Increasing the Capacity of Transmission Lines via Current Uprating: An Updated Review of Benefits, Considerations and Developments

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***Abstract*—Constraints to power transfer in the network may limit the load that can be supported by the transmission lines. To overcome these constraints various current uprating methods can be used. This paper discusses the developments in the use of Dynamic Line Thermal Rating (DLTR) techniques to obtain a higher rating of conductors, the general considerations for thermal uprate and High Temperature Low Sag (HTLS) conductor usage in uprating.**

***Index Terms*—power transfer, construction, current uprating, design, Dynamic Line Thermal Rating (DLTR), High Temperature Low Sag (HTLS) conductors, right of way.**

I. Introduction

Electricity demand has increased in recent years, due to population growth and industrialisation. There are new requirements for a power generation mix to towards renewable energy sources, and the location of such energy plants at the peripheral of the network, this has meant that power lines design to carry low load are being used to transfer large amount of electrical power. This has resulted in a power system that is constraint [1, 2].

An overhead power line's capability to transfer power is related to the distance over which the power must be transmitted. Three main limitations depending on the power transfer distance are imposed on the overhead power lines. These are the thermal limits for lengths of less than 80 km, voltage drop limits for lengths of between 80 km and 320 km and the steady-state stability limit for lengths greater than 320 km [3, 4].

Various methods of maximising power transfers of a power system are discussed in [4-7]. These methods include the use of shunt and series compensation devices, FACTS devices and phase-shifting transformers which modify the power system reactive power requirement and line reactance parameters resulting in increased power transfer.

Another of the most obvious methods to increase capacity is to construct a new overhead line. However, increasing land costs and continued opposition to new transmission lines due to the following: (1) negative visual effect, (2) loss of property value, (3) negative health effects due to the electromagnetic fields (EMF) , and the prolonged process of issuing right of way permits, has meant the power system will remain constrained for a long time [4, 7, 8]. Therefore, one way of dealing with these challenges is to maximise power transfer of existing power lines.

Other ways of increasing power transfers of existing overhead power lines include voltage uprating and the conversion of AC to DC. Voltage uprating entails increasing the operating voltage of a power line. This requires a change of insulation to meet the requirements of the new operating voltage level [9]. Voltage uprating results in potentially higher power transfers and costs to implement it are quite high [8, 10, 11]. Major power transfer gains can be attained by converting from a HVAC system to a HVDC system. The cost of HVDC terminal stations is exorbitantly high and only makes DC a viable option for transfer distance beyond 600 km [1, 12, 13].

Thermal uprating is one of the options that can provide immediate increased power transfers with minimal modifications to the overhead line. This paper discusses the developments in the use of Dynamic Line Thermal Rating (DLTR) techniques to obtain a higher rating of conductors, the general considerations for thermal uprate and high temperature low sag (HTLS) conductor usage in uprating.

The paper is organised as follows: Section II provides a theoretical discussion on the determination of overheard line rating; Section III discusses factors to consider when uprating; Section IV discusses the various thermal uprating methods and recent developments, whilst Section V discusses the conclusions.

II. Overhead Line Rating Determination

The amount of current flowing in an overhead power line has an impact on the conductor sag and consequently on the conductor height above ground. As a result the line safety is impacted. The acceptable power transfer is not only calculated based on the conductor properties, but conductor height above ground as well. Therefore safety is an important factor when determining the line rating [15].

In [14], the thermal or current rating of an overhead power line is described as the maximum current that produces the allowable loss of conductor tensile strength resulting in no change of conductor mechanical properties and maintaining acceptable electrical ground clearance in all-weather conditions. In order to operate an overhead power line in a safe manner, the current through the line conductor must not exceed the maximum current that results in the maximum allowable conductor temperature being achieved [14].

In most cases the ground clearance limits are the determining factor in the determination of the overhead line thermal rating limit, not necessarily the annealing. The overhead line templating temperature is the temperature that results in the minimum ground clearance being reached. This temperature is of importance as it plays a role in determining the maximum current that is allowed through the conductor. Due to the varying weather conditions, the line thermal rating limit is always changing [8].

Weather conditions play an important role in the determination of the thermal rating of a power line. Traditionally the thermal rating of power lines has been determined in a conservation way, by assuming worst cooling conditions. These conditions are low wind speed, high ambient temperature and full solar radiation. Based on the bad cooling conditions, the current resulting in the minimum permissible conductor height above ground is calculated [15].

