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**Electricity Supply to Africa and Developing Economies –
Challenges and Opportunities**

Technology solutions and innovations for developing economies

Uprating of high voltage overhead transmission lines using intermediary catenary suspenders

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1. Introduction

The proposal of the synopses is to establish a low cost alternative for the uprating of existing overhead lines by use of intermediary catenary suspenders.
Cigre (International council on large electric systems) study committee SCB2 on overhead lines has three main goals:

- Increase acceptability of overhead lines.
- Increase capacity of existing overhead lines.
- Increase reliability and availability of overhead lines.

2. Problem statement

The problem of increasing the capacity of existing lines, especially in urban areas, is one that has plagued utilities for some time and is why it is one of the main strategic directives of Cigre. In urban areas the congestion of overhead power lines by buildings and other infrastructure causes a big problem for uprating the lines. Further to this, the lines tend to feed commercial- and domestic properties and areas and it is very difficult to get extended outages on the lines.
Infrastructure such as roads and parking lots get built inside the power line servitudes restricting the amount of allowable sag on the lines.
Some of the proven solutions include:

- Re-tensioning of existing conductors.
- Re-conductoring / re-stringing of the existing lines under live conditions with HTLS conductors.
- Probabilistic study of the lines operating under increased loading conditions.

This proposal is for a cheaper solution which can be installed under live conditions and will allow existing lines to increase current by as much as 40% without increase in sag of the conductor.

2.1. Scale of the problem

Increasing the current in a line has a direct influence on the conductor temperature. The old lines were designed to run under a specific temperature and capacity and to increase it without having security measures in place to minimize the impact of increased temperature on the conductor could have very bad mechanical consequences.
Looking at a normal fictitious span with a single conductor, if the temperature of the conductor would be increased from 40 ℃ to 80 ℃ ov er a span length of 400 m, the sag would increase by 1.87 m. This increase in sag could create severe under clearance which could create very dangerous situations.
The increase in temperature could however allow for a dramatic increase in the current in the line.
Using the steady-state heat balance equation, the load capacity can be calculated:

Equation 1: Steady-state heat balance equation

$$Heat\ gain = Heat\ loss$$
$$P_J + P_S + P_M + P_i = P_c + P_r + P_w$$

The maximum load capacity of a short line is most often determined by the operating temperature of the conductors. The maximum allowable temperature would be that which will create the greatest allowable sag or the maximum loss of tensile strength through core degradation.
The increase of the electrical current on the bare overhead conductor has a direct influence on the temperature. The temperature is also influenced by the environmental parameters and the conductor properties. When carrying a specific current, a conductor would be cooler during winter than during summer. Environmental parameters that play a role are wind speed and direction (m/s and angle with conductor), ambient temperature (℃), and the applied solar radiation (W/m^2) [22].
The steady-state thermal rating of a line is the current carrying capacity of a line calculated using constant weather conditions.
Although other technical documents show the thermal behaviour of overhead lines in slightly different ways, the result is very similar. As stated in Equation 1, the heat balanced equation is also used with the following inputs:

Equation 2: Joule heat gain [23].

	$P_J = I^2 R_{dc}\left[1 + \alpha\left(T_{avg} - 20\right)\right]$	W/m
I	Effective DC current	A
R_{dc}	DC Resistance at 20°C per unit length	
α	Temperature coefficient per degree kelvin	1/K
T_{avg}	Mean temperature of the conductor	°C

Equation 3: Solar heat gain [23].

	$P_S = a_s SD$	W/m
a_s	Absorptivity of conductor surface (For avg. use 0.5)	
S	Global solar radiation	W/m^2
D	External diameter of conductor	m

Equation 4: Convective cooling [23].

	$P_c = \pi\lambda_f (T_s - T_a) Nu$	W/m
Reynolds number	$Re = \frac{\rho_r V D}{v_f}$	
Nusselt number for natural convection cooling:	$Nu = A_2 (Gr \cdot Pr)^{m_2}$	
Gr	Grashof number	
Pr	Prandtl number	
Nusselt number for forced convection cooling:	$Nu = B_l (Re)^n$	
V	Wind velocity	m/s
v_f	Kinematic viscosity ($1.32 \times 10^{-5} + 9.5 \times 10^{-8} T_f$)	m^2/s
ρ_r	Relative air density ($\exp(-1.16 \times 10^{-4} y)$)	Kg/m^3

T_f	0.5 (T_s + T_a)	
λ_f	Thermal conductivity ($2.42\text{x}10^{-2} + 7.2\text{x}10^{-5}\ T_f$)	W/mK
R_f	Surface roughness (d/[2(D-d)])	

Equation 5: Radiative cooling [23].

