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Experimental Validation and Comparison of IEEE and CIGRE Dynamic Line Models

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***Abstract*- In Northern Ireland, wind generation is mainly located in the west of the country, being connected to the major loads in the east through the transmission and distribution network. With the expansion of wind generation in the west it is envisaged that during wind intensive periods power flow through the limited network capacity, in times of contingency outages and low demand, will see overhead lines breaching their thermal limits. On the Northern Ireland Electricity (NIE) network, dynamic line ratings (i.e. ratings which are dependent on actual weather conditions, as opposed to static line ratings which are based on assumed weather conditions) of overhead lines are being investigated as an interim measure to accommodate distributed generation, as network reinforcement is commissioned. This paper presents analysis from two physical models based on the IEEE and CIGRE standards. Comparison of the modelling techniques is made, with both models used to predict conductor temperatures utilising data gathered from the NIE network and laboratory data from wind tunnel tests.**

***Index Terms*-- Dynamic line ratings, power system operation, wind generation, distribution network**

I. Introduction

Transitioning from a legacy network, designed for centralised power production and control, to a network topology which allows for the integration of central and distributed generation (DG) presents many challenges. The transformation of networks coincides with EU and national targets on reducing the emission of greenhouse gases. The utilities, regulators and governments of both Northern Ireland and the Republic of Ireland are considering the implications of a target as high as 40% of energy from renewables [1]. The introduction of this target along with the ever-increasing demand for power has led to significant DG being connected to the existing network. A possible issue resulting from such wide scale connection is that of the conductors operating beyond their nominal thermal ratings. The conductor's thermal rating generally depends on the maximum allowable continuous conductor temperature which provides low risk to the public and limited damage to the conductor, in terms of loss of tensile strength and creep criteria. It is believed that accommodating the extra generation on the NIE network will require approximately 200 km of new or up-rated transmission network [2].

Traditionally, increased overhead line power flows would have been accommodated by developing the network. Nowadays, it is much harder to obtain planning permission for such development. One option to accommodate higher generation capacities, whilst planning permission is acquired, is to increase the permissible current carried by the conductors. This can be achieved using numerous methods such as: high temperature conductors, dynamic line ratings, and bundling of conductors. However, it should be noted that larger currents produce higher energy losses, thus higher conductor temperatures, leading to increased sag and reduced mid-span clearance from the critical clearance heights. In comparison to alternative measures, an important topic of interest is using dynamic line ratings as an interim measure to transmit more power, due to its relatively low implementation cost [3].

Dynamic line ratings allow for increased amounts of power to be transmitted by adjusting the rated line current when weather conditions permit, thus deferring the need for network reinforcement. Line rating methodologies are broadly classified into two categories, static and dynamic. For each line section the rated current is chosen so as not to exceed the conductor's thermal rating. Many networks operate using static line ratings utilising fixed long time, seasonal ratings, as outlined in [4]. Such rating methods are adopted because of their simplicity. The static rating of a line, in a particular location, is generally determined based on conservative meteorological assumptions for that region. One major issue with this methodology is that, in general, worst-case weather conditions are assumed. The presumption is usually that weather has a minimal cooling effect, i.e. low wind speeds, high solar radiation, and high ambient temperatures. As static ratings are generally conservative it inevitably leads to conductors being thermally limited when actual weather conditions would permit larger ampacities. The ampacity of a conductor is the maximum constant current which will meet the thermal rating of the conductor. However, there can also be times when static ratings are too high, such as periods with very low wind speeds, high solar radiation and high ambient temperatures, with respect to those assumed in determining the static rating. A dynamic line rating can be realised using several methods including: conductor sag and tension monitoring, vibration mode analysis, and conductor temperature and local weather data monitoring [5].

For the work presented in this paper a composite method has been adopted, such that both the weather data and conductor temperature are recorded. This information is applied to standard physical line models, namely IEEE and CIGRE [6, 7], to predict the ampacity of the line; it is, however, noted

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that statistical models are also available, such as proposed in [8]. The conductor temperature is recorded so that the relationship between weather conditions and conductor temperature can be fully understood.

