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Techno Economic Analysis of the Use of High Temperature Low Sag (HTLS) Conductors in the Sri Lanka's Transmission System

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Abstract: High Temperature Low Sag (HTLS) conductors are introduced with the intention of mitigating some of the disadvantages of the conventional overhead conductors. When compared to conventional conductors, HTLS conductors have better electrical and mechanical characteristics and by using these conductors in overhead transmission lines, some of the complex issues related to power transmissions could be resolved. However, most of the utilities are still in a quandary about using these conductors in place of conventional overhead conductors which have provided a commendable service to them over a period of a century or so. It is because of their lack of experience in using them in the field as well as because of the novel appearance of the conductors. Almost the entire transmission system in Sri Lanka comprises of overhead lines constructed using conventional conductors, especially ACSR conductors. Utility engineers therefore do not have much knowledge on HTLS conductors and also have very little experience in using them.

This paper discusses the possibility of adopting the HTLS conductor technology in the Sri Lanka's transmission system. The properties, behavior and special characteristics as well as the techno-economic feasibility of using HTLS conductors instead of the conventional conductors are discussed in depth. Lastly, the issues and challenges related to the application of HTLS conductors are discussed.

The results of this research will provide valuable information on the possibility of using HTLS conductors in the Sri Lanka's transmission system.

Keywords: HTLS conductors, Energy loss, Electromagnetic field, Knee point temperature, Thermal expansion, Sag, Tension

1. Introduction

Most of the overhead transmission lines in the transmission system in Sri Lanka have been developed using ACSR (Aluminium Conductor Steel Reinforced) conductors. There have been however occasions when other types of conductors such as AAAC (All Aluminium Alloy Conductors) have been used, especially in coastal areas where problems related to corrosion have to be mitigated. The ACSR conductor is the best among the conventional types of conductors, mainly due to its robustness, low unit weight, flexibility and cost-effectiveness.

However, ACSR conductors have limitations. Conventional ACSR conductors cannot be operated at high temperatures and their energy loss during bulk power transmission is significant. At the same time, with the increase in the electricity demand in the country, the capacity of most of the older transmission lines has become insufficient and the construction of new lines has become more and more challenging due to constraints imposed by ROW (Right of Way) requirements. Therefore, many transmission lines in the system are being proposed to be uprated, to cater to the increasing electricity demand in the country. However, the conventional types of conductors cannot be used to increase the capacity of existing lines mainly due to the mechanical limitations of towers. As existing towers have been designed for a particular type of conductor, conductors with higher cross sections which have a higher capacity cannot be strung on them without violating safety limits.

To mitigate all these restrictions, conductor manufacturers have come up with a new technology called HTLS, and the conductors made using this technology are said to be of

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superior performance compared to the conventional conductors. Basically, they have been designed to operate at elevated temperatures which result in lower conductor sags and improved loss reduction. However, in Sri Lanka, utility engineers have very limited knowledge and experience in the use of HTLS conductors.

Some of the most popular HTLS conductors available in the market are[1] as follows:

- G(Z)TACSR – Gap Type (Super) Thermal Resistant Aluminium Alloy Conductor Steel reinforced
- ZTACIR – Thermal Resistant Aluminium Alloy Conductor Invar Reinforced
- ACCC – Aluminium Conductor Composite Core
- ACSS – Aluminium Conductor Steel Supported
- ACCR – Aluminium Conductor Composite Reinforced

2. Necessity of HTLS Conductors

More than 95% of the transmission lines in the Sri Lankan grid have been developed using conventional ACSR conductors. They cannot be operated at temperatures above 90° C.

Most of the proposed lines in the system that are to be uprated also have been constructed using ACSR conductors. Because of their operating temperature limitations, they are unable to tolerate additional current flows. Their operation beyond 90°C could cause their aluminium outer layers to lose their mechanical properties due to annealing.

The second option would be to replace the existing conductors with the same type of conductors of a higher cross section. By doing so, the current flow can be increased up to the desired limit without exceeding the maximum operable temperature. However, with the introduction of larger conductors, the increased forces that will acton the towers will violate the safety factors of the towers.

Therefore, conductors having mechanical properties similar to those of ACSR conductors capable of withstanding higher temperatures will have to be used in the thermal uprating of the existing lines.

When conductors are operated at elevated temperatures, the thermal sag of the lines will increase, violating the stipulated ground clearances. This may cause the violation of the Electro Magnetic Field (EMF) limits under the power lines. It can also be observed that the Right of Way (ROW) of most of the older lines has been disturbed by the public, for instance, by constructing illegal buildings beneath the lines.

The increase in the thermal sag may violate the electrical clearances and will require the removal of such illegal constructions leading to complicated social issues.

Therefore, conductors having higher thermal limits and lower thermal expansion will be required to overcome the limitations of the conventional overhead conductors. Typically, HTLS conductors could be operated at elevated temperatures in the range of 150°C to 250°C, with reduced sag[2].

With the reduction of the natural energy sources and the high investments required for power generation, most of the utilities are compelled to improve the efficiency of their existing electricity systems. HTLS conductors have been formed in such a way that they have lower thermal resistance, thus improving the efficiency of the transmissions.

