Implementation of Dynamic Line Rating technique in a 130 kV Regional Network

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Abstract—**This paper investigates the possibility of using Dynamic Line Rating (DLR) to increase the existing power transmission capacity of overhead lines. The main contribution is to combine theoretical calculations and modeling with real application to conclude benefits of DLR. Both introduction of relevant theory and a case study on a power distribution system in Sweden are included. The concept of DLR implies that the capacity of a component dynamically varies as a function of external parameters, such as weather conditions and loading history. Traditionally, the rating is statically set from simulations of worst-case scenarios. Based on conventional static line rating (SLR) methods, the actual current carrying capability of overhead conductors is underestimated. When an increase in the line current capacity is needed, overhead lines may be rated based on a method that allows system operators to run the lines closer to their actual real-time capacity.**

Furthermore, the paper addresses the problems of observing safe ground clearance requirements. Knowing the conductor temperature, when it transmits the required electricity is an important factor to be taken into consideration. Therefore, based on real-time ambient conditions with actual line loading and with the help of IEEE-738-2006 standard, the conductor temperature is also calculated in this paper. Finally, an economic analysis is performed to evaluate the financial advantages of applying the dynamic line ratings approach compared to traditional static line ratings technique for a specific overhead conductor (VL3).

I. INTRODUCTION

Power system owners are facing major challenges with changed electricity consumption patterns and increases in distributed generation [1] [2]. Furthermore, quality regulations in many countries (e.g. UK, Sweden and Norway) have increased the demand for cost efficiency and at the same time the demand for higher reliability [3]. Smart structural refurbishments are thus needed to increase the overall efficiency in the future. Today, power system capacity is set with a static limit based on worst-case scenarios. One solution to significantly decrease and/or delay future investment costs and still meet the same requirements (increase in capacity of overhead lines) is Dynamic Rating (DR) [4] [5] [6] [7].

DR is therefore identified as an important topic in the quest for the development of the electrical grid [8]. The concept implies that the capacity of a component dynamically varies as a function of external parameters, like weather conditions and loading history [9]. Traditionally, the rating is statically set from simulations of worst-case scenarios referred to as static rating (SR) [10]. This leads to a margin between the actually available capacity and the rating itself, which is left unused [9]. The value of DR lies in utilizing existing equipment to a greater extent without passing loads which could lead to outages, broken components or extensive premature aging [9].

The DR concept can be used on different parts of power systems; in this paper, the specific case of applying DR on power line is referred to as DLR. By applying the technique of DLR in the power system, the removal or postponement of new line's construction is observed [11] [12]. The methodology of this paper was developed around a real case study, i.e. the SLR and DLR across an overhead conductor (VL3) in a 130 kV sub-transmission system were calculated and compared with the line current in terms of knowing its actual loading.

II. THEORY BEHIND DYNAMIC LINE RATING

By using equations 2.1-2.14 (based on IEEE-738-2006 Standard), the DLR of overhead conductors (equation 2.34) can be calculated. The parameters in equations (2.1-2.14) are followed in their S.I units to calculate the conductor ampacity in Amperes. Further, based on these equations, it will be observed that conductor temperature actually varies with respect to heat input (gain rate) and heat output (loss) sources.

The heat input (heat gained by the conductor) observed across the overhead conductor is due to ohmic losses and the solar heat gain (solar radiation or solar flux) [13]. After being heated up, the heat energy gained by the conductor is lost by means of two factors, i.e. convection and radiation [13], known as heat output sources. According to the law of conservation of energy, there should always be a balance between heat gain and heat loss rates when not facing changes in conductor temperature, i.e. the following heat balance equation [14] must be followed at times of steady state.

$$Heat_{GAIN} = Heat_{LOSS} \quad (2.1)$$

The following heat balance equation [14] represents the balance amongst heat gain and heat loss rates, i.e.

$$P_{loss} + Q_{solar} = Q_{convection} + Q_{radiation} \quad (2.2)$$

Further, the ohmic loss P_{loss} (W) causes heat gain in the conductor and is calculated based on below equtaions [14], i.e.

$$P_{loss} = I_i^2 * R_{T_C} \tag{2.3}$$

Similarly, the solar heat gain can be calculated with the help of below equation [14]. From this equation, it is observed that this heat gain (Q_{solar}) depends upon four main factors, i.e. on the projected conductor area ($A_{p,i}$), ability of the conductor to absorb sun rays (β_i), the conductor latitude (θ) and the number of hours of the day (φ).