Due to the more favourable weather conditions in most instances, the overhead line can handle higher currents almost all the time. Therefore, when the line current is equivalent to the conservatively determined thermal rating, the conductor temperature will lower than the maximum allowable temperature [8].

III. Key Thermal Uprating Considerations

An increased current will constrain various aspects of the overhead line and these must be analysed. An assessment of the capability of current carrying clamps to handle increased current must be carried out. The verification of the line's actual templating temperature must be conducted, because it might be different to that used in determining the line's thermal rating limit.

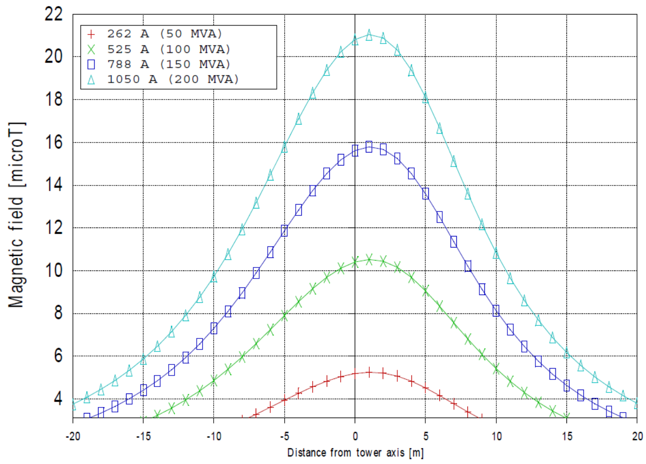

Fig. 1. Impact of increased current on the magnetic field [18]

The conductor condition appraisal must be conducted to assess damage resulting from lightning strikes, vibration and substandard installation of clamps.. The current handling capabilities of substation terminal equipment such as busbars, isolators, breakers and transformers must be assessed in light of increased current [9, 16, 17].

Increasing overhead line current results in increased magnetic fields whist the electric field stays the same. Therefore, a proper analysis of the impact the increased current will have on the right of way must be conducted. In [18], the impact of increased current on the magnetic field was investigated on a 110 kV overhead line and the results are shown in Fig. 1.

IV. Thermal Uprating Methods

Numerous alternatives for uprating an overhead line's thermal rating exist. Generally these alternatives can be classified into two groups: ones requiring no physical changes and ones requiring moderate to major changes [2]. In this section three thermal uprating methods are discussed, commencing with methods requiring no physical changes to the overhead line to ones that require major changes.

A. Dynamic Line Thermal Rating

The purpose of the Dynamic Line Thermal Rating (DLTR) system is to determine the overhead power line thermal rating in real-time taking into account real-time weather conditions. The system monitors certain line parameters and determines the line rating in real-time and ensuring that the minimum conductor height above ground is not violated. If a line loading is constraint by the static thermal limit and there is available margin with regards to maximum allowable conductor temperature then the DLTR systems are a good choice [7]. In most cases the dynamically determined line rating is higher that the conservatively determined rating due to the improved weather conditions in which the line operates [19].

Dynamic line thermal rating systems are placed at various locations along the line, particularly if the line is long. This is because the line might be experiencing more than one weather systems. The corresponding conductor temperature and prevailing weather condition data are collected and processed to determine the dynamic rating [20].

1) DLTR technologies

The monitoring of the conductor temperature of an overhead power line can be implemented by using two methods that are, the direct and indirect methods. The direct method requires the actual installation of the DLTR device on the overhead line. This device measures the actual conductor temperature and parameters such as sag, tension and conductor height above ground. The indirect methods use DLTR devices that are placed in the vicinity of the overhead line, in conjunction with weather stations. The conductor temperature is determined using theoretical models, by using the measured weather data and line load [19]. The various technologies are discussed.

2) Direct DLTR technologies

The Power Donut monitors the current, line-to-ground voltage, conductor temperature and the conductor angle of inclination (catenary parameters). It can also be used for line sag and tension monitoring [20].

The CAT-1 load cells are installed at the dead-end structure of a power line and they measure tension of the line suspension section. The sag on the suspension section span is determined by the conductor tension [20].

Fig. 2. Ampacimon installation on a 400 kV line [21]

The Sagometer uses a smart machine-vision camera that captures an image on a target attached to the conductor and calculates the ground clearance or sag. The camera also works at night due to near-infrared laser illumination [20].