3. Features of HTLS Conductors

3.1 Higher Thermal Rating

As discussed above, HTLS conductors can be operated at elevated temperatures, and their current ratings will be higher than those of the similarly sized conventional conductors. Their current ratings can be found using IEEE 738-2006 or IEC 61597 standards. This current rating is measured using the heat balance equation[3]:

$$I_{max} = \sqrt{\frac{P_{Rad}+P_{Conv}-P_{Sol}}{R_T}} \qquad \dots(1)$$

where R_T-Unit resistance at a given temp. (Ω)
P_{Sol}-Solar heat gain by the conductor (W)
P_{Rad}- Heat loss by radiation (W)
P_{Conv}-Convection heat loss (W)

HTLS conductors are so manufactured that their AC resistance is lower than that of similarly sized (diameter) ACSR conductors at any given temperature. This is usually achieved by altering the heat treatment of their aluminium outer layers and by increasing the fill factor using trapezoidal outer strands.

Table 1 - Aluminium conductor outer layer

Type		% IACS*	Max. Operating Tem. (°C)
Hard Drawn	1350-H19	61.2	90
Fully Annealed	1350-O	63	250
Thermal Resistant	TAL	60	150
Ultra-Thermal Resistant	ZTAL	58	200

Source: CTC conductor manual

**IACS (International Annealed Copper Standards) a value of 100% refers to a conductivity of 5.8 x 10⁷ Siemens per meter*[4]

Table 1 shows the heat treatment methods of various types of outer layers made of aluminium and aluminium alloy that are used for bare overhead conductors. The outer layer of ACSR conductors is made of hard drawn aluminium and thus they cannot operate beyond 90°C.

However, HTLS conductors are made of other types of aluminium alloys or by using alternate heat treatment methods and they can therefore withstand higher temperatures.

3.2 Lower Linear Thermal Expansion

The conductor sag will depend on the linear expansion of the conductors. It is calculated using Equation (2).

$$D = \frac{WS^2}{8T} \qquad \ldots(2)$$

where D- Conductor Sag (m)
W - Unit weight of the conductor (N/m)
T- Conductor tension at any given temperature (N)
S- Span (m)

The conductor tension (T) at a given temperature will depend on several factors. Usually, it is calculated using the State Equation given by;

$$H_2^2\left[H_2 - H_1 + \frac{E.A.(S.m_{c1}.g)^2}{24H_1^2} + E.A.\alpha(t_2 - t_1)\right] = \frac{E.A.(S.m_{c2}.g)^2}{24} \ldots(3)$$

where H_2- Stress at given temperature (N/mm^2)
H_1- Initial Stress (N/mm^2)
E- Modulus of Elasticity (N/mm^2)
A - Conductor Cross Section (mm^2)
m_{c1}- Initial unit mass (kg/m)
m_{c2}- Unit mass at given temp. (kg/m)
g- Gravitational Constant (ms^{-2})
α- Thermal Expansion coefficient (°C^{-1})
t_1- Initial Temperature (°C)
t_2- Operating temperature (°C)
S - Span Length (m)

"T" can be calculated by multiplying the stress by the conductor cross section. With the increase in the temperature, the conductor tension will decrease. However, according to Equation (3), when the thermal expansion is reduced, the reduction of the tension can also be lowered and according to Equation (2) the sag will then not increase. This phenomenon is used in the HTLS conductors in a unique way.

3.3 Knee Point Temperature

Knee Point Temperature (KPT) is the temperature at which the conductor tension is completely takenup by the conductor core. Normally, conductors are made up of two layers which are known as inner and outer layers. The outer layer is mainly responsible for conducting the current flow while the inner layer is responsible for takingup the mechanical tension of the conductor.

Usually during the initial stage, conductor tension is shared between the outer and inner cores. When the temperature of the conductor is increased, the amount of tension taken up by each core will get changed as the two cores have different expansion coefficients. Since steel has a lower thermal expansion coefficient, there will be more tension in the steel core and the aluminium outer layer will begin to compress.

In ACSR conductors, the total tension cannot be taken up by the steel core since the temperature cannot exceed a particular temperature. However, HTLS conductors have been formed to enable the core material to take up the entire tension beyond a certain temperature, which is known as the KPT. Therefore, when finding the tension of a HTLS conductor at a temperature higher than the KPT, the state equation will have to be used twice, initially for the tension shared between the outer and the inner layers when the temperature is between the initial (minimum) temperature and the KPT and later for only the inner layer when the temperature lies between the KPT and the final operating temperature.

Modulus of Elasticity

The value of "E" in Equation (3) has to be selected depending on whether the temperature is less than or more than the KPT.

$$E_{AS} = E_{AL}\frac{A_{AL}}{A_{TOTAL}} + E_{ST}\frac{A_{ST}}{A_{TOTAL}} \qquad \ldots(4)$$

where E_{AL}- Elasticity of aluminium (GPa)
E_{ST}- Elasticity of steel (GPa)
E_{AS}- Elasticity of aluminium +steel (GPa)
A_{TOTAL}- Total cross sectional area (mm^2)
A_{AL}- Area of aluminium strands (mm^2)
A_{ST}- Area of steel strands (mm^2)

Expansion Coefficient

In Equation (3), "α" shall also be selected based on the temperature as the effective expansion will depend on the amount of tension shared between the core and the outer layer.

$$\alpha_{AS} = \alpha_{AL}.\left(\frac{A_{AL}}{A_{TOTAL}}\right).\left(\frac{E_{AL}}{E_{AS}}\right) + \alpha_{ST}.\left(\frac{A_{ST}}{A_{TOTAL}}\right).\left(\frac{E_{ST}}{E_{AS}}\right) \qquad \ldots(5)$$

Where α_{AS} -Conductor coefficient of thermal expansion
α_{ST} - Steel coefficient of thermal expansion
α_{AL}- Aluminium coefficient of thermal expansion

Usually, the conductor core is made of material that has a lower thermal expansion co-efficient.