$$Q_{solar} = \beta_i \varphi \sin(\theta) A_{p,i} \tag{2.4}$$

Furthermore, the heat loss rate is classified into two types, i.e. the heat loss due to convection and the heat loss due to radiation [13]. The convection heat loss rate is further classified into two types: natural convection and forced convection [9]. The natural convection heat loss rate Q_{NC} (W/m) is dependent upon conductor diameter (D_i), the temperature across the conductor ($T_{C,i}$), and the ambient temperature (T_A) [14]. It can be calculated with the help of following equation [14]:

$$Q_{NC} = 0.0205 * \sigma^{0.5} * D_i^{0.75} * \left(T_{C,i} - T_A\right)^{1.25} \tag{2.5}$$

The forced convection heat loss rate mainly depends upon wind speed (V_w) and its direction [13]. This heat loss rate is also classified into two categories, depending upon the magnitude of wind speed. At low wind speeds (lower than 4.47 m/sec [14]), the forced convection heat loss rate $Q_{FC_{low}}$ (W/m) will be calculated from following equation [14]:

$$Q_{FC\_low} = \left[1.01 + 0.0372 \left(\frac{D_i * \sigma * V_w}{\varepsilon}\right)^{0.52}\right] * \alpha * K_{angle} * \left(T_{C,i} - T_A\right) \tag{2.6}$$

Similarly, at high wind speeds (higher than or equal to 4.47 m/sec [15]), the forced convection Q_{FC_high} (W/m) is calculated by using following formula [10].

$$Q_{FC\_high} = \left[0.0119 \left(\frac{D_i * \sigma * V_w}{\varepsilon}\right)^{0.6} * \alpha * K_{angle} * \left(T_{C,i} - T_A\right)\right] \tag{2.7}$$

Moreover, in case of low wind speeds, the larger of the two methods (natural or forced ventilation) should be used [14]. At zero wind speed, the forced convection heat loss rate will be zero. However, natural convection will help to reduce the conductor temperature [14]. To find the forced convection heat loss rate, the wind direction factor (K_{angle}) [14] needs to be calculated as:

$$K_{angle} = 1.194 - \cos(\phi) + 0.194 * \cos(2\phi) + 0.368 \sin(2\phi) \tag{2.8}$$

where, ϕ (angle between wind direction and conductor axis) is kept almost fixed, i.e. around 90°. Further, the following equation provides thermal conductivity of air (α) at temperature T_{film} [14].

$$\alpha = 2.424 * 10^{-2} + 7.477 * 10^{-5} * T_{film} - 4.407 * 10^{-9} * T^2{}_{film} \tag{2.9}$$

The average of ambient and conductor temperature (T_{film}) is given in the following formula [14]:

$$T_{film} = \frac{T_{C,i} + T_A}{2} \tag{2.10}$$

The dynamic viscosity (ε) of surrounding air [14] is given as:

$$\varepsilon = \frac{1.458 * 10^{-6}\left(T_{film} + 273\right)^{1.5}}{T_{film} + 383.4} \tag{2.11}$$

The air density (σ) [15] can be calculated as:

$$\sigma = \frac{1.293 - 1.525 * 10^{-4} * h_e + 6.379 * 10^{-9} * h_e^2}{1 + 0.00367 * T_{film}} \tag{2.12}$$

Following equation from IEEE-standard [14] gives the radiated heat loss rate $Q_{radiation}$ (W/m), i.e.

$$Q_{radiation} = 0.0178 * D_i * \epsilon_i * \left[\left(\frac{T_{C,i} + 273}{100}\right)^4 - \left(\frac{T_A + 273}{100}\right)^4\right] \tag{2.13}$$

Like the forced convection heat loss rate, the radiated heat loss rate depends upon the difference in temperature between overhead conductors and ambient: the greater the difference, the higher the radiation heat loss rate. After establishing the heat gain and heat loss parameters, the ampacity of conductor *i* (I_i) can be calculated from following equation [14]:

$$I_i = \sqrt{\frac{(Q_{convection} + Q_{radiation}) - Q_{solar}}{R_{T_C}}} \quad (A) \tag{2.14}$$

Based on ampacity of the conductor as shown in the above equation, it is evident that the convection and radiation heat loss rates affect the capacity of the conductor by allowing higher currents. Similarly, its ampacity is increased when the solar radiation is lower. Moreover, the thermal AC resistance (R_{T_C}) also plays its role in determining the ampacity of the overhead line.