As of December 2009, NIE have a capacity of 218 MW of wind generation connected to their network, with a further 225 MW of committed wind generation, and more than 1000 MW in planning [9]. It is expected that this generation will overload the Omagh-Dungannon circuits during periods of contingency outage [2]. This is a critical circuit for wind farm development as it is used to transmit power from the typically remote wind farms in the west of Northern Ireland to the east, where the majority of the load is situated. As network development in this area lags behind the demand for the network capacity, the proposed method of connecting further DG by using dynamic line ratings is being investigated [3]. NIE are monitoring 20 locations on the Omagh-Dungannon circuits. A Davis Vantage Pro2 weather station, [10], is utilised to monitor weather conditions: wind speed and direction, ambient temperature and solar radiation. Line temperature and current are also measured using a customised industrial unit [2]. This paper utilised data from these field tests and wind tunnel testing to validate and compare the prediction capabilities of the IEEE and CIGRE physical models.

II. Comparison of IEEE and CIGRE Standards

Many factors affect conductor temperature including ohmic losses, skin effect, conductor type and the geographical location. Furthermore, weather conditions such as wind speed and direction, ambient temperature, and solar radiation will also have a dramatic effect on the conductor's temperature. These factors can be categorised into two main groups: the physical properties of the conductor and the atmospheric conditions in which it operates. If the weather conditions are assumed to be constant, as they are in the CIGRE and IEEE models, the steady-state (1) and non-steady-state (2) heat balance equations, as shown in [6, 7], can be used to determine the ampacity or surface temperature of the conductor.

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

$$P_J + P_M + P_S + P_i = P_c + P_r + mc\frac{dT_{av}}{dt} \tag{2}$$

where m is the mass of the conductor (kg); c is the specific heat capacity of the conductor (J/(kg°C)); T_{av} is the average conductor temperature (°C); P_J, P_M, P_s and P_i are the per unit length joule, magnetic, solar and corona heating factors respectively (W/m) and P_c, P_r and P_w are the per unit length convection, radiation and evaporation cooling factors respectively (W/m).

The steady-state models assume that the conductor is in thermal equilibrium and there is no heat stored in the conductor. By contrast, the non-steady-state modelling approach assumes that the conductor has stored heat and is in the process of either storing more heat or dissipating its stored heat. The non-steady-state model, therefore, better represents the short-term variability in weather conditions and line loading. The CIGRE and IEEE modelling techniques examined in this paper use the thermal equilibrium or heat balance equation (1) to predict the ampacity or temperature of the conductor. However, each method does so by simplifying the equation in a slightly different manner.

Evaporation was found in [11] not to alter significantly with the presence of water vapour in the surrounding air, unless the conductor became wetted. Corona heating is only significant when convective and evaporative cooling are high: this produces a stronger electric field, which increases corona heating [12]. It is stated in [11] that heat transferred by corona and evaporation usually occurs arbitrarily and must therefore be dealt with on a probabilistic basis. There is a general consensus, adopted by both CIGRE and IEEE model standards, that for ampacity calculations both evaporation and corona heating should be neglected, due to their probabilistic nature.

A. *Conductor heating*

There are two main mechanisms that contribute heat to a current carrying conductor, namely joule heating and solar heating. Joule heating occurs when an electrical current passes through a conductor and some of the electrical energy is converted to heat by the conductor's resistance. Both CIGRE and IEEE standards calculate the conductor's temperature dependent DC resistance in a similar manner, based on a linear-resistance temperature approximation. This is adequate for rough calculations up to a temperature of approximately 150 °C [6, 7]. In ampacity calculations the current is assumed constant (steady-state), or it is assumed to undergo a step change (non-steady-state) from an initial current to a final current. The main difference in joule heating between the two models is that the CIGRE model provides an AC to DC current conversion, based upon a frequency of 60 Hz. The IEEE model incorporates no conversion method.