Table 2 shows the coefficient of expansion values of different conductor material.

Table 2 - Properties of conductor core material

Description	Modulus of Elasticity (GPa)	Tensile Strength (N/mm^2)	Coefficient of Exp. (x 10^{-6}/°C)
HS steel	200	1379-1488	11.50
EHS steel	200	1517	11.50
Aluminium Clad	162	1103-1344	13.00
Carbon Hybrid Epoxy	110-150	2275-2585	1.60
Invar Alloy	160	1034-1069	3.00

Source: CTC conductor manual

Unlike ACSR conductors, all HTLS conductors achieve their KPTs within their operating ranges. However, different HTLS conductors have different KPTs, depending on the conductor material, conductor formation etc. It is always better to have a smaller KPT, so that low sag properties could be achieved beforehand. Figure 1 summarizes KPTs of different types of conductors[5].

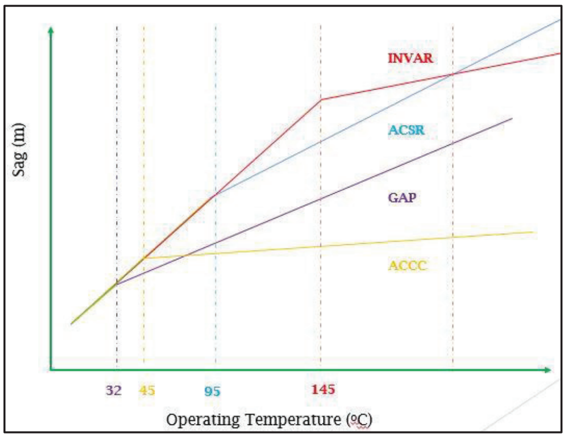

Figure 1 - KPT of different types of conductors

It can be seen from Figure 1 that the KPT of ACSR conductors is more than their maximum operating temperatures. ACCC and GTACSR have lower KPTs, thus they start showing lower sags at low operating temperatures.

4. Formation of various conductors

4.1 ACSR Conductor

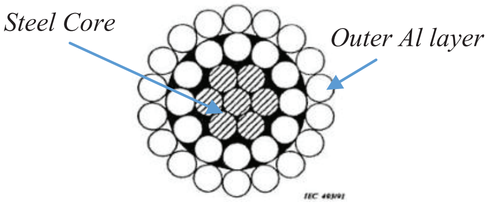

Figure 2 - ACSR Conductor

The ACSR conductor is non-homogeneous. The outer layer is made of hard drawn aluminium (1350-H19) and the inner layer is made of galvanized steel. Conductor strands are circular in shape. Hard drawn aluminum is not heat treated and hence ACSR conductors cannot be operated at temperatures above 90°C.

4.2 GTACSR Conductor (Gap)

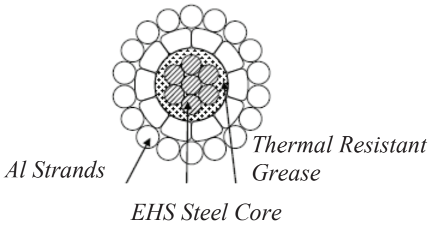

Figure 3 - Gap Conductor

In this conductor, there is a gap between the outer and the inner layers. The outer layer is made of a zir conium doped hard drawn aluminium alloy. The strands in the outermost layer are circular in shape and the strands in the layer below are trapezoidal in shape. The annular gap is filled with thermal resistant grease. The inner core is made of high strength steel. The steel core and the aluminium core can move independently due to the presence of grease [6].

GTACSR conductors can be operated at 150°C (TAL) and GZTACSR conductors can be operated at 210°C (ZTAL). Stringing requirements of these conductors are different to that of conventional conductors. Two-stage stringing is used with gap conductors where 70% of the conductor is tensioned together with Al and steel cores. The rest of the 30% is tensioned on the steel core alone. By doing so, conductor sag can be made to depend only on the expansion behavior of the steel layer.

4.3 ACCC Conductor

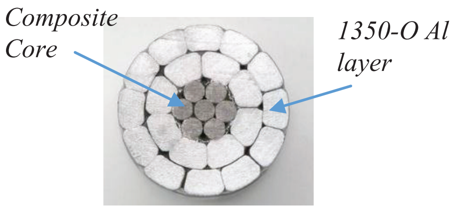

Figure 4 - Formation of ACCC conductor

The core of the ACCC conductor is made of hybrid carbon and the glass fiber composite core utilizes a high temperature epoxy resin matrix to bind hundreds of thousands of individual fibers into a unified load bearing tensile member. The central carbon fiber core is surrounded by high grade boron free glass fibers to improve flexibility and toughness. This also prevents galvanic corrosion between the carbon fiber core and the aluminium strands. The aluminium strands are made of annealed aluminium (1350-O) which has a higher conductivity compared to hard drawn aluminium and they are trapezoidal in shape. ACCC conductors can be safely operated up to 180°C. These conductors require special installation methods and careful handling during stringing [7].

4.4 ZTACIR Conductor

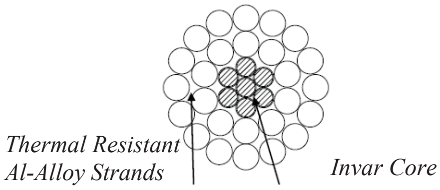

Figure 5 – ZTACIR conductor

The outer strands of the Invar conductor are made of heat treated annealed aluminium strands which can operate at elevated temperatures. The core of the conductor is made of nickel iron alloy (Fe – Ni) which has a lower thermal expansion coefficient. These conductors can be operated up to 210°C[8].