III. IMPLEMENTATION OF A CASE STUDY

A. Objectives

An important goal of this paper is to evaluate the technical and economic aspects of dynamic line rating (DLR) across an overhead conductor (VL3) in a meshed 130 kV sub-transmission electricity network. The following specific objectives were formulated in this paper:

- Evaluation of line loading based on conventional worst-case scenarios.
- Calculation of conductor ampacity based on real-time measurements.
- Comparison of SLR and DLR with actual line loading.
- Economic analysis of DLR implementation compared with traditional solutions.

B. Overall System Introduction

The area studied (area 160) belongs to the Värmland regional power system of Fortum Distribution AB and is located in western Sweden. The operational voltage is 135 kV and incorporates both industrial and residential loads. Initially, this power system was built by several large industries (paper and steel) around the mid-20th century and expanded during the exploitation of hydro power in the region.

In the north of the country there is large scale hydro power generation, whereas the south is dominated by consumption of electricity. Hence, this power system connects the electric power generation from the north with the loads in the south. Further, the system is also connected with other network owners, such as Norway in the west and Vattenfall in the east. The network is also connected with the Swedish national grid via two 400-kVstations. The overhead line (VL3) connects an area with mainly power production in the north to a load-focused area in the east. Furthermore, the eastern area also includes a 400-kV connection.

High stress on VL3 is observed during periods of low industrial loads and high hydro power production. The total load pattern in Värmland is found to follow annual fluctuations, as described in *Fig.1*. For each month, the power system balance was chosen with a load reduction according to *Fig.1* and maximum power production, causing high stress across the conductor VL3.

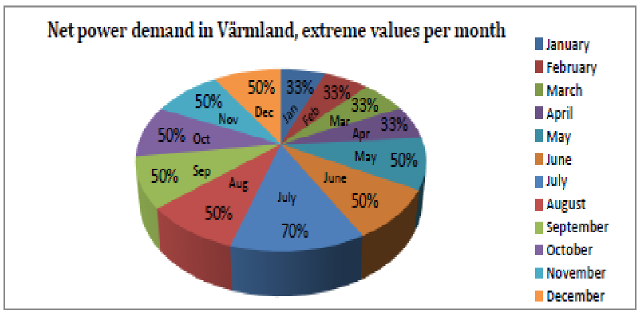

Fig.1 – Net monthly power demand in Värmland regional network

In *Fig.1*, the percentage indicates net power demand on monthly basis compared to the total connected load in the 130 kV regional network of Fortum, i.e. 910 MW in the whole year of 2012. From this figure, it is observed that during summer, power demand is comparatively lower than in the winter. The lowest power demand is observed in July with 70% load remained switched off. The real-time weather data related to ambient temperature, wind speed and its direction was first gathered before calculating the DLR. This data was based on Karlstad municipality in Sweden and was obtained from the Swedish Metrological and Hydrological Institute (SMHI) [16].

IV. DYNAMIC LINE RATING APPROACH IN THE CASE STUDY

A. Weather based dynamic rating

The ampacity of a power system conductor is its ability to carry the maximum RMS (root mean square) current continuously without exceeding the temperature limit [17]. Hence, it limits the actual capability of transmitting electric power [18]. If the real-time weather-based information is used in place of fixed assumptions, then actual capacity of overhead lines can be obtained. This study is developed on the basis of equations provided in IEEE-738-2006 standard (see section II) [14] and the real-time weather data [18].

Mainly, DLR is used for two purposes: first, to increase the capacity of overhead conductor in terms of transmitting the maximum electric current and second, to help in the transfer of electricity during peak load and emergency states [18]. To gain an overall picture of the changes in conductor (VL3) ampacity based on SLR assumptions, see Table I. The results shown in Table I are calculated based on typical fixed weather assumptions.

TABLE I. A TYPICAL EXAMPLE OF WEATHER EFFECT ON LINE AMPACITY, VL3 OH-LINE (30 KM) WITH SLR ASSUMPTIONS: 30°C, 0.6 M/SEC AND DAY-TIME

Variation in Weather Parameter (s)	**Change in Conductor ampacity**
Ambient Temperature (°C) • +5°C Variation • −5°C Variation	• 21.7 % Decrease in Capacity • 17.7 % Increase in Capacity
Wind Speed (m/sec) at line corridor 1 m/sec Increase • 45° angle • 90° angle	• 24.8 % Increase in Capacity • 36.9 % Increase in Capacity

Furthermore, it is observed from Table I that wind speed and its direction have a huge impact on increasing or decreasing the conductor ampacity compared with changes in ambient temperature.

