TOWARDS THE GRID OF THE FUTURE: BUILDING ON AND EXPANDING THE CAPACITY OF THE EXISTING NETWORK

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Abstract: The problem of massive electricity transmission is addressed by presenting alternatives, including new technology implementation, for optimising the power capacity of existing Overhead Line Systems (OHL) that require minimum additional expenditure on new lines. We particularly demonstrate significant improvements in power transfer capacity of an existing L3 overhead line tower typically used at 275kV in the United Kingdom, that are afforded with the use of smart technologies like composite cross-arms (CCA) and alternative conductor technologies (such as HTLS). The performance of high-voltage overhead lines under the various improvement scenarios is guided by a unified evaluation framework, which includes sag, ampacity, and losses calculations and also incorporates more operational indicators, relevant to voltage upgrading. Results include insulation co-ordination of the upgraded OHL system as well as analysis of corona effects and electromagnetic fields. A comparison of the relative increases in current and voltage ratings that can be achieved by different technology combinations is carried out through the holistic performance evaluation of the system with and without smart technologies. The implications of the results for future flexible grids are finally discussed.

1 INTRODUCTION

Modernisation of the existing Overhead Line (OHL) System has become essential, given the current lifestyle which is highly dependent on a continuous and sufficient electricity supply, the arrival of electrical cars, and many environmental concerns. The underlying claim of recent publications [1] is that in order to deliver a sustainable energy sector, network companies will need to test and employ new technologies, and ensure that the existing infrastructure is used efficiently to its maximum potential.

There has been great activity to identify ways to increase the capacity of an existing OHL avoiding the huge expenses of new structures. This usually can be achieved by either increasing the thermal or/and dynamic limits of an OHL system. The focus of this paper, however, is on methods of improving the power transfer capacity through existing OHL that require small structure modifications, thereby keeping the cost and permission requirements at low levels. In particular, these methods involve re-conductoring or re-tensioning the line.

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 loss of 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 [2, 3].

We previously showed that novel HTLS conductors have better mechanical and electrical performance at elevated operating temperatures [4-7]. However, larger ground clearance is required to achieve the full potential of HTLS conductor on existing OHLs. Composite cross-arms (CCA), which replace conventional cross-arm and suspension insulators, increase the ground clearance of the same OHL structure, and thus provide opportunities for better utilization of HTLS conductor technologies. Such solutions could also reduce the need for tower painting, reduce electromagnetic fields or improve pollution performance of a system. The idea of insulated cross-arms on OHL systems dates back to the 1960s and later [8-10] including some patented designs [11, 12].

In this paper, we analyse the potential improvements in power transfer capacity of an existing lattice tower OHL system through the use of smart technologies like CCAs and alternative conductor technologies. This is possible through the demonstration of different scenarios of voltage uprating using both CCA and HTLS conductors, and their evaluation with a holistic methodology which is briefly summarised next.

2 METHODOLOGY

The performance of high-voltage overhead lines under the various improvement scenarios is guided by a unified evaluation framework, which includes sag, ampacity, and losses calculations and also incorporates more operational indicators, relevant to voltage upgrading scenarios.

2.1 Power Rating Computations

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 [13]. 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 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 Figure 1 emphases the key electromechanical elements that influence a conductor's sag and ampacity calculations.

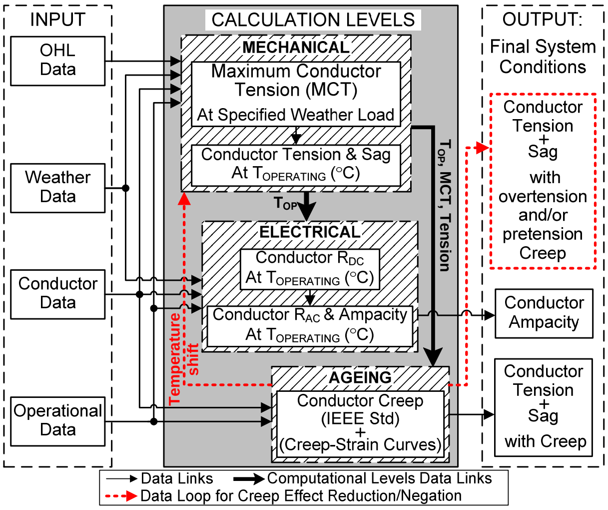

Figure 1: Flowchart of power rating computations of OHL [5]

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) [4-7]. Calculations are performed in the three different levels shown in Figure 1 (i.e. mechanical, electrical and ageing) to give as output the final system conditions (i.e. conductor tension and sag, with and without creep, and conductor ampacity).