4.5 ACSS Conductor

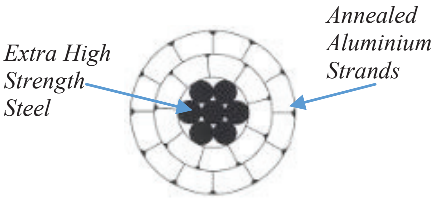

Figure 6 - ACSS conductor

The outer strands of the ACSS conductor are made of heat treated fully annealed aluminium of trapezoidal shape. The core of the conductor is made of Extra High Strength(EHS) steel. This conductor is very popular in the USA, as well as in some European countries. ACSS conductors can be operated at 250°C without compromising their tensile strength. The stringing requirements of this conductor are very similar to those of conventional conductors[9].

4.6 ACCR Conductor

The ACCR conductor is similar to the ZTACIR conductor in shape. However, it has a unique conductor core which is made of an aluminium fiber matrix. The Al-Zrouter layer is fully annealed and can operate up to 240°C[10].

5. Use of HTLS Conductors in the Transmission System in Sri Lanka

In this paper, the use of HTLS conductors in the Sri Lanka's grid is discussed under the following three main categories.

- Re-construction of existing lines
- Clearance improvement of existing lines
- Construction of new transmission lines

A separate algorithm is proposed for each category to enable the identification of the most appropriate conductor.

5.1 Re-construction of Existing Lines

As old transmission lines are not capable of catering to the increasing electricity demand, capacity improvement is required. Due to the unavailability of ROW requirements, new line construction has become increasingly difficult, leaving design engineers with only the option of re-conductoring the existing transmission lines.

The algorithm in Figure 7 is proposed for the selection of appropriate conductors when improving the capacity of an existing transmission line.

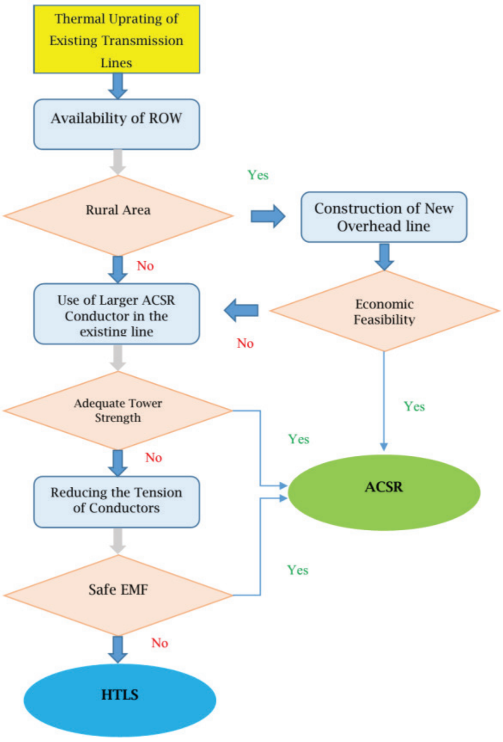

Figure 7 - Algorithm for capacity improvement

Case Study 1

The Pannipitiya – Ratmalana 132 kV double circuit, ACSR Lynx transmission line was to be uprated according to the transmission plan of the Ceylon Electricity Board (CEB). Due to the difficulty of ROW allocation, re-conductoring seemed to be the best option. The original requirement was to double the existing capacity of the ACSRLynx conductor.

Therefore, this same line was first considered to be uprated using an ACSR conductor with a larger cross section. The new selection was an ACSR Zebra conductor. Table 3 shows the properties of Zebra and Lynx conductors.

Table 3 - Zebra and Lynx conductor properties

Conductor	Zebra	Lynx
Diameter (mm)	28.62	19.53
Unit Weight (kg/km)	1621	842
Ultimate Tensile Strength (kN)	131.9	79.8

The next step was to check whether the existing towers were capable of handling these additional forces exerted by the larger sized Zebra conductor.

Usually, there are three types of forces on towers.[11] They are,

- Transverse force due to wind pressure on conductors,
- Longitudinal force due to conductor tension and
- Vertical force due to conductor weight

The forces on the towers with the Zebra conductor were calculated and the additional forces due to the Lynx conductor are summarized in Table 4.

Table 4 - Additional Forces exerted by the Zebra conductor compared to the existing Lynx conductor

Additional Transverse force	46.5%
Additional Vertical Force	92.5%
Additional Longitudinal Forces	68.0%
Reduction of Safety Factor	39.5%

With these additional forces present, it was noted that the safety factors were reduced by 39.5 in the worst case which is a considerable violation of the current transmission tower design philosophy.

However, most of the transmission towers in a line are not using their maximum wind and weight spans for which they have been originally designed. Therefore, some of the towers are still capable of handling additional vertical and transverse forces.

The longitudinal force on the tower will depend on the tension of the conductor and will be limited to 40% of the maximum UTS of the conductor(based on the CEB design specification).

Therefore, with the reduction of the initial tension in the conductor, the safety factor of the towers can be improved. When the initial tension is reduced, the conductor sag will increase and this increase can be calculated using Equation (2). The results given in Table 5 were observed for different initial tensions on the ACSR Zebra conductors.

