minimum failing load [20]. Each dish has a 146 mm spacing and 440 mm creepage distance. The total length of the insulator is 2920 mm and has an aggregated creepage distance of 8800 mm which corresponds to 29 mm/kV specific creepage distance. This is just below the very heavy level of pollution corresponding to 31 mm/kV of minimum nominal creepage distance [21].

For the modified hypothetical case study examined in this paper, it is assumed that each of the conventional steel tower cross-arms is replaced with a composite insulated cross-arm of equivalent external dimensions and mechanical strength. The modified tower is shown on the right hand side of Fig. 2. In this design no further insulators are required, since the insulator cross-arm provides the full requirements for insulation between phase and earth. Steel work of approximately 0.4 m in total is considered for the attachment of the conductors at the outer-edge of the cross-arm.

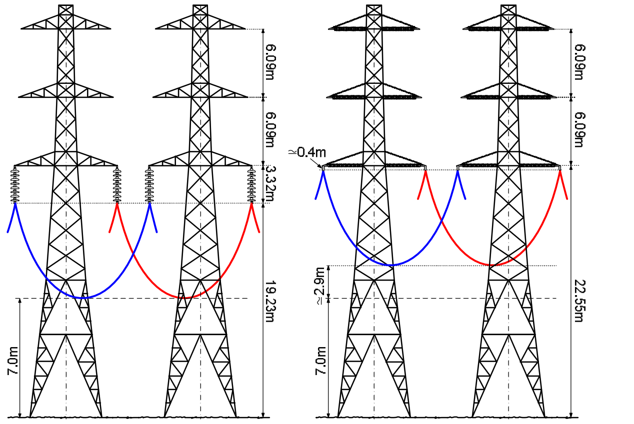

Figure 2. Outline diagram of existing (left) and modified (right) 275 kV L3 type lattice structure.

B. *Conductor Case Studies*

The performance of two different conductors on the above system is investigated within this study. The first case involves LYNX Aluminum Conductor Steel Reinforced (ACSR) and was selected because it is the conductor the tower was initially designed for and therefore represents a real scenario of the existing system [22]. This conductor has a 19.55 mm diameter. As a comparative case, the 397-T16 Aluminum Conductor Composite Reinforced (ACCR) is chosen because of previous results [9] and its equivalent size (18.4 mm) [2, 19]. The twin bundle configuration is investigated for both case studies.

C. *Initial System Conditions for Calculations*

The MCT of the OHL structure is evaluated here at a “normal” altitude loading case with wind pressure of 380 N/m2 and radial glaze ice thickness of 12.5 mm and 913 kg/m3 density at -5.6 °C. Furthermore, the everyday tension (20% rated breaking strength for aluminum based conductors) is applied at the everyday temperature of 5 °C. The maximum electrical loading conditions for the steady-state thermal rating are taken as clear atmosphere, wind speed of 0.61 m/s, 90° wind direction, 0.5 emissivity and solar absorptivity, 90° azimuth and 30° latitude. The ambient air temperature is 20 °C. Conductor resistance at TOP is calculated as in [11, 12]. The plastic elongation is calculated for 10 years and no elevated creep effect is used for these particular conductors [23].

Table I presents the calculated clearance values for the three types of withstand voltages that the L3 tower is designed for. These types include the 35° swing angle wind load condition (U_S), at still air (no wind) load condition for switching and lightning impulses (SI and LI). For the calculation of the electrical distances (eq. 1) values of 1000 m altitude, 35° swing angle, and k_1=0.65 are used. The electrical distances (D) are increased by 10% at no wind load [15].

TABLE I. CLEARANCES REQUIRED FOR THE 275 KV SYSTEM

	Withstand Voltage Type		
	U_S	**SI**	**LI**
Voltage Level (kV)	300	850	1050
Standard Required Distances (m)	1.37	2.4	2.2

IV. RESULTS

A. *Insulation Co-ordination Study*

The design ensures the appropriate clearances between the conductors and the earthed metallic lattice tower body or cross-arms are kept to prevent flashovers under operational conditions including the steep fronted surges which occur during line switching as well as the reduced clearances that are accepted for the maximum swing angle of 35°. Fig. 3 shows the results of the calculations with minimum clearance at 0° angle. These are approximately 10 cm more than the required withstand distance of switching impulses that dominate the 275 kV voltage level tower design (Table I).

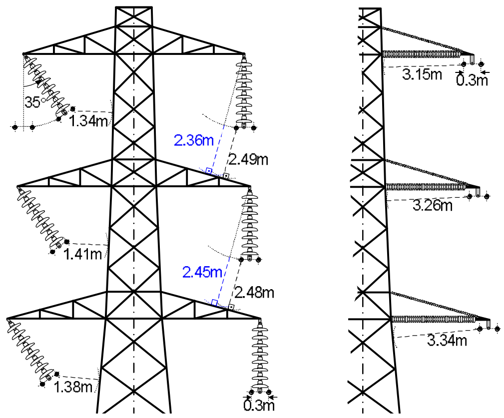

Figure 3. Clearances of the 275 kV L3 type tower with normal suspension set (left) and modified with composite cross-arm (right).