An Ampacimon is an intelligent sensor module that can be directly secured on an overhead power line. This device can be secured anywhere on the line span. It analyses conductor vibrations and detects fundamental frequencies of the span. The sag can be determined from the fundamental frequency with gravity (constant) being the only additional needed parameter [20]. Fig. 2 shows the installation of an Ampacimon unit on a 400kV line [21].

3) Indirect DLTR technologies

The ThermalRate technology uses conductor replicas made of the same material as overhead line conductor, in determining the line rating. The conductor replicas are positioned in close proximity to the overhead power line to ensure that the replicas experience the same ambient conditions as the actual line conductors. Based on the cooling and heating of the conductor, and the actual current through the overhead line, the system calculates the line rating [20]. Fig. 3 shows the installation of a ThermalRate unit [22].

An Alstom P341 relay employs weather station data in determining ampacity or DLTR and is used as a back-up protection for possible line over-loading (line loading exceeding the determined ampacity) in the context of wind power integration. In a case of line loading exceeding the power line ampacity, the relay can act by reducing the wind farm power output in order to maintain the transmission line loading below ampacity level and maintain transmission reliability or even trip off the wind farm [20].

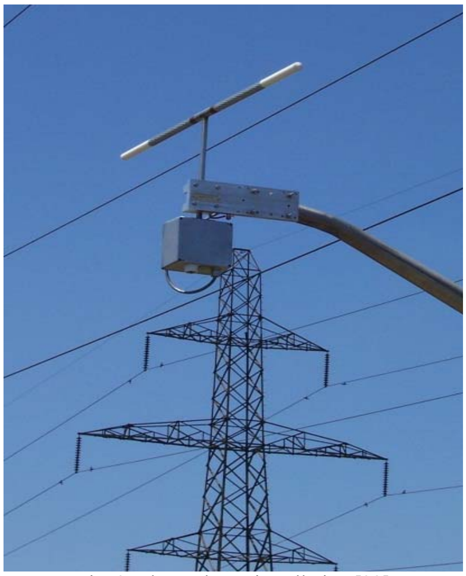

Fig. 3. ThermalRate installation [22]

4) Experiences of using DLTR technologies

DLR technologies have been deployed in many countries ensuring that there is vast experience regarding the use of these technologies. In [23], in order to accommodate thirty percent more generation in the network, the power donuts in conjunction with weather stations measuring ambient weather conditions were used to determine the line rating dynamically.

To relieve potential future grid bottlenecks, the CAT-1 was used in conjunction with measured ambient temperature and radiation [24]. The DLTR provided between 43% and 100% more capacity depending on the weather conditions.

In [21], Ampacimon units were installed on various networks to maximise power transfers. No other additional measured data is required when using the Ampacimon. In [25], ThermalRate units were installed to avoid the need to curtail wind generation plants due to excess generation. For 96% of the time the actual line rating exceeded the static rating. Table I, provides a summary of the utilisation of the DLTR technologies.

TABLE I
UTILISATION OF DLR TECHNOLOGIES

Location	**Technology**	**System voltage**	**Measured parameters**	**Reference**
UK	Power donut	132 kV	Wind speed, ambient temperature & conductor temperature	[23]
New Zealand	CAT-1	220 kV	Ambient temperature, radiation & tension	[24]
Belgium, France	Ampacimon	400 kV, 225 kV	Conductor vibration	[21]
US	ThermalRate	115 kV	Temperature	[25]

B. General current uprate methods

General current uprate methods are mostly considered when there is certainty that the maximum allowable conductor temperature has been reached and there is no longer a margin in terms of conductor sag. The thermal rating of the line can be increased by increasing the conductor templating temperature. The conductor's ability to accommodate higher temperatures must be assessed. By increasing the templating temperature, the clearance to ground distance has to be increased. Various techniques of increasing the conductor's height above ground are discussed.

1) Conductor re-tensioning

Re-tensioning increases the height of the conductor in ground clearance limited spans. Thus the line templating or operating temperature is increased to allow a higher current. An effective way of re-tensioning a line is by reducing the conductor length within a critical span, this is done by cutting out small lengths of wire [3, 4, 16].

2) Insulator change

Increasing the conductor ground clearance can be achieved by raising the conductors' suspension point; for example by reconfiguring insulators from tangent to floating dead-end configurations [26]. Glass disc insulators can be replaced by composite insulators with a shorter overall length and the same creepage distance [16].

3) Tower reconfiguration

Increasing the tower height is another alternative that can be explored to increase the conductor templating temperature, this option can be quiet costly. [8]. Increments in the tower height have generally been achieved by inserting a new steel panel into the lower portion of the tower. This results in increased lower body stresses, which may make foundation reinforcement necessary [27].