Table 5 - Tension versus conductor sag

Longitudinal Force (kN)	Sag @ Maximum Operating Tem. (m)	Ground Clearance (m)	Safety Factor (% UTS)
52	7.52	8.195	66.12
50	7.96	7.755	62.66
45	8.85	6.865	56.39
40	9.91	5.805	50.13
35	11.22	4.495	43.86
32	12.21	3.505	40.00

From Table 5, it can be seen that the ground clearance is only 3.5 m when the desired safety factor of 40% is achieved while the required minimum value is 6.7 m. This will increase the EMF level under the power line as shown in Figure 8a and Figure 8b.

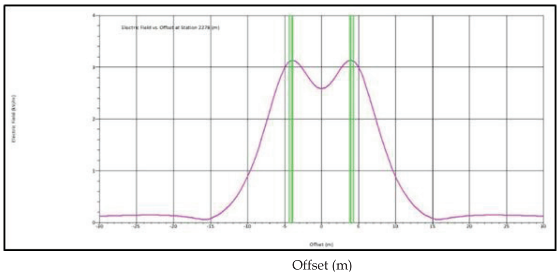

Figure 8a - Existing Electrical Field

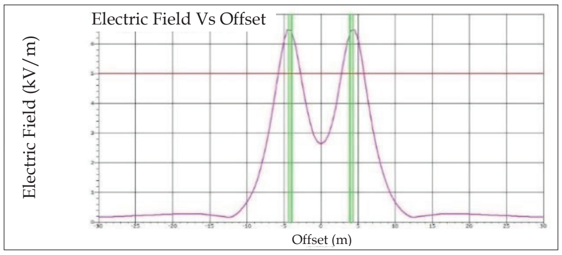

Figure 8b - New Electrical Field

ICNIRP (International Commission on Non-Ionizing Radiation Protection) is an independent organization, which provides scientific advice and guidance on the health and environmental effects of non-ionizing radiations. Table 6 shows the limitations under power lines published by ICNIRP.[12]

Table 6 – ICNIRP published values for permissible EMF levels

	Electric Filed (kV/m)	Magnetic Field (μT)
Public	5	100
Occupational	10	500

However, once the initial tension is reduced up to 32kN (40% UTS), it could be observed that the electric field and the magnetic field under the power line become 6.4 kV/m and 12.2 μT respectively. Therefore, it is clear that the electric field has violated the required ICNIRP limitations.

In conclusion, it can be seen that the capacity uprating is hard to achieve with conventional conductors due to issues related to the safety of the towers and ground clearance.

As a solution, the option of using HTLS conductors was considered.

Table 7 - HTLS Conductors considered for the case study

	ACCC	GAP	ZTACIR	ACSS
Name	Oriole	200 mm^2	159-160	Lark
UTS (kN)	98.3	80	63.7	77.8
Safety Factor	5.5	4.5	3.5	4.4
RTS	18.1	22.2	27.8	22.8

HTLS conductors having similar dimensions, unit weights and UTS as the existing Lynx conductor had to be selected, to avoid any additional forces on towers.

Table 8 summarizes conductor operating temperatures when the intended Current Carrying Capacity (CCC) of 800A is delivered and the consequent sag as well as the annual energy losses due to the resistance of the line.

Table 8 - Performance of HTLS conductors

	ACCC	GAP	ZTACIR	ACSS
Operating Temp. when CCC is 800A (°C)	114	140	173.5	147.8
Sag @ operating Temp. (m)	5.72	7.81	7.33	8.84
Annual Energy Loss (MWh)	15,774	18,720	23,295	17,810

Note: Amb. Tem32°C, Emissivity and solar absorption 0.5, Solar Radiation 1000 W/m^2, Atmosphere clear, wind speed 0.5 ms^{-1}

It can be seen from Table 8 that by selecting HTLS conductors, the required capacity improvement could be achieved without affecting the tower safety. Additionally, it can be observed that the ACCC conductor provides the lowest sag and lowest energy loss. If Zebra conductors are used, the energy loss will be 7,111 MWh. Therefore, the energy loss in HTLS conductors will be higher as shown in Table 8. Thus, designers will have to make compromises on the energy loss when selecting HTLS conductors for capacity upgrading.

5.2 Clearance Improvement of Existing Lines

Most of the older transmission lines have violated their required safe clearances due to reasons such as,

- Conductor creep which has taken place over the years
- Alteration of ground profile by human activities and weather
- Construction of illegal buildings/ residences under the power lines

Some of the conventional methods used to improve such clearances are as follows:

1. Reduction of number of discs in suspension insulators strings wherever possible.
2. Use of suspension towers as section towers.
3. Use of new conductors replacing the conductors that have crept
4. Tower modifications such as addition of body Extensions

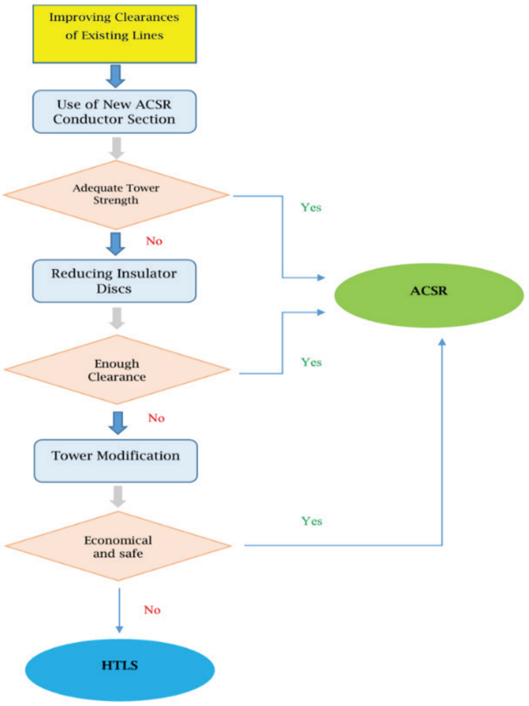

Figure 9 - Algorithm for clearance uprating

All these methods have their own risks and the designers will have to analyze the best option for the successful improvement of clearances. In this regard, HTLS conductors can be a very good selection due to their lower sags and lower unit resistances. Usually HTLS conductors with similar dimensions could achieve the required current at a lower temperature compared to the existing conductor and due to their low sags, the required clearance could be achieved without going into high risk options.