	$P_r = \pi D \varepsilon \sigma_B [(T_s + 273)^4 - (T_a + 273)^4]$	W/m
σ_B	Stefan-Boltzmann constant ($5.67\text{x}10^{-8}$)	W/m^2-K
ε	Emissivity (0.23 to 0.95, 0.5 for average)	

Calculating the resistance of the conductor
As seen in Equation 8 regarding the calculation of the temperature of the conductor, the calculation of the resistance of a conductor plays a crucial role, especially for the Joule heat gain calculation.

Equation 6: Calculation of DC resistance of an ACSR conductor.

	$\frac{1}{R_{dc}} = \frac{\pi {d_s}^2}{4\rho_s}\left[1 + \sum_1^{n_s} \frac{6n_s}{k_{ns}}\right] + \frac{\pi {d_a}^2}{4\rho_a}\left[1 + \sum_1^{n_a} \frac{6n_a}{k_{na}}\right]$	
	$k_n = \sqrt{1 + \left(\frac{\pi D_n}{l_n}\right)^2}$	
d	Diameter of wire	(m)
D	Mean diameter of layer – subscript n for layer number	(m)
l	Lay length of layer	(m)
ρ	Resistivity of material	(Ωm)
α	Temperature coefficient	(1/K)
	Note: Subscript "s" and "a" is for steel and aluminium respectively.	

The DC resistance for known conductors is most often tested and given by the suppliers (see Table 4Table 4: Conductor properties and DC resistances.). A calculation of the AC resistance at high current densities is however necessary [24].
As the temperature gradient between the core and outer layers may be as much as 10 ℃, combined with the uneven current distribution through the Aluminium layers, the simplified methods should not be used [24].
The resistance for a conductor is more when it is carrying AC current than when carrying DC current of the same magnitude due to the skin effect pushing the current to the outer layers of the conductor. The resistance could be as much as 10% more.
At the same time the Eddy current and magnetic hysteresis losses in the steel core increases the resistance of the conductor. If the steel core would be removed, all magnetic effects would be negligible.
The skin effect factor is given by **Error! Reference source not found.**:

Equation 7: Skin effect equation.

	$k_j = \frac{R_{ac}}{R_{dc}}$	Ωm

If this is combined with Equation 2 the Joule heat gain equation can be changed to:

Equation 8: Joule heating equation including AC/DC conversion [25].

	$P_J = k_j I^2 R_{ac}\left[1 + \alpha\left(T_{avg} - 20\right)\right]$	W/m
I	Effective AC current	A
R_{ac}	AC Resistance	Ωm
α	Temperature coefficient per degree kelvin	1/K
T_{avg}	Mean temperature of the conductor	°C
k_j	Skin effect resistance factor - for average use 1.0123	

An algorithm was used to calculate the increase in current for the increase in the Temperature of the conductor from 50 ℃ to 75 ℃ fo r different weather conditions. The current and weather conditions for the conductor at 50 ℃ and 75 ℃ are shown in Table 1 and Table 2.

Table 1: Conductor current rating for different weather conditions and a conductor temperature of 50 °C.

Current (Ampere)	Wind speed (m/s)	Wind direction (deg)	T_{amb} (°C)	Solar (Watt/m^2)
560.857	0.88	14.85	6.6	500.5
555	3.4	270	35.6	1036
566.24	0.598	43.73	18.5	0

Table 2: Conductor current rating for different weather conditions and a conductor temperature of 75 °C.

Current (Ampere)	Wind speed (m/s)	Wind direction (deg)	T_{amb} (°C)	Solar (Watt/m^2)	Increase in Current (%)
740.25	0.88	14.85	6.6	500.5	24
707.5	3.4	270	35.6	1036	22
966.64	0.598	43.73	18.5	0	41

It can be seen that for an increase in conductor current from 50 ℃ to 75 ℃ (1.2 m increase in sag for a single Sycamore conductor, 400 m span), a current increase between 24% and 41% can be expected.

This increase can be seen as a dramatic improvement but still poses some problems. The operator would not be sure of the environmental conditions that the line is operating in and would then not be able to increase the current. Further to this, the increase in temperature would cause degradation in the material and would cause a permanent increase in the sag on the conductor because the tension in the conductor would remain almost constant.

2.2. Problem statement summary

The conductor temperature difference between the core and the surface will increase at high current densities for ACSR conductors. In some cases the temperature of the core will greatly increase and the core will degrade which will lead to an increase in sag [16], [12], [24].

If the gradient of temperature between the core and the surface exceeds 10 ℃ (according to many literature references) it is suggested to reduce the surface temperature of the conductor.

One of the main reasons for the increase in sag includes the conductor weight and tension for any given span that will remain the constant based on the catenary equations even if the conductor extends slightly in length due to temperature increase.
If the increase in temperature resulted in a drastic decrease in the conductor tension, the conductor core would not deteriorate during an increase in the load because it would not be under the same tension.
If the operator of the line could increase the current in the line (by as much as 40%) while knowing that the sag would not increase, the line could be operated safely at higher temperatures even if the ambient conditions were not known.