B. Line Current

In this paper, line current was changed by varying the loads in the region around VL3. The load situation was adjusted according to the philosophy discussed in the previous section B. After variations in system loads, the current and temperature across 'VL3' overhead line were analyzed.

Calculation of line currents as well as the modeling of network was done in PSS/E® (power system simulation) software. Rating of these loads was observed for both summer and winter case scenarios. The critical span of conductor VL3 was considered around 6 m. Hence, the loading across this conductor and its dynamic ampacity were calculated based on its critical span.

C. Static and Dynamic ampacities

The dynamic and/or static ampacity is based upon two main factors, i.e. physical characteristics of the conductor and environmental parameters [9], with sub categories such as conductor diameter, conductor temperature, ambient temperature, wind speed, angle between wind speed and conductor, and solar radiation.

The dynamic and static line ampacities for VL3 overhead line are calculated in this section in addition to line current (based on the monthly load changes and the hourly wind power generation), which is illustrated in *Fig.2*. Note that the static rating is not totally static since it is divided into one static "winter" and one static "summer" rating.

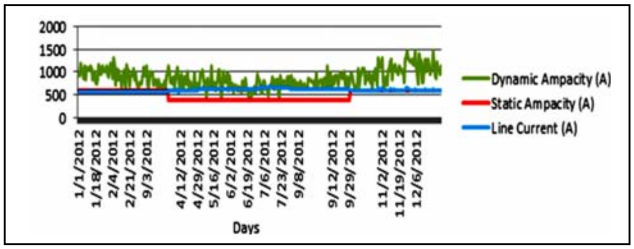

Fig.2 – Static and Dynamic Ampacities (A) versus the Line Current (A) in 2012 observed through VL3 overhead conductor

Regarding network operations, the analysis shows that during winter, the dynamic and even the static line ampacity is sufficient in terms of electricity flow through the overhead conductor as required based on the load demand. However, in summer, the situation is different, due to excessive ambient temperature: the line cannot be allowed to transmit the required flow of electricity due to the risk of conductor deterioration or sag problems.

From *Fig.2*, it is observed that in winter, both SLR and DLR are higher than the line current and hence the line can be loaded up to its full capacity without any risk during this period. However, during summer timings, the line cannot be allowed to carry the required current (as is clear from the graph, both SLR and DLR are seen to be lower than the line current).

V. ECONOMIC ANALYSIS OF AMPACITY UPGRADING METHODS

A. Introduction

Based on DLR, better information on the actual ampacity of an overhead line may allow an increased flow of energy. A direct economic advantage for a DSO can be to save money in the short or long term by postponing or avoiding upgrade of existing line (s) or construction of new line (s). Moreover, the delay investments may help in enhancing the effectiveness of spent money [11]. However, since power system infrastructure is a regulated natural monopoly, it can be difficult to estimate exactly the share of the benefits each stakeholder receives.

From a DLR perspective, many financial benefits can be directly or indirectly achieved (depending on the type of regulation) [11].

- Cheaper electricity for consumers (a DLR advantage for society).
- Better prices for the wind power owners (in terms of lower connection fee).
- Improvement in economic use of transmission lines (useful for the DSO).
- Making asset utilization cost effective (valuable from a DSO perspective)

B. Net annual income based on DLR approach

The dynamic ampacity in this project was calculated for the whole year of 2012 and was based on a particular hour of the day. The selection of that hour was assumed as random and was chosen within a 13-hour range (7 am to 7 pm). Based on this ampacity rating, the allowed energy flow E_{DLR}during the selected hour was calculated for the whole year of 2012 and is given as:

$$E_{DLR} = 38.51\ GWh/year$$

Similarly, based on the static ampacity rating, the allowed energy flow E_{SLR} (for a single hour in a day) through a 'VL3' overhead line for the whole year of 2012 was calculated as:

$$E_{SLR} = 21.68\ GWh/year$$

From the calculations of E_{DLR} and E_{SLR}, the theoretical maximum energy flow through the 'VL3' overhead line on the basis of dynamic ampacity is around 1.8 times higher than if static ampacity is used. Hence, the energy that is curtailed by the SLR approach can be transferred with the help of the DLR technique across the same overhead conductor. Hence, the increased possible transfer of energy through VL3 overhead line by replacing SLR with DLR is equal to:

$$\Delta E_{DLR} = E_{DLR} - E_{SLR} = 16.83\ GWh/year$$

Furthermore, applying the real-time dynamic rating technique across an existing overhead conductor requires equipping the line with useful communication and computer tools for transferring the real-time data from the line corridor to the control room. The different monitoring and communication tools are available in this regard; CAT-1 transmission line monitoring system is one of them [19].