2.2 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. These analytical considerations are described next.

2.2.1 Electrical and Magnetic Fields

Ground level electric and magnetic fields (EMF) of OHL became of increased concern recently, with the increase of transmission voltages. These effects are particularly important because of their influence on humans and animals. The magnitude of EMFs in proximity to a transmission line results from the superposition of the fields due to the 3-phase conductors. According to [14] the electrical field is described by the electrical strength E, and is measured in kV/m. The magnetic field, however, is determined by the magnetic induction or magnetic flux density B, rather than the magnetic field strength H, because it is quantifiable and therefore more measurable; both quantities are linked with equation (1).

$$B = H \cdot \mu_0 \cdot \mu_r \qquad (1)$$

Where: H is measured in A/m

μ_0: the permeability of the vacuum $\left(\mu_0 = 4 \cdot \pi \cdot 10^{-7} V \cdot s / (A \cdot m)\right)$

μ_r: the relative permeability ($\mu_r = 1$ in air)

2.2.2 Corona Phenomena

Corona effects on conductors are generated by the disruption of air dielectrics around the conductor when the electrical field on conductor surface reaches the critical surface gradient. Since the corona discharges are not permanent, but instead occur as sparks around the conductor, electromagnetic radiation are emitted from the conductor causing different undesirable effects. Such effects include: (a) Emission of radio interference, (b) the production of audible noise in the vicinity of the line, and (c) the generation of corona losses.

Because of these effects, it is usually recommended to keep the conductor surface gradient within certain limits and usually at a range close to the 20 kV/cm and not exceeding the 25 kV/cm. Usually OHLs are designed to give a conductor surface gradient close to 17 kV/cm [14]. The widely used CDEGS software [15] is employed for these analyses.

2.2.3 Insulation Coordination

Insulation coordination is required to ensure an adequate and balanced line design. Computations to assess insulation coordination are performed 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 [16-19]. This analysis for the particular investigated system is presented in detail in [20] so this information is mainly summarised here and illustrated through Figure 2.

3 SYSTEM DESCRIPTION

A typical double circuit 275kV aerial line used in the United Kingdom is employed for the case studies presented in this paper. The lattice tower is a typical L3 275kV type standard suspension tower. The diagram of this L3 lattice tower with the key dimensions is illustrated in Figure 2, as well as its modification with CCAs.

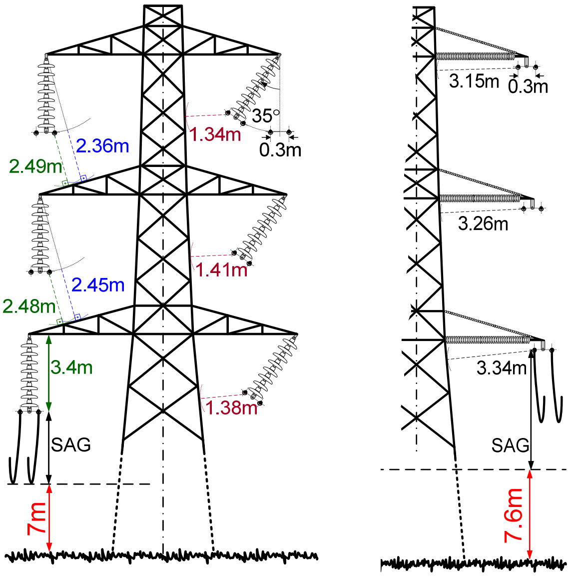

Figure 2: Clearances of the 275 kV L3 type tower with normal suspension set (left) and modified with composite cross-arm (right).

The span length employed for the purposes of these analyses is set at the standard value of 366m, used in UK. The maximum loading tension permitted by the strength of the structure is 180 kN and the maximum weight that can be supported by each cross-arm is 30 kN. These values do not consider any safety factors and therefore the appropriate safety factors have to be included during modelling. A total of 3.40 m for the insulator set is employed including the steel work for the twin bundle configuration and at the cross-arm that holds the insulator [18, 21, 22].

When the composite cross-arms are installed on the L3 275kV type standard suspension tower, the tower is configured as illustrated in the right hand side of Figure 2. The increase in ground clearance for this system when compared to the one without composite cross-arms is 2.98 m; this is the result of the insulator string removal and some steelwork. Therefore, the increase in ground clearance depends on the insulator string length.