3. Solutions

3.1. Re-tensioning of existing lines

The practice of re-tensioning an existing line puts some severe strains on the conductor. The core of the phase conductor is placed under higher tension which degrades it further when operating under higher temperatures.
Higher tensions on the phase conductor also increase the stresses on structures and foundations. This is of particular concern if the line is already old and the state of all components of the line isn't known. The line therefore needs to undergo a comprehensive study to check all components (including the conductors and structural members) for corrosion and other factors which degrade the line with time.
Once this is done, the re-tensioning exercise can be done but also requires extended high risk work. All of the conductors need to be placed in running blocks at suspension structures and regulated to the higher tension. The conductor needs to be cut and shortened. To do this requires extensive outages.

3.2. Re-conductoring / re-stringing of the existing line

To re-string an existing line with a conductor such as a high temperature low sag conductor requires extensive outages or creates a high risk process if it is to be done live. The cost of the conductor is also very expensive and requires newer expensive fittings at all connection points. The conductors alone could cost as much as five times the price of current ACSR conductors. The conductors already account for 35 – 45% of the line cost for new lines and thus show the dramatic cost increase that can be expected with the use of such types of conductors.

4. Intermediary catenary suspenders

The use of the intermediary catenary suspender has the goal of being the cheapest and easiest solution to the problem of the increased sag of the phase conductor at higher operating temperatures.
The intermediary suspender is connected to the earth wire of the overhead power line and uses a low weight composite insulator and extension links to maintain the same length to the conductor as would be seen under low sag conditions. At certain positions such as road crossings, the conductor ground clearance could even be increased.
The suspender places a small uplift force on the conductor at strategically selected positions in the span. With finite element analysis software, the conductor tensions and clearances were modelled. It was found that with the increase in the conductor temperature, the sag that would have increased in the phase conductor simply increases the tension in the earth wire. The phase conductor, which operates at a higher temperature,

has very little increase in sag and the tension in the phase conductor actually decreases with the increase in temperature. The decrease in tension of the phase conductor with the increase in temperature would result in slower degradation of the core of the conductor and less creep.