The solar heating of a conductor is dependent upon: the absorptivity and orientation of the conductor, time of year and time of day, latitude of the operating area, and the clarity of the local atmosphere. For the prediction of a conductor's solar heating, two properties of the sun must be determined: solar positioning, and solar intensity. The CIGRE and IEEE methods determine solar intensity by measuring the direct and diffused solar radiation. However, due to the cost of equipment and maintenance requirements the field tests do not measure direct solar radiation and diffused solar radiation. Instead both presented models utilise an alternative, more practical and simplified method to calculate the solar heating based on knowledge of the global solar radiation, as provided by the CIGRE model [6]. Global solar radiation is a measure of all incoming radiation incident on the earth's surface. The absorptivity of the conductor, to incident radiation, is

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assumed constant and ‘engineering judgment’ must be used for parameter selection.

The spiralling current around the steel core of an ACSR conductor causes longitudinal magnetic flux in the core [6]. This cyclic magnetic flux causes heating due to eddy currents, hysteresis, and magnetic viscosity. Magnetic heating is therefore dependent on current flow and the number of aluminium layers that surround the steel core. It is accounted for in the CIGRE model as part of an approximate correction equation which lumps together skin effect and magnetic losses associated with ACSR conductors. The IEEE standard ignores both the skin effect and magnetic losses.

B. *Conductor cooling*

Two main mechanisms remove heat from a current carrying conductor, namely convective cooling and radiative cooling. Radiative cooling depends upon the temperature gradient between the conductor’s surface and the surrounding atmosphere, and the ground. It is also a function of the conductor’s diameter and its coefficient of emissivity, as a measure of the conductor’s ability to radiate energy. When determining radiative cooling, both methods ignore the effect of ground temperature as it only contributes a small fraction of the total heat loss, particularly in the presence of forced convection [11]. Both methods calculate radiative cooling in the same way and require ‘engineering judgment’ for the selection of the emissivity constant.

The most significant difference in the CIGRE and IEEE models comes in the form of modelling convective cooling. Convective cooling consists of natural convection, which is the natural motion of air due to temperature / pressure gradients, and forced convection, wind, which is a function of meteorological effects. Convection cooling is therefore affected by wind speed and direction, the temperature gradient between the ambient and conductor temperatures, and the conductor’s diameter, roughness and latitude. For ampacity calculations, both methods assume that wind speed is constant. This is an unrealistic assumption as in reality both the wind speed and turbulence are determined by many factors including pressure differentials and local terrain. The IEEE model calculates forced convection cooling using a combination of two equations, both of which account for the clarity of the local atmosphere. One is designed for low wind speeds and the other for high wind speeds. In contrast, the CIGRE model neglects the operational conditions and uses dimensional analysis: utilising Nusselt, Reynolds, Grashoff and Prandtl numbers to model the turbulence and vortices associated with the stranding of conductors in a bid to determine the heat transfer between the conductor and surrounding air. Like the IEEE model, the CIGRE model selects the largest cooling value, leading to conservative ampacity predictions.

III. Verification of CIGRE and IEEE models

For given weather conditions and the conductor’s thermal rating / current the conductor’s subsequent ampacity / temperature can be predicted. However, as convective cooling, radiant cooling, conductor resistance and so forth are all functions of the conductor temperature it follows that the calculation must be performed using an iterative approach.

Prior to using the CIGRE and IEEE models verification tests were performed to ensure that each model predicted plausible temperatures and ampacities. This section outlines the verification testing carried out using data obtained from wind tunnel laboratory experiments.

A. *Wind tunnel experimental validation*

At The Queen’s University of Belfast a test rig has been established to verify the models. A short line section of ‘lynx’ 175 mm^2 ACSR conductor was placed in a wind tunnel, and subjected to various step changes in current whilst being exposed to wind speeds between 0 – 15 m/s. Further details are described in [13]. The experimental data presented in Table 1 was measured using calibrated thermocouples. The measurements were obtained in the absence of solar radiation, which reduces the number of input variables and hence possible sources of errors in temperature prediction. The conductor was subjected to a step-change in current, with the steady-state values being presented in Table 1. For the wind tunnel results, laminar wind subjected perpendicular to the conductor’s axis and steady-state measurements can also be assumed. Table 1 shows that both the CIGRE and IEEE models tend to over-estimate the surface temperature. The CIGRE model gives better conductor temperature predictions when forced convection is present. The predicted temperatures from the CIGRE model, in the presence of forced convection, are within ± 2.1 ºC of the measured values as opposed to ± 2.5 ºC for the IEEE model. For ampacity and conductor surface temperature predictions the assumption is made that the average conductor temperature is equal to its surface temperature. However, radial temperature differences were observed during the experiments, especially in the absence of wind. Hence, the calculated resistance for ampacity modelling could be slightly inaccurate, which may account for some of the difference between the predicted and measured temperatures.