It can also be seen that the reduced clearance at 35° wind loading is marginally below the required values indicating that the voltage level on the existing system cannot be further increased without changing the current common practice (i.e. without altering the k_1 factor). The minimum clearances from conductor to the cross-arm beneath are also shown in the figure and these occur at approximately 20° swing angle. This indicates that the clearance required for small swinging angles (in this case 2.1 m) is preserved.

The corresponding clearances for the hypothesized system with the insulated composite cross-arms are shown on the right hand side of Fig. 3. These are increased to such a level to allow voltage uprating of the system to 400 kV. This voltage uprating is permitted since the clearances provided by the modified structure are larger than the required clearances (Table II) and the cross-arms can deliver the required creepage distance.

TABLE II. CLEARANCES REQUIRED FOR A 400 KV SYSTEM

	Withstand Voltage Type		
	U_S	**SI**	**LI**
Voltage Level (kV)	420	1050	1425
Standard Required Distances (m)	1.83	3.1	3

B. Power Uprating with Existing System

The insulation co-ordination study of the existing system showed that voltage uprating is not feasible. Therefore, the only way to increase its power transfer capacity is by re-conductoring. Results so far indicate that novel HTLS conductors have better mechanical and electrical performance at normal operating temperatures [9, 10]. The system is also governed by strength limitations which makes heavy conductors inappropriate for installation. The two illustrative case studies chosen for this investigation involve the conductor that is already installed on the system (LYNX) and a novel composite ACCR conductor (397-T16) [19].

Fig. 4 shows the plots of ampacity and sag per conductor at different operating temperatures for three different conductor installation conditions. The plot of initial condition does not consider any creep (denoted as Initial in Figures). "Final" indicates the conductor sag after 10 years in operation including creep. "Final O-T" results include an over tensioning of the conductor at installation time and represents the sag values with 10 years creep. The vertical dotted lines in the figures denote the 12.2 m maximum permitted sag of this structure, which consequently defines the maximum permitted operating temperatures for this system.

Observation of both figures shows that the over-tensioning does not totally negate the aging effects on sag because by employing it the system alters the initial conditions and therefore more creep is developed. The maximum conductors operating temperature when creep is mitigated is 73 °C for ACSR and 95 °C for the composite conductor, with ampacities of approximately 1170 A and 1480 A, respectively.

Therefore, when using the new composite conductor the increase of power achieved for the same system is approximately 25%. Another implication of these results is that although the novel conductor can operate continuously at 210 °C [2] the structure does not permit operation above 100 °C as this will infringe the minimum safety clearance to the ground.

C. Power Uprating with Hypothesised System

When using composite cross-arms, clearances are increased towards the tower as well as to the ground. This, therefore, allows for voltage uprating to 400 kV and increase of the power transfer capability of the OHL system.

Fig. 5 shows the plots of percentage in ampacity increase and sag per conductor at different operating temperatures for the three different conductor installation conditions (defined as before). The origin of the plots (zero point) indicates the maximum permitted sag and ampacity of the existing 275 kV system, for each installation condition. The new maximum allowed sag limits for the original and uprated systems are denoted here with the dotted vertical lines.

The new system with composite cross-arms allows LYNX to operate at 100 °C with an approximate 20% increase in ampacity without infringing the clearance to the ground for both voltage levels. It also appears that this conductor can operate up to 146 °C (for the overtensioned case on the uprated system) without infringing the ground clearance, however it is unrealistic to operate LYNX at temperatures above 100 °C due to annealing mechanisms that damage the conductor [23].