The algorithm in Figure 9 is proposed to find out the most suitable conductor when there is a necessity to improve safe clearances.

Case Study 2

It was observed that the ground clearance between Tower Nos. 11 and 12 of the Pannipitiya-Kolonnawa 132 kV line was around 5.6 m (required value was 6.7 m as per the CEB design specifications). Investigations revealed that the original ground profile had been altered by the people. To achieve the required clearances, the possibility of using HTLS conductors was considered.

The conductor used in the line was of the ACSR Lynx type. The maximum current carrying capacity of the line was 450 A. The HTLS conductor had to fulfill the current requirement as well as the clearance improvement.

Table 9 - Selection of HTLS conductors

	GAP	ZTACIR	ACCC	ACSS
Thermal Exp. Coef. (x 10^{-6} °C^{-1})	11.5	3.78	1.6	11.5
KPT (°C)	32	>110	30-80	50-100
Temp. when I = 450 A	69.6	69.5	60.2	62.9
Sag at operating Temp. (m)	5.82	5.89	4.39	5.91

From Table 9, it could be seen that Gap conductors and ACCC conductors could be quite suitable for the improvement of clearances in this case. Unlike in the case of uprating, the energy loss was not be an issue as the operating temperature of the conductors was low. However, the stringing requirements of the conductors had to be taken into account as the performance of the conductor section was heavily dependent on its workmanship.

5.3 Construction of New Lines

The use of HTLS conductors is technically a good option in the construction of new transmission lines. However, the cost of HTSL conductors is usually higher than the cost of ACSR conductors. The special characteristics of the HTLS conductors would result in additional benefits that could compensate their high initial costs. Therefore, a proper cost benefit analysis had to be done before making the final decision.

The Net Present Value (NPV) approach is one of the methods that could reveal the economic feasibility of new projects with fairly long life spans. Typically, in transmission line projects, 30 to 40 years are considered as the life time of a project. Some of the major cost components involved in a transmission line project are listed below.

Capital Investment Cost: This is the sum of all expenses associated with engineering, procurement and construction of the line including the costs related to environmental assessments, compliance with regulatory requirements etc.

Total Annual Cost: The total annual cost is defined as the sum of the annual capital cost and the annual cost of loss. This includes the total cost of energy loss, interest for borrowed funds, cost of operation and maintenance, depreciation etc.

Annual Cost of Energy Loss =

(Phase current)^2×Unit Resistance ×Line Length × Number of Conductors × Loss Factor × 8760

Note: *Load Factor = Average Demand/ Peak Demand*
Loss Factor = 0.2 x Load Factor + 0.8 x Load Factor

Life Cycle Cost (LCC): The life cycle cost associated with a transmission project is the sum of all recurring expenses including annual capital costs and cost of line losses. The LCC, by definition, is dependent on dynamic market factors such as escalating energy costs, load growth etc. Therefore, the Net Present Value (NPV) approach is more appropriate when determining the best estimate of long term project feasibility.

$$NPV = -C_0 + C \times \left[\frac{\left\{1-\left(\frac{1}{1+i}\right)^n\right\}}{\left\{1-\frac{1}{1+i}\right\}}\right] \qquad \ldots(6)$$

where I =discount rate
n =number of years
C_0 = Initial Investment
C = Recurring cash flow

Nowadays in the CEB, it is a common practice to use Zebra conductors for new transmission lines. Zebra conductors are cheaper compared to similarly sized HTLS conductors. Therefore, to be economically feasible, HTLS conductors during their operation need to save an amount sufficient enough to compensate their higher capital cost. This can only be achieved through the reduction of line losses.

