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Comparative analysis of dynamic line rating models and feasibility to minimise energy losses in wind rich power networks

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ABSTRACT

Wind power generation has indicated an exponential increase during last two decades and existing transmission network infrastructure is increasingly becoming inadequate to transmit remotely generated wind power to load centres in the network. The dynamic line rating (DLR) is one of the viable solutions to improve the transmission line ampacity during high wind penetration without investing on an additional transmission network. The main objective of this study is to identify the basic differences between two main line rating standards, since transmission network service providers (TNSPs) heavily depend on these two standards when developing their line rating models. Therefore, a parameter level comparison between two line rating models is a timely requirement, in particular for high wind conditions. Study has shown that roughness factor causes a significant difference between both standards. In particular, the IEEE model indicates more conservative approach due to this parameter. In addition, solar heat-gain calculation has also resulted in significant difference in ampacity ratings between two standards. A case study was developed considering a wind rich network and it has shown that by implementing DLR in wind rich regions, it can effectively reduce line overloading incidents and accommodate wind power flows in the network without any curtailment. Moreover, ability of DLR to reduce network energy losses is also demonstrated and emphasised the importance of selecting suitable DLR candidates to minimise energy losses in the network.

1. Introduction

Ampacity is used to describe the maximum current carrying capacity of an overhead transmission line which is directly related to the temperature of the conductor. Ampacity is usually calculated considering static weather conditions, which utilises *worst case* weather parameters in order to determine the maximum current the conductor can handle without exceeding the temperature limits. The consequences of exceeding this temperature limit can be detrimental as the conductor can sag enough to cause an arc fault to earth, or become permanently deformed and require replacement. Therefore, static line ratings (SLRs) have been designed in such a way to conservatively rate the conductors to minimise the possibility of these faults. The dynamic line ratings (DLRs) have been determined considering the real time weather data and now being received immense attention from power industry with the increased wind penetration in power networks.

Two major standards (i.e. IEEE and CIGRE) are being used for SLR and DLR to determine the conductor ampacity [1,2]. Both standards incorporate the convection cooling, the radiated cooling, the solar heating and the conductor electrical resistance (i.e. Joule heating) to accurately calculate the ampacity of the line, and conversely, the temperature of a line at a specified current. Transmission network service providers (TNSPs) have also designed thermal rating standards, which have branched specifically from the CIGRE and the IEEE standards. However, very limited number of studies have analysed the difference between these two standards considering individual parameters [3,4]. In particular, two standards have been analysed considering measured data without investigating the parameters influencing the line rating [4]. However, differences between the two standards, in terms of individual parameters have not been taken place. Moreover, a limited number of studies are performed at high wind speeds which may have a considerable effect on line rating when significant wind penetration present in a power network.

Wind turbines are installed in remote regions in power network and it has been emphasised that transmission corridors become congested due to increased penetration levels of renewable energy generators [5]. In number of studies transmission congestion has been identified as the major curtailing factor for wind power generation [6,7] and requires considerable time and investment to develop a new transmission network. The convection cooling of the conductors will be at its highest during times of high wind generation assuming high wind speeds experienced at transmission lines, hence wind cooling effect can be effectively utilised without

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implementing expensive transmission network upgrade. Weather deterministic ampacity ratings (i.e. DLR) utilise weather data obtained from weather stations located in the vicinity of the overhead line. Typically, wind direction, wind speed, ambient temperature, conductor temperature and solar ambience are taken and sent to a control centre for further analysis. From these values, the real time ampacity ratings based on conductor temperature are determined, and the power to be sent down the line can be controlled and maintained at the most effective level.

The main issue with the DLR is quality of data [8,9]. The wind attack angle and the wind speed affecting a transmission line is not always a constant for long distance lines, hence current methods for calculation the DLR become unsuitable [8,10]. This can cause large variance between the ampacity ratings for a line at various positions [11]. In another study, real time measurements are taken from four locations along a transmission line and they were reasonably similar [12], which indicate that one set of data may accurately represent the entire line. Based on preliminary judgement, the vastness of the transmission network to be analysed will greatly depends on the suitability of the weather deterministic model, and the extent to which data is collected. In [13], authors have developed a statistical model using measured data in a transmission line and demonstrated the potential of DLR in a wind rich power network. The conductor sag based dynamic line rating models have also been investigated in the published literature [14,15]. Furthermore, potential of DLR to reduce system losses have also been demonstrated in [16], assuming all transmission lines have DLR capability.