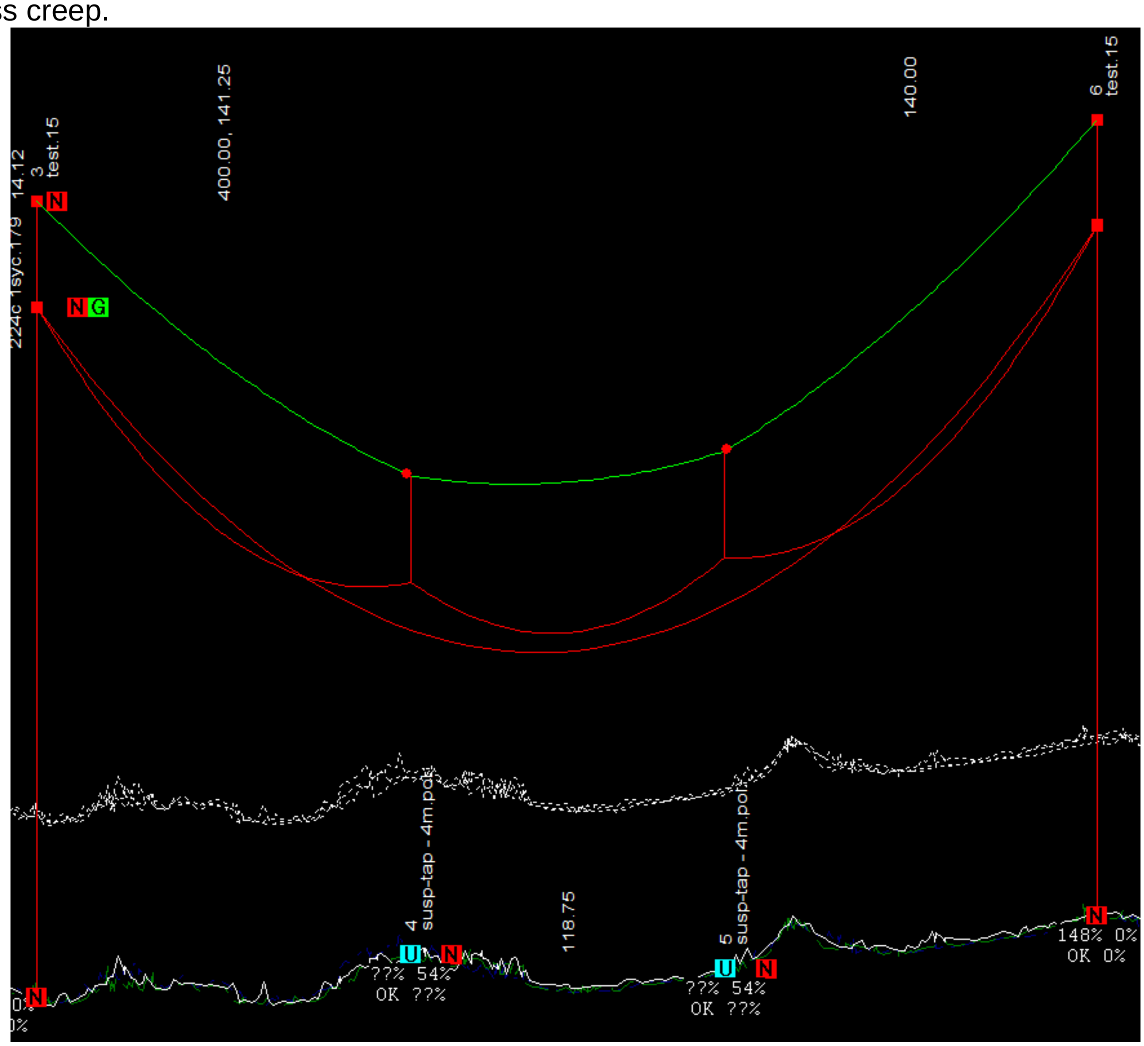

Figure 1: Comparison between using inter catenary suspenders and not.

The amount of tension increase in the earth conductor is by only 15 – 17% more than the everyday tension. This would only be for short periods of time while the line is run at increased capacity and the ambient conditions results in the conductor running at higher temperatures.

Figure 1 shows a finite element model with all conductors (excluding earth wires) at 80 ℃. Comparison of the FEA model and calculations of the model show this to be an accurate model. The model shows a 400 m span of single Sycamore conductor strung at an everyday tension of 1800 m and an earth wire strung at an everyday tension of 2100 m. The clearances are shown in

Table 3.

Table 3: Vertical clearance comparison of suspended vs. non-intermediate suspended catenary

	Vert. clearance @ 50 °C	Vert. clearance @ 80 °C
Non-suspended conductor	13.93	12.55
Inter-catenary suspended conductor	14.26	13.25
Earth wire	19.6	18.92

If the phase conductor temperature is increased to 80 ℃ in the FEA model and the earth wire temperature held at 40 °C, the vertical mid-span clearance of the earth wire will remain almost the same and the mid-span clearance of the phase conductor with the inter catenary suspenders will increase from the amount in

Table 3 – 13.25 m to (19.6-18.92 = 0.68 m) 13.93 m. This is the same as the non-suspended phase conductor at 50 ℃.

The conductor with no inter-catenary suspenders shows a 1.37 m vertical clearance decrease (13.93 m to 12.55 m).

The earth wire shows an increase in tension up to 2470 m. This is 17% more than the everyday tension (2100 m) but is only for a short period of time and while the line is operating under the worst environmental conditions for heating of the conductor as well as increased current. This still has no impact on the ground clearance though, which is the greatest safety concern.

4.1. Installation and cost

To install the intermediary suspenders is also a very safe activity, the line needs to be profiled and the positions necessitating the use of suspenders identified. The length of the suspenders would then be described for each position and they can be installed by simply attaching them to the live line using an insulated bucket truck. The cost of the installation therefore seems very low in comparison to re-tensioning of conductors or re-stringing a whole line. Outages would also not be required.

4.2. Limitations of use

The concept would only be for use on lines with single conductors or lightweight conductor bundles. This is due to the limitation being the tension in the earth wire placing additional load on the structures.

4.3. Additional areas for study

Using the same concept, new lines could be designed using the same inter-catenary suspenders to decrease the amount of sag in a span. This would lead to longer span lengths between structures. To construct fewer structures could result in a drop in the cost of lines.

5. Conclusion

The increase in temperature can result in no increase in sag and a drastic decrease in the conductor tension, the conductor core would not deteriorate during an increase in the load because it would not be under the same tension. The current can be increased by as much as 40%.

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Table 4: Conductor properties and DC resistances.

Conductor name	Stranding	St strand dia. (mm)	Al strand dia. (mm)	DC resistance @ 20 °C (Ω/km)
Mink	1//6	3.66	3.66	0.4546
Hare	1//6	4.72	4.72	0.2733
Tiger	1/6//12/18	2.36	2.36	0.2202
Panther	1/6//12/18	3	3	0.1363
Goat	1/6/12/18	3.71	3.71	0.0891
Tern	1/6//9/15/21	2.25	3.38	0.0718
Zebra	1/6//12/18/24	3.18	3.18	0.0674
Dinosaur	1/6/12//12/18/24	2.37	3.95	0.0437
Bersford	1/6//10/16/22	3.32	4.27	0.0420