4) Negative sag devices

Another effective way of re-tensioning a line is by using line tensioning devices on key spans. While not widely applied, a device has been developed which actually mitigates sag by causing line current to mechanically shorten spans when the current exceeds a certain level [29].

A device that has been developed to mitigate conductor sag is the Sagging Line Mitigator (SLiM). This device is triggered by the same high temperatures that negatively affect the conductor sag. The device does not need intervention of controls, since it operates passively. The SLiM behaves in an inversely way compared to the line conductor, when exposed to higher or lower temperatures. The device ensures that the conductor height above ground is always within limits [28].

5) Increasing conductor cross-section area

Increasing the ampacity of an overhead line can be achieved by replacing an existing aluminium conductor steel reinforced (ACSR) conductor with one having a larger cross-section area. The increase in cross-section area results in increased weight, which means that the mechanical requirements of the towers must be assessed. In most cases there is a need to reinforce the tower and the foundation [8].

6) Experiences of general uprate

General current uprating methods have been implemented by various utilities around the world. Conductor re-tensioning has been implemented in Brazil, with particular focus on structural analysis of the transmission line [29]. In [16] a case study conducted in South Africa there was a possibility of increasing the overhead line templating temperature from 50 ^{o}C to 80 ^{o}C. In [27] an overhead power line templating temperature was increased by increasing the tower height. In the US, a SLiM device was installed on a 69 kV overhead line, the device reduced the variance in sag by approximately 54% relative to the control line [30].

C. Use of HTLS conductors in uprating

Most of today's overhead power lines use the ACSR conductor. Under normal operations this conductor can be operated at temperature of approximately 100 °C, while under emergencies temperatures of approximately 125 °C are allowed for a limited time. This is to ensure that the conductor's physical characteristics are not changed [31].

While increasing the cross-section of the ACSR conductor results in higher ampacity, this method has negative consequences for the structures or towers. This method results in an increased weight and tension on the existing structures. In order to mitigate these increases, tower strengthening or replacement is required. HTLS conductors are an effective way of increasing the line rating without having a negative effect on the line structures [1, 15].

Due to their bonded cores and specialised conductors, HTLS conductors are able to carrying higher current compared to ACSR conductors without losing tensile strength and they sag less at higher temperatures. The typical ampacity range of HTLS conductors is 1.6 to 3 times that of conventional ACSR conductors [31, 32].

Table II illustrates HTLS types of conductors that are currently on the market and the typical current capacity and pricing compared to the ACSR conductor of approximately the same diameter [33, 34].

TABLE II
COMPARISON OF VARIOUS HTLS CONDUCTOR TYPES WITH ACSR CONDUCTOR

Code	Name	Current Capacity	Price
ACSR	Aluminium Conductor Steel Supported	1	1
ACSS/TW	Aluminium Conductor steel supported / trapezoidal wire	1.8 - 2	1.2 - 1.5
GTACSR	Gap type thermal resistant aluminium alloy conductor steel reinforced	1.6 - 2	2
ACIR	Aluminium conductor invar reinforced	1.5 - 2	3 - 5
ACCR	Aluminium conductor composite reinforced	2 - 3	5 - 6.5
ACCC	Aluminium conductor composite core	2	2.5 - 3

1) Experiences of using of HTLS conductors

The use of HTLS conductors has gained popularity due to the benefits they provide. Examples of cases where ACSR conductors were replaced by HTLS conductors are presented in Table III.

TABLE III
CASES OF RECONDUCTORING USING HTLS CONDUCTORS

Location	Voltage	Original Conductor	New Conductors	Reference
Romania	220 kV	ACSR 450/75	ACSS Canary	[35]
Spain	132 kV	ACSR Hen	GTACSR 240	[36]
Italy	150 kV	ACSR	G(Z)TAZCSR & ACSS	[37]

V. CONCLUSION

With the increased cost of building new power lines and the lack of right of ways, particularly in urban areas, utilities are looking at ways of maximising the utilisation of existing overhead lines. DLR techniques provide a quick and immediate way of increasing an overhead line power transfer capability. There are times when the increased power capability is not available due to the influence of weather conditions. General current uprate methods provide considerable increases in capacity. This method requires minor tower modifications depending on the method applied. Reconductoring using HTLS conductors has an advantage that the line capacity can be doubled without the modification of the towers.

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