Now, if these tools are installed across an existing overhead conductor for continuous real-time monitoring and transmission of data to the DSO's control center then it costs around \$200,000 (one time product cost estimation) for a single existing transmission line conductor (excluding the shipment, installation and O&M costs) [19]. Now converting it to SEK (1 SEK≈\$0.15), the first time expenditure D_{DLR}will be equivalent to:

$$D_{DLR} = 1.317 MSEK$$

With the help of DLR technique, the transfer of electricity through the existing overhead conductor is significantly higher than its flow based on the traditional SLR approach. The net annual income I_{DLR}based on this allowed energy flow at an assumed electricity price (λ) of $0.369 SEK/kWh$ [20] for the year of 2012 will be:

$$I_{DLR} = \Delta E_{DLR} * \lambda - D_{DLR} = 4.89\ MSEK$$

Furthermore, due to the involvement of different stakeholders in the electricity market, it is difficult and complex to estimate the income or profit for each stakeholder involved, i.e. how much share should be allocated to the wind power owners, the utilities and the DSOs when the energy is transferred based on the DLR approach (particularly due to its dynamic nature). Hence, to avoid such assumption-based profits or incomes for each stakeholder, it is better to focus on the economic analysis based on the benefit of capacity increase across an overhead line. This financial benefit after implementation of the DLR approach across the existing overhead line (VL3) is now calculated as:

$$B_{DLR} = \frac{I_{DLR}}{\Delta E_{DLR}} = 0.29\ MSEK/GWh$$

B_{DLR}, indicates that an increment of 1 GWh energy flow through an existing overhead line (VL3) may yield a *theoretical* benefit of 0.29 MSEK during the first year (as it assumes 1.317 MSEK/year in operating costs, i.e. valid for first year only). The economic benefit in reality is more complex and will be discussed later in section E.

C. Net annual income in case of upgrading the line

The allowed energy flow E_u through the new planned overhead conductor of area 593 mm² based on its static ampacity (63% of that of the existing conductor) during the whole year of 2012 is found to be around 35 GWh/year:

$$E_u = 35.37 GWh/year$$

Replacement of the existing line 'VL3' with a new conductor that has an area of 593 mm² and the length of 30 km will require an approximate total capital cost $C_{u,t}$ of:

$$C_{u,t} = 32.1\ MSEK$$

Assuming that the cost related to upgrading the conductor is financed by a loan at a nominal interest rate of 7.5% (real interest rate + expected inflation) and the loan is required to be paid in a period of 20 years, then based on this data, the capital cost of upgrading the conductor on annual basis $C_{u,a}$ can be calculated with the help of the annuity method. Moreover, by this method, the value of the annuity (based on pay-back period and the interest rate) can be calculated with the help of following formula [21], i.e.

$$a = \frac{r*(1+r)^n}{(1+r)^n-1}, \tag{5.1}$$

where, a is the annuity, r is the nominal interest rate, and n is the pay-back period in years. Now, based on above equation, the annuity will be:

$$a = \frac{0.075*(1+0.075)^{20}}{(1+0.075)^{20}-1} = 0.097$$

After calculation of the annuity, the annual capital cost of replacing the existing overhead conductor (VL3) with a new overhead conductor (of area 593 mm²) can be calculated with the help of following formula [21], i.e.

$$C_{u,a} = a * C_{u,t} \tag{5.2}$$

$$C_{u,a} = 0.097 * 32.1 * 10^6 = 3.11 MSEK$$

After replacement of the existing conductor with a new overhead line that has 1.1 times larger cross-sectional area, the transfer of electricity (based on SLR approach) through this new overhead line is increased significantly compared to its flow through the existing smaller cross-sectional area overhead line. Moreover, the energy (based on static ampacity) that is curtailed by existing conductor $\Delta E_{u,a}$ can be transferred through the new overhead line and is given as:

$$\Delta E_{u,a} = 13.69\ GWh/year$$

$$\lambda = 0.369\ SEK/kWh$$

$$I_{u,a} = \Delta E_{u,a} * \lambda - C_{u,a}$$

or,

$$I_{u,a} = 13.69 * 0.369 - 3.11 = 1.94 MSEK/year,$$

where, λ is the current electricity price and $I_{u,a}$ is the net annual income after the line upgrading. The economic analysis of the increase in conductor capacity when the existing overhead line is upgraded with a new overhead conductor with the aforementioned specifications will be:

$$B_u = \frac{I_{u,a}}{\Delta E_{u,a}} = 0.14\ MSEK/GWh$$

Based on this value, it is observed that after upgrading of the existing conductor, an increment of 1 GWh energy flow through the new overhead line may yield a theoretic maximal benefit of 0.14 MSEK during a single year.