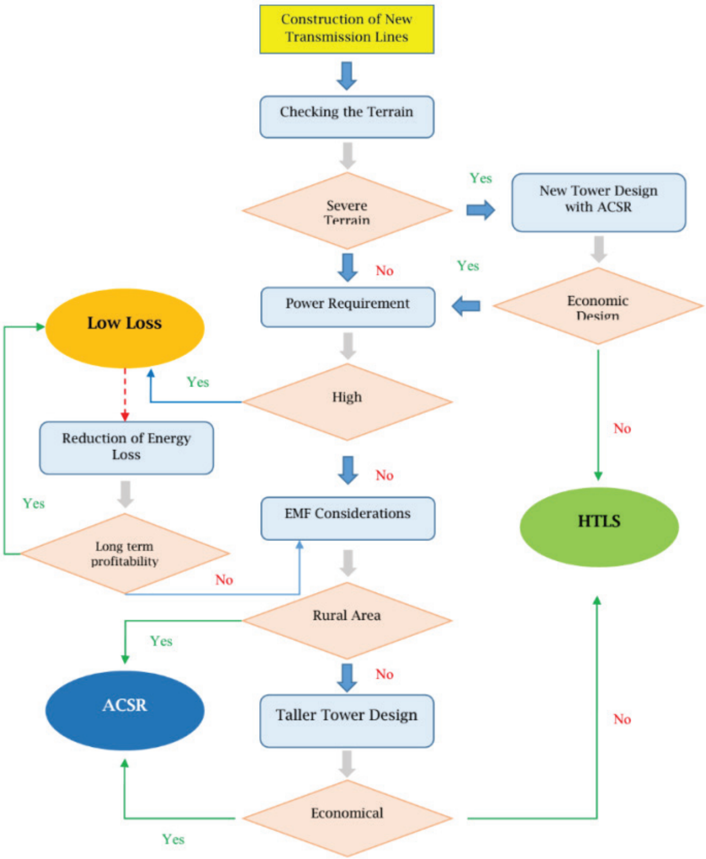

Figure 10 - Algorithm for new constructions

Therefore, in order to analyze the project, a hypothetical double circuit transmission line of 50 km length was considered. The maximum current requirement of the line was taken as 600 A and with the use of IEEE 738-2006, the operating temperature of each HTLS conductor was calculated for delivering the same current. Table 10 shows the results of the analysis.

Table 10 - Selection of HTLS conductors for new lines

Base Conductor	**ACCC**	**GAP**	**ZTACIR**
% Reduction in line loss	22.62	12.57	-1.53
Saving (MLKR/year)	82	46	-6
CO_2 Saving (MLKR/year)	9.4	5.2	-0.6
Reduction in 30-year line losses (MLKR)	948.9	527.1	-64.3
Initial Cost (MLKR)	2400	1950	2700
Net Saving over 30-year period compared to Zebra (MLKR)	**48.9**	**77.1**	**-1246.3**

Note: *i = 10% and construction cost of Zebra line = 30 MLKR/km. cost factors of above conductors were taken as 4, 2.5, 5 respectively. Average Electricity Cost=13 LKR/kWh,* CO_2 *emission=0.8 kg/kWh, Carbon Credit 1860.2 LKR/MT*

According to Table 10, the use of correct HTLS conductors could become profitable in the long run when considering the cost of Zebra lines. However, this decision is highly sensitive to economic factors that could vary with time due to many external factors. Moreover, the cost of operation and maintenance and the cost of additional construction time required for HTLS conductors because of the need for unique stringing methods have not been considered in this study.

The algorithm in Figure 10 shows the way to select the most appropriate conductor for the construction of new transmission lines.

The other advantage of HTLS conductors is that they can reduce the number of towers required for a transmission line. This is due to the low sags of these conductors. Unlike the typical galvanized steel core in the ACSR conductors, the rate of expansion of the cores of HTLS conductors is not high. Their cores are designed with material such as St-Ni, epoxy carbon matrices, aluminium fibres etc, and thus they exhibit lower sags even at high temperatures. This phenomenon becomes very helpful in situations where the construction of new towers becomes difficult due to the presence of marshy lands, archeologically important terrain, river crossings etc.

Figures11a and 11b show the PLS-CADD simulation of Kirindiwela – Kosgama proposed 132 kV line with the use of Zebra ACSR and ACCC drake conductors. The line is around 11 km in length and requires 43 towers to construct the complete line using ACSR Zebra conductors. However, with ACCC conductors 30 towers would be sufficient.

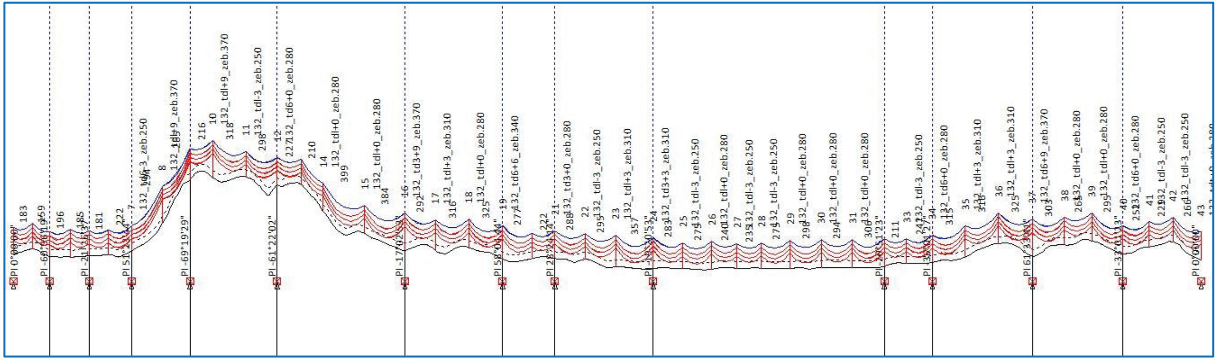

Figure 11a- PLS Simulation of Kirindiwela- Kosgama line with ZebraACSR conductor

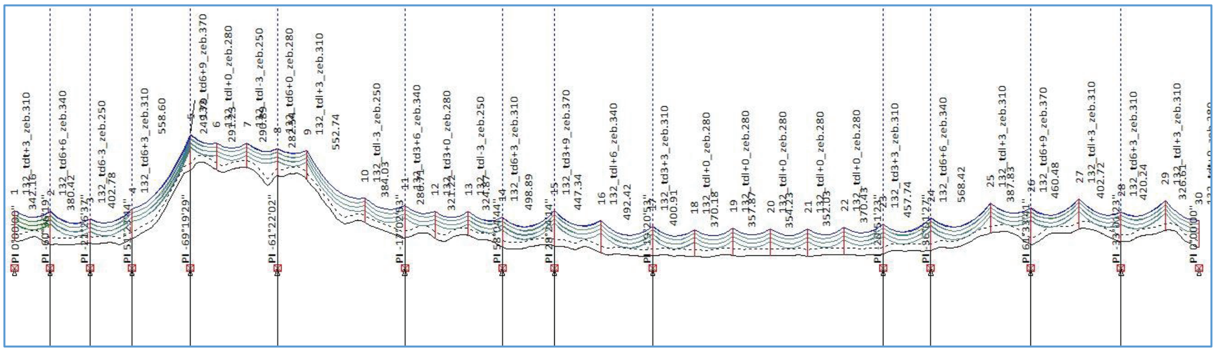

Figure 11b- PLS Simulation of Kirindiwela- Kosgama line with ACCC Drake conductor