The maximum conductor tension (MCT) of the OHL structure is evaluated at a "normal" altitude loading case with wind pressure of 380 N/m^2 and radial glaze ice thickness of 12.5 mm and 913 kg/m^3 density at -5.6°C. Furthermore, the everyday tension (20% rated breaking strength for aluminium 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. The creep mitigation technique employed involved 20°C of negative temperature shift, independently of the initial system limitations of tower strength, as well as conductor vibration limit and strength.

The performance of five different conductor types on the studied system is considered in the analysis:

- All Aluminium Alloy conductors (AAAC)
- Aluminium conductors steel-reinforced – low steel content (Soft ACSR)
- Aluminium conductors steel-reinforced – high steel content (Hard ACSR)
- Aluminium conductors composite - reinforced (ACCR)
- Aluminium conductors composite core /trapezoidal wire (ACCC/TW)

4 RESULTS

4.1 Current uprating

The first result of the analysis involves the combined performance of sag and ampacity of the conductors on the existing system. Figure 3 shows an example of such analysis with the UPAS conductor under probabilistic design criteria (i.e. with reduced safety factors on the system) as employed in the UK system, with ice loading of 35.5 mm radial thickness. By employing the composite cross-arm technology an additional 2.98 m of ground clearance (Figure 3) can be provided. This can be used efficiently to increase the thermal rating of this system by allowing higher thermal ratings. In particular, Upas can operate up to 75°C without altering its mechanical properties (due to annealing) and can hence result in 10% (under the over-tension condition) increase in ampacity.

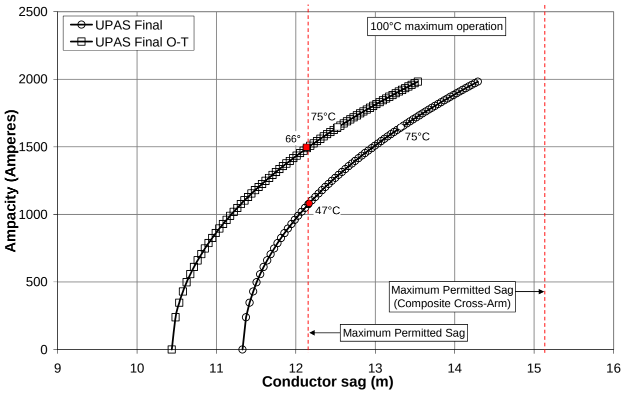

Figure 3: Plot for ampacity and sag for different temperatures for UPAS (AAAC) conductor.

Figure 3 includes elevated temperature operation of 72 hours, however, longer durations are feasible. Therefore, it is important to note that further increase in ampacity can be achieved by increasing the operating temperatures of the conductor up to 100°C assuming that controllable elevated operating temperature is allowed due to increased ground clearance.

When novel conductor technologies [2, 3] are examined on the L3 system there is a further increase in power transfer capacity since these conductors can operate at elevated temperatures (e.g. 200°C) without losing their mechanical properties. The sag performance of these conductors, compared to conventional technologies is presented in Figure 4 for maximum weather loading conditions, because it is reported that the novel conductors sag more under these conditions (compared to maximum electrical loading at 70°C) [4, 6, 7, 23] .

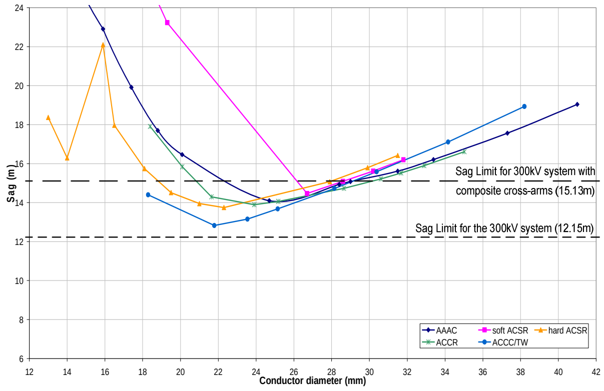

Figure 4: Sag performance of different conductors under maximum weather loading conditions.

As shown in Figure 4, when MCT is applied on the system the sag performance exceeds the maximum allowed values in all cases. Even when the ACCC conductors are installed on the system the minimum ground clearance is infringed at MCT conditions due to increased elastic modulus of the conductor. This ground clearance infringement is effectively addressed by employing the CCAs in all cases examined within the comparable weight range (i.e. between 2kg/m to 3.5 kg/m).