The main objective of this study is to illustrate the parameters which cause major differences between the two line rating standards and to illustrate the potential of utilising the dynamic line rating (DLR) in wind rich power networks to reduce network energy losses. A parameter level comparison is a timely requirement, since it will enable utilities to identify and tune the existing line rating models suit to their network. In addition, DLR can be implemented in wide-scale in a smart transmission system; hence network losses can be effectively reduced while coordinating the power flows in the network. This paper is organised as follows: The basic parameter level differences between two line rating models are discussed in Section 2. A comparison between two models considering various parameters is presented in Section 3. A sensitivity analysis between various parameters of the IEEE model is presented in Section 4. A case study based on the New England-39 bus system to illustrate the benefits of the DLR is presented in Section 5. The conclusions of the study is summarised in Section 6.

2. The IEEE and the CIGRE dynamic line rating models

A number of physical factors of the conductor and of the surrounding environment affect the total ampacity of a conductor. These are conductor material properties, conductor diameter, conductor surface conditions, and ambient weather conditions [5]. The SLR of a current carrying conductor is based on a *worst case* set of criteria, including limited wind speed and maximum conductor temperature (due to current flow) [17]. These *worst case* values are used to ensure that there is a significant room in the event of substantially different weather conditions and conductor parameters. The IEEE [1] and the CIGRE [2] standards are the two major frequently used industry standards to determine the maximum current capacity of overhead transmission lines. Each standard is based on a fundamental heat balance equation. However, there exist some differences when determining various contributing factors to the final ampacity rating of the conductor. Eqs (1) and (2) depict the basic heat balance formulas specified by the IEEE and the CIGRE standards respectively.

$$P_c + P_r = P_S + P_J \tag{1}$$

$$P_c + P_r + P_w = P_S + P_J + P_M + P_i \tag{2}$$

P_c, P_r, P_S, P_J, P_w, P_M and P_i denote convection heat loss, radiated heat loss, solar heat gain, conductor joule heating, evaporative cooling, magnetic heating and corona heating respectively. The CIGRE standard incorporates additional parameters to that of the IEEE standard, which include corona heating (P_i), magnetic heating (P_M) and evaporative cooling (P_w). Minimal references can be found on the effects of these parameters; however it is stated in [3] that only a very small fraction of corona heating is passed into the conductor. Although the CIGRE standard mentioned evaporative cooling, it does not outline any method for its calculation [2]. Therefore, in this study, same general heat balance equation has been used for both the IEEE and the CIGRE standards. Eq. (1) can be rearranged in order to determine the ampacity (I) as shown in the following eq:

$$I = \sqrt{\frac{P_c + P_r - P_s}{R(T_c)}} \tag{3}$$

Therefore, fundamental components will be used to make a comparison between the two standards. In following subsections a comparison between the IEEE and the CIGRE calculation methods for convection heat loss, solar heat gain and radiated solar heat loss are discussed and thus for brevity the formulas for calculating each of the components is not presented in this paper.

2.1. Convection cooling

Convection heat loss is concerned with the removal of heat due to the presence of wind surrounding the conductor. The IEEE standard utilises two formulas to determine the convention cooling effect; one for low wind speeds and another for high wind speeds. However, irrespective of the wind speed the largest value from two formulas is selected for ampacity calculation. The CIGRE equivalent of these equations is slightly different, however based on the same fundamental physical laws. The CIGRE standard defines a Nusselt number (N_u) which is defined as the ratio of convective and conductive heat transfer at the boundary for the conductor. The constants (i.e. B_1, n) which determines the N_u, is based on the Reynolds number and the surface roughness (R_f) of the conductor. The CIGRE model factors in the surface roughness of the conductor, which further increases the forced convection effect on the conductor. In light of this point, the IEEE standard can be considered as the more conservative method for convection cooling calculation. Neither the IEEE nor CIGRE standard takes into account the dynamic nature of wind speed with regard to pressure differentials and height variations. In most cases, the weather data is obtained at a different height to that of the transmission line, which could mean a slight variation in the true wind speed acting on the line. This could be considered a means of factoring in safety in the ampacity calculations. Furthermore, both standards have given formulas for the natural convective cooling and it will not be considered in this study, since this study focuses on wind speeds above 0 m/s.

2.2. Solar heat gain

The solar heat gain determines the effect on conductor temperature due to solar irradiation. Both standards outline similar approach in determining the solar heat gain by a conductor; however, the IEEE method utilises certain correction factors based on conductor elevation from the sea level. In both methods the global solar radiation (S) for a particular location is taken into account,