6. Stringing of HTLS Conductors

Unlike with conventional ACSR conductors, stringing plays a big role in the case of HTLS conductors. The stringing requirements of HTLS conductors are different to each other and the process of stringing depends on many factors such as conductor formation, KPT, material etc.

Conductors such as those made of ZTACIR do not require special stringing techniques as they have a higher KPT. ACCC, ACCR and ACSS conductors require additional care during handling/ stringing as they have been constructed with 1350-O aluminium that could get damaged rather easily compared to hard drawn aluminium. At the same time, conductors made of GTACSR have a KPT below ambient temperature and requires a two-stage stringing through which aluminium and steel layers are tensioned during two different stages. To achieve the KPT at a lower value or to release the tension on the outer layers, pre-stressing is required for conductors such as those made of ACSS and ACCC. Therefore, the workmanship plays a vital role in the use of HTLS conductors. Though, manufacturers provide such special services which could be expensive, the utilities will definitely have to manage their own staff in the operation and maintenance work. At the same time, stocks will have to be maintained for the special types of accessories and there will be many indirect cost components with the introduction of HTLS conductors. Therefore, the use of HTLS conductors in new transmission lines still remains as grey for most of the utilities in the world including the CEB [13].

7. Conclusion

Based on the above analysis, it is clear that HTLS conductors are the most suitable for the capacity improvement of existing transmission lines. The selection of the most appropriate HTLS conductor will depend on many factors such as current rating, stringing method, cost etc. Also in the clearance improvements of older lines, HTLS conductors can provide a decent solution mainly due to their low sags.

HTLS conductors can provide cost effective solutions in terms of loss reduction when constructing new transmission lines. However, their selection has to be done after a proper techno economic analysis, as most of the factors used for the calculation could vary with time. Moreover, some of the indirect cost components which may get involved with the introduction of HTLS conductors, such as the cost of operation and maintenance, cost of spares etc. need also to be considered in the analysis.

HTLS conductors can become advantageous in unique situations such as when there is a necessity to construct a lower number of towers due to ROW restrictions as its conductor sag at high temperatures is lower than the sag of conventional ACSR conductors.

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References

1. Zamora, I., Mazón, A. J., Criado, R., Alonso, C., & Saenz, J. R. ,"Uprating using High-Temperature Electrical Conductors [overhead power lines]", *In Electricity Distribution, 2001. Part 1: Contributions. CIRED. 16th International Conference and Exhibition on(IEE Conf. Publ No. 482)*,Vol. 1, pp. 5.

2. Reddy, B. S., & hatterjee, D., "Performance Evaluation of High Temperature High Current Conductors," *IEEE Transactions on Dielectrics and Electrical Insulation, V*ol. 23, No. 3, pp. 1570 - 1579, June, 2016.

3. Colin, B. "Transmission and Distribution Electrical Engineering." Newnes , 1996.

4. CTC Global, *Engineering Transmission Lines with High Capacity Low Sag ACCC Conductors*, 2026 McGaw Avenue, Irvine, CA 92614 USA: CTC Global, 2011.

5. Civili, G. & Handel, M., "New Types of Conductors for Overhead Lines with High Thermal Resistance, which Increase the Current Transmission Capacity and Limit Thermal Expansion at High Current Intensity", *Bulk Power System Dynamics and Control VI*, Cortina d'Ampezzo, Italy ,August, 2004.

6. www.jpower.co.jp/english, Visited, 20th June 2016.

7. Alawar, A., Bosze, E. & Nutt, S.,"A Composite Core Conductor for Low Sag at High Temperatures," *IEEE Transactions on Power Delivery,* Vol. 20, No.3, pp. 2193 - 2199, 2005.

8. Nishikawa, T., Takaki, Y., Sanai, M., Kitamura, S., Nakama, K., & Kariya, T., "Development of High Strength Invar Alloy Wire for High Voltage Overhead Power Transmission Line", *SEI Technical Review*, Vol. 71, 2010.

9. http://www.southwire.com/products/ACSS.htm, Visited, 20th August 2016.

10. http://solutions.3m.com/wps/portal/3M/en_US/EMD_ACCR/ACCR_Home/, Visited, 10th May 2016.

11. Havard, D. G., & Perry, O. C., "Lattice Tower Member Fatigue and its Control using a Novel Damping Scheme." *In Power Engineering Society Summer Meeting*, IEEE, Vol. 4, pp. 2560-2565, 2000.

12. International Commission on Non-Ionizing Radiation Protection, "ICNIRP," [Online]. Available: www.icnirp.org, Visited, 11th May 2016.

13. Oscar, A., "New Trend in Transmission Power Lines and Related Stringing Equipment Development." *In 2013 IEEE Power & Energy Society General Meeting*, pp. 1-5, 2013.