4.2 Summary of insulation coordination

The CCA technology increases considerably the clearances of the L3-Std structure window that allows the voltage uprating to 400 kV without infringing the minimum required clearance distances as well as those used by the standards and technical specifications. Furthermore, the elimination of the suspension components (i.e. insulator string, insulator fittings and conductor fitting) reduces quite considerably the horizontal disposition of the conductor due to swinging and therefore the mid span clearances become larger than the ones provided by the L2-Std 400 kV tower. This clearly indicates that there are no clearance constraints for upgrading the voltage of the L3-Std to 400 kV when the CCA technology is employed on the structure. However, corona effects evaluation is required to complete the voltage upgrading analysis of the L3 system with cross arms (L3-CCA) [20].

4.3 EMF and Corona Related Phenomena

According to the insulation coordination analysis, the CCA technology can be employed to upgrade the 275 kV L3 standard UK system to 400. Such upgrading, however, would increase EMF at both ground and conductor as well as corona related phenomena.

The maximum EMF values, which usually occur beneath the OHL, as well as values at 25 m to side are presented for the L3-Std and L3-CCA systems in Table 1 along with a range of typical values within UK. As can be seen, the L3-CCA at 400 kV reduces the maximum EMF values by a third. Although there is a small increase of the electric field values at the edges of the corridor (i.e. at 25 m from the central axis of the tower) the values remain at the lower end of the range of typical values within UK, indicating that the EMFs at ground do not pose a limitation for voltage uprating.

Table 1: Comparison of the critical values of electric and magnetic fields

Steel Lattice Tower Structures					
		Electric Field (kV/m)		Magnetic Field (µT)	
		Maximum	25 m to Side	Maximum	25 m to Side
275 kV	L3-Std	1.94	0.2	2.6	0.42
	L3-CCA	1.26	0.26	1.63	0.43
	Change	**-35%**	**+30%**	**-37%**	**+2%**
400 kV	L2-Std	3.22	0.51	2.6	0.42
	L3-CCA	1.81	0.38	1.63	0.43
	Change	**-44%**	**-25%**	**-37%**	**+2%**
Typical Values*		3 – 5	0.2 – 0.5	5 – 10	1 – 2

Red indicates increased values **Green** indicates reduced values
*Values adopted from NG (http://www.emfs.info/Sources+of+EMFs/Overhead+power+lines/)

Analysis of corona phenomena for the same system under the twin bundle conductor configuration showed infringement of limits with all conductors, hence a triple bundle configuration is employed. The conductor voltage gradients for the L3-Std and L3-CCA systems are illustrated in Figure 5 for both 275 kV and 400 KV voltage levels. The continuous line indicates the existing 400 kV system (L2-Std) conductor gradient. Figure 5 shows that the triple Upas, Grosbeak from CTC, Dove and Grosbeak from 3M produce lower surface gradients than those of the existing L2-Std system.

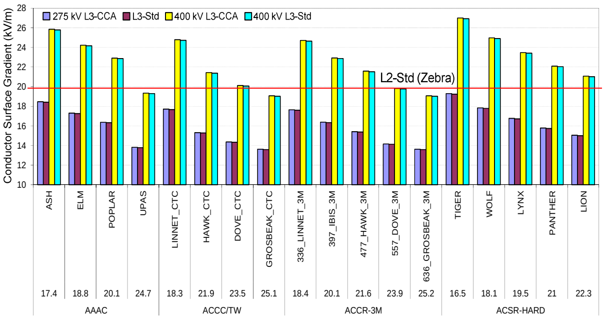

Figure 5: Maximum conductor surface gradients for the 275 kV L3-CCA system with different conductors – triple bundle configuration.

Analysis also gave the conductor performances on audible noise, radio noise and corona losses, when triple bundle configuration is employed on the examined L3 systems. We only present the first (Figure 6) because of space limitations - the pattern was similar though.