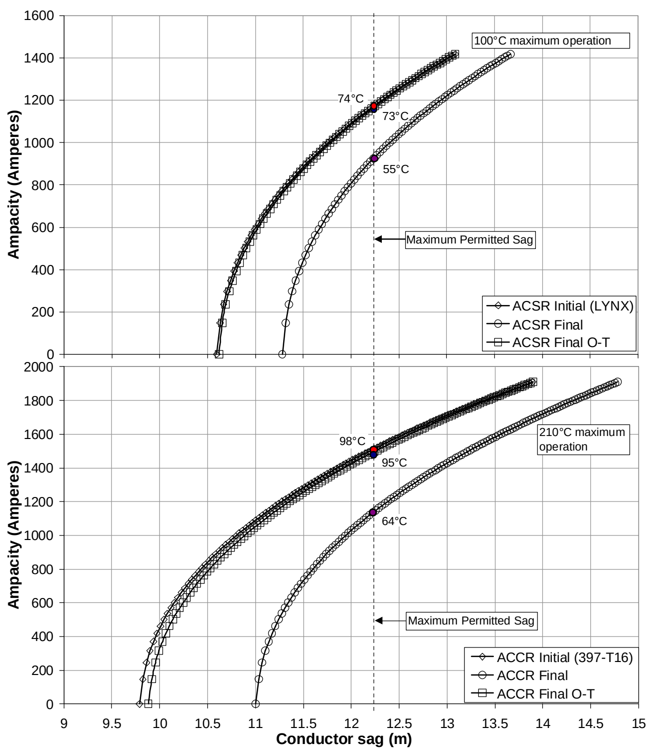

Figure 4. Plots of ampacity and sag for different temperatures for ACSR and ACCR conductors.

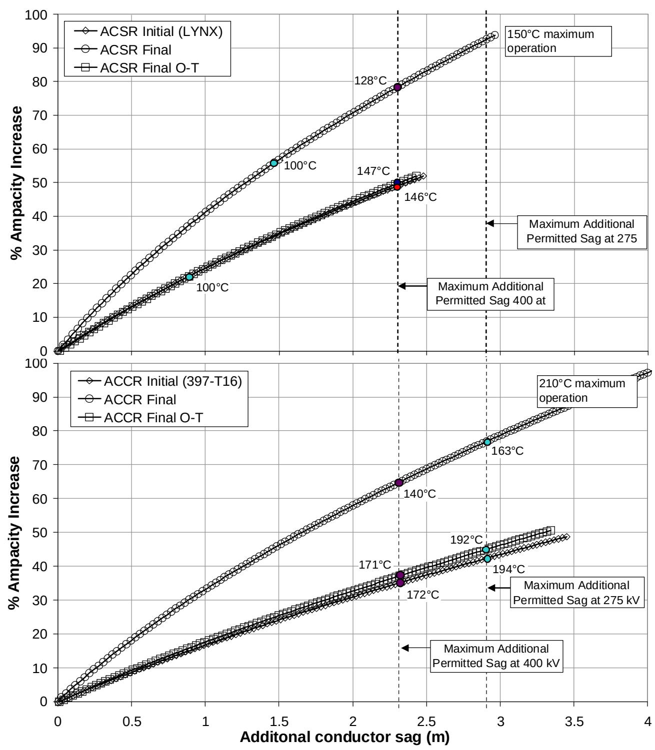

Figure 5. Plots of additional ampacity and sag for different temperatures, under the modified system, for ACSR and ACCR conductors.

In the case of re-conductoring the hypothesized system with a novel composite conductor, temperatures up to 172 °C and 194 °C can operate (for the final overtensioned case) without infringing ground clearances for the 275 kV and 400 kV voltage levels respectively (Fig. 5).

V. Discussion & Conclusion

The scenarios studied here are only indicative of the potential benefits that can be offered by novel technologies, implemented on existing OHL systems. Further analysis could involve more re-conductoring scenarios, with different HTLS conductors, as well as conventional ones.

It should also be noted that the voltage uprating scenarios have not included the required electromagnetic field and corona analysis which is the second step involved in such investigations. This would be the next step linked closely with exhaustive investigation of further scenarios, to identify the optimum solution for implementation.

The investigation of the different scenarios in this study showed that the hypothesized system with composite cross-arms has the following potential benefits:

I. It allows voltage uprating to 400 kV without infringing the required clearances to the tower and ground that dominate the design.

II. It permits the utilization of the elevated temperature operation capabilities of the novel HTLS conductors, which cannot be realized with the existing system.

An additional benefit of this structure is that there is no swing angle and hence the k_1 factor is not included in the calculations at the point of tower. This simplifies the insulation coordination study at the tower level by eliminating this quite arbitrary factor which is used for the reduction of clearances at the maximum swing angle.

Table III compares the systems in respect to their power transfer capabilities under the investigated scenarios.

TABLE III. Clearances Required for a 400 kV System

System Configuration Scenarios		Max. Op. Temp. (° C)	Ampacity (A)	Power per phase (MVA)
Std (LYNX)	275 kV	73	1170	185
Std re-conductored (397-T16)	275 kV	95	1480	237 (28.1%)
Cross-Arm (LYNX)	275 kV	100	1427	226 (22.2%)
	400 kV	100	1427	330 (78.4%)
Cross-Arm re-conductored (397-T16)	275 kV	172	2116	336 (81.6%)
	400 kV	194	1198	461 (149.2%)

The use of novel technologies can provide power uprating of up to almost 150% compared to the existing capability. Even when voltage uprating is not an option for the operator a simple increase of maximum conductor operating temperature is feasible due to increase in maximum permitted sag.

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