D. Net annual income in case of building a new line

An approximate total capital cost $C_{n,t}$ associated with building a new overhead line of about 30 km in length with an area of 593 mm², designed for 130 kV operating voltage is:

$$C_{n,t} = 39.3 MSEK$$

Similar to upgrading of the line, if the construction of a new overhead conductor is financed in the form of a bank loan at a nominal interest rate of 7.5% with a pay-back period of 20 years, then the annual capital cost $C_{n,a}$ calculated with the help of annuity method from equations 5.1 and 5.2 will be:

$$C_{n,a} = a * C_{n,t}$$

where,

$$a = \frac{0.075*(1+0.075)^{20}}{(1+0.075)^{20}-1} = 0.097$$

Hence, the annual capital cost for the new line construction will be:

$$C_{n,a} = 0.097 * 39.3 * 10^6 = 3.81\ MSEK$$

After construction of a new overhead line with 1.1 times larger cross-sectional area, the transfer of electricity (based on the SLR approach) through this new overhead line is significantly increased compared with its flow through the existing smaller cross-sectional area overhead line.

Furthermore, the energy (based on static ampacity) that is curtailed by existing conductor $\Delta E_{n,a}$ can be transferred through the new overhead conductor and is given as:

$$\Delta E_{n,a} = \Delta E_{u,a} = 13.69\ GWh/year$$

$$\lambda = 0.369\ SEK/kWh$$

$$I_{n,a} = \Delta E_{n,a} * \lambda - C_{n,a}$$

or

$$I_{n,a} = 13.69 * 0.369 - 3.81 = 1.24 MSEK,$$

where, λ is the current electricity price and $I_{n,a}$ is the net annual income after the new line construction. The economic analysis related to increase in the conductor capacity when a new overhead line (with aforementioned specifications) is constructed in place of existing conductor will be around:

$$B_n = \frac{I_{n,a}}{\Delta E_{n,a}} = 0.09\ MSEK/GWh$$

Based on this value, it is observed that an increment of 1 GWh energy flow through the new overhead line may yield a theoretical benefit of 0.09 MSEK during a single year.

E. Comparison amongst ampacity upgrading methods

In this section, a comparison amongst different ampacity upgrading techniques is taken into account. From a technical perspective, any of these conventional ampacity upgrading methods can be considered useful in terms of required electricity transmission but from an economic perspective, these methods are less desirable. Now, from Table II, it is observed that the DLR approach is significantly profitable in comparison to conventional ampacity upgrading techniques.

However, on the basis of limited information, it is difficult to find and compare the exact turnovers from the aforementioned ampacity upgrading techniques. Therefore, the revenue-based comparison cannot be estimated amongst static and dynamic line ratings.

TABLE II. ANNUAL BENEFIT ROM AMPACITY UPGRADING SOLUTIONS

Ampacity Upgrading Solution (s)	**MSEK/GWh**
Dynamic Line Rating	0.29
Conductor Upgrading	0.14
New Line construction	0.09

VI. CLOSURE

This paper presents analytical results from an application study where dynamic line rating was implemented across an overhead line located in a 130 kV sub-transmission system. The static as well as dynamic ampacities have been calculated to estimate the accurate range of loading an overhead line throughout the whole year. Thereafter, a comparison amongst conductor ampacities and the line current was carried out to investigate how much further the overhead conductor can be rated (loaded). The results of this paper indicate that the dynamic line rating technique has the potential to improve the capacity of a power component (here exemplified by an overhead conductor) and to facilitate wind power integration.

From an economic study, it is observed that the ampacity upgrading of an overhead conductor on the basis of dynamic rating is significantly profitable in comparison with conductor replacement or new line construction techniques. The main contribution of the paper is to combine theoretical calculations and modelling with real application. Beside received results, data from this paper can be valuable as a reference material within other studies of wind power and/or dynamic rating.

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