TABLE I

MEASURED AND PREDICTED SURFACE TEMPERATURE OF A ‘LYNX’ CONDUCTOR IN THE ABSENCE OF SOLAR RADIATION

			Predicted temperature (ºC)	
Wind speed (m/s)	Current step (A)	Measured temperature (ºC)	CIGRE	IEEE
0	0 - 513	92.1	94.2	90.0
1	0 - 515	52.2	50.9	50.9
3	0 - 525	39.3	39.0	39.0
5	0 - 525	31.8	33.0	34.2
10	0 - 521	27.8	28.6	30.3
15	0 - 519	27.3	27.9	29.6

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IV. COMPARISON OF MODELLING TECHNIQUES

Having verified the models' predictive capabilities using wind tunnel results, comparisons of the models' conductor temperature predictions are made using data from the field studies. Figure 1 is a plot of the conductor temperature using data from one of the 20 monitored locations during the period from 7th - 10th November 2008. Both models account for the variations in the conductor's temperature which are caused by changes in the weather and line loading. This particular location, for the given period, experienced wind speeds ranging from 0 to 15 m/s, with an average wind speed of 8 m/s, far exceeding the 0.5 m/s threshold utilised in determining the static ratings. The ambient temperature ranged from 1.3 °C to 10.7 °C, averaging 5.2 °C, whilst the current mainly varied between 3 and 140 A for the presented test period. Both the ambient temperature and current are much lower than the P27 (static line rating documentation [4]) thresholds of 9 °C and 623 A for the autumn period. The figure indicates that the steady-state CIGRE and IEEE models adequately predict the conductor temperature. The mean absolute error and standard deviation of the error for the steady-state CIGRE model are both 0.70 °C whilst the IEEE steady-state model has equivalent values of 0.70 °C and 0.68 °C. However, a significant difference between the steady-state predictions and measured conductor temperature occurs during the day for both the IEEE and CIGRE models, with each underestimating the conductor temperature. This error is correlated to the solar radiation, suggesting that solar radiation is having more of an effect on the conductor's temperature than implied by the model prediction.

For the temperature prediction, the CIGRE and IEEE models generally underestimate the conductor's temperature particularly during the day time. However, in the calibration of the CIGRE and IEEE models both generally indicate temperatures exceeding those measured using calibrated thermocouples. A number of factors could have caused this: weather parameters in the wind tunnel testing were ideal, in that they changed slowly and the wind was non-turbulent. Furthermore, in the verification tests two weather conditions remained unchanged: solar radiation and wind direction. It is possible that these factors could be better represented in the

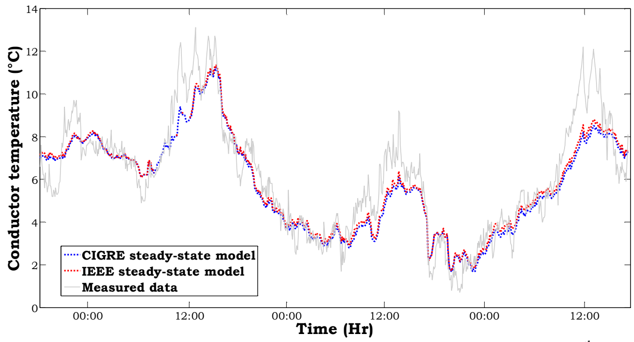

Fig. 1. Steady-state CIGRE and IEEE temperature predictions for 7th – 10th November 2008.

IEEE and CIGRE models. The most likely cause of the discrepancies is a combination of measurement errors and mis-representation of the weather dependent heating / cooling effects, which would include the selection of the emissivity and absorptivity values. Furthermore, it is assumed that weather conditions are uniform along the line section.