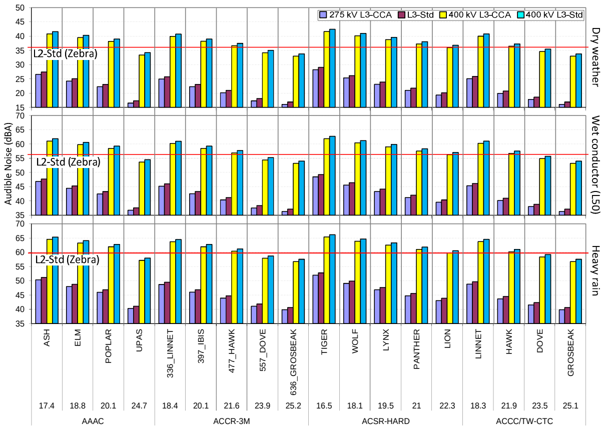

Figure 6: Maximum audible noise at ground for the L3-Std and L3-CCA systems-triple bundle configuration.

According to the results, the L3-CCA at 400kV system produces acoustic noise at the same level as the L2-Std system only when the installed conductors have a diameter greater than or similar to approximately 22.5 mm. The larger conductors in triple bundle configuration reduce the elevated corona effects, resulted by the voltage uprating of the L3 system to 400 kV, to levels below those of the L2-Std system. However, by using three sub-conductors instead of two the total resultant weight per phase conductor configuration increases to such levels that require the overhead line system weight span to be reduced or lighter conductor technologies to be implemented. For example, the triple 3M-Hawk conductor configuration can only be afforded by the tower mechanical strength and foundations when the resultant conductor weight is reduced from 35.5 mm ice thickness to 28.4 mm or the OHL system's weight span is reduced from 732 m to 554 m.

5 DISCUSSION AND CONCLUSION

Table 2 compares the systems in respect to their power transfer capabilities under some of the investigated scenarios. Table 3, then summarizes the electrical performance of the system under the voltage upgrading and with tripe bundle configuration when weight span reduction up to 20% is required. The CTC conductors have trapezoidal strands, and hence higher fill factors, which lead to more weight for the same diameter. Conductor size to weight ratio is very important for voltage upgrading in order to avoid excessive corona phenomena and thus, this conductor technology is not shown in Table 3.

Table 2: Power transfer capability of the L3 system under different thermal uprating scenarios

OHL system	Creep Mitigation	Conductor Name	Max. operating temp. (°C)	Ampacity (A)	Power per phase	
					(MVA)	%
L3-Std	Not employed	Upas*	47	1076	171	0
		636-T16(3M)	104	2090	332	94
		Grosbeak-E (CTC)	200	3228	513	200
	Employed	Upas*	66	1490	237	0
		636-T16(3M)	122	2286	363	53
		Grosbeak-E (CTC)	200	3228	513	117
L3-CCA	Not employed	Upas	75	1641	261	53
		636-T16(3M)	200	2384	467	173
		Grosbeak-E (CTC)	200	3228	513	200
	Employed	Upas	75	1641	261	53
		636-T16(3M)	200	2384	467	173
		Grosbeak-E (CTC)	200	3228	513	200
*Highlight indicates the reference (existing) systems						

Table 3: Power transfer capability of L3-CCA system with voltage upgrading at 400 kV

Conductor Name	Max. operating temp. (°C)	Ampacity (A)	Power per phase	
			(MVA)	%
Creep Mitigation is not employed				
Upas*	47	1076	171	0
Elm	75	1753	405	137
Poplar	75	1897	438	156
397-T16 (3M)	177	3092	714	318
Creep Mitigation is employed				
Upas*	66	1490	237	0
Elm	75	1753	405	71
Poplar	75	1897	438	85
397-T16 (3M)	195	3237	748	216

From the analysis the CCA technology has been shown to be very beneficial for thermal uprating of the investigated L3 lattice tower used in UK. It allows increased values of sag and therefore higher operating temperatures particularly for the novel HTLS conductor technologies. The thermal uprating of the L3-CCA system can increase the power transfer of the system up to 200% in some cases providing enough clearance at maximum thermal as well as weather loading conditions.

Voltage upgrading is also feasible with CCA technology installed on the L3 system. However, in order to reduce the corona effects and acoustic noise, triple bundle configuration is required with a consequent increase in resultant conductor weight. If a reinforcement of the tower and/or foundations is not an option, then reduction in weight span as well as in bundle separation distance is required. Installing larger conductors in triple configuration can lead to further increase of thermal uprating, but at the expense of weight span length reduction or requirements for tower and foundation reinforcements, in some cases. Further analysis is needed in this area.

6 ACKNOWLEDGMENTS

This work was supported by the EPSRC Supergen V, U.K. Energy Infrastructure (AMPerES) Grant in collaboration with U.K. electricity network operators (http://www.supergenamperes.org).

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