In order to assess the errors in predicted conductor temperatures it is necessary to understand the accuracy of the monitoring equipment and the effects its inaccuracies have on the predicted temperatures. Table 2 summarises errors associated with the accuracy and precision of the weather stations [10]. Also presented are the absolute errors which result due to the effect of these equipment errors on the conductor temperature predictions. The 'predicted conductor temperature absolute error' is sub-divided into CIGRE and IEEE sections. Each subsection is further subdivided into 60 A, 574 A, 623 A and 651 A sections. These currents correspond to the average current which flowed through the Omagh-Dungannon circuit during the period from February 2008 to January 2009, and the seasonal (summer, spring/autumn and winter) static ratings. The weather conditions used when determining the conductor temperature were: an ambient temperature of 9.1 °C, a wind speed of 3.2 m/s with a wind direction of 31° and a solar radiation of 7 W/m^2. These values are the yearly average values experienced on the Omagh-Dungannon circuit for 2008/2009.

The effect of loading of the circuit at the seasonal static ratings can be seen from Table 2. It shows that the most likely factor to affect the predicted temperature reading is the ambient temperature, giving an error of 0.51 °C when using the CIGRE steady-state model and 0.50 °C for the IEEE model, whilst wind speed errors are less likely to affect the conductor's temperature with an equivalent value of 0.04 °C and 0.03 °C for the respective models. Also, errors in the wind direction have little impact on the conductor's temperature. However, as the loading of the conductor is increased, errors in the ambient temperature reading have less of an effect on the conductor's predicted temperature when compared to the effect of wind speed and wind direction. The error associated with the current is ±1%, corresponding to a predicted conductor temperature error of up to 0.54 °C for the presented data.

Comparing the CIGRE and IEEE model predictions it is apparent that errors in wind speed for the CIGRE model can have a greater impact on the conductor's temperature than is the case for the IEEE model. Both models are similarly affected by errors in the solar radiation and ambient temperature measurements. It can be concluded that the CIGRE model is affected more by errors in the measurement equipment, and consequently for the equipment being used the IEEE modelling technique better realises the conductor's temperature for the given weather conditions.

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V. CONCLUSIONS

This paper has presented the temperature predictions of the CIGRE and IEEE steady-state models showing that each predicts the conductor's temperature satisfactorily. Both models gave a mean absolute error of 0.70 °C and comparable standard deviations of the error of approximately 0.70 °C. The paper highlighted possible errors resulting from the inaccuracies of the monitoring equipment being utilised. For a heavily loaded conductor the errors will be dominated by wind speed and therefore dependent on the anemometers used. It should, however, be mentioned that the initial increase in wind speed, from zero, provides the greatest benefit in cooling of the line with subsequent increments in wind speed having less of an effect on the conductor's temperature [13]. Hence, at 'high' wind speeds, errors in wind speed should be less significant. The cup anemometer utilised in the field trials tends to overestimate the wind speed in gusty conditions. It is stated in [14] that they whirl continually because the drag of the wind is greater when blowing into the mouth rather than into the back of each cup, but this results in greater lags in a falling rather than in a rising gust, with the result that wind speeds are significantly overestimated in gust conditions. A further issue related to the anemometers used is that they measure wind speeds based on horizontal wind flow. The prediction accuracies may be enhanced if the vertical component of wind speed was monitored and utilised in the models, as it has been shown in [13] that even low wind speeds have a dramatic effect on conductor cooling.

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TABLE 2
MEASURED AND PREDICTED SURFACE TEMPERATURE OF A 'LYNX' CONDUCTOR IN THE ABSENCE OF SOLAR RADIATION

		Predicted conductor temperature absolute error (°C)							
		CIGRE				IEEE			
Variable	**Resolution**	**60 A**	**574 A**	**623 A**	**651 A**	**60 A**	**574 A**	**623 A**	**651 A**
Solar radiation	1 W/m^2	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01
Ambient temperature	0.1 °C	0.11	0.11	0.12	0.12	0.10	0.10	0.11	0.11
Wind direction	1°	0.00	0.27	0.33	0.37	0.00	0.28	0.34	0.38
Wind speed	0.45 m/s	0.02	2.42	2.96	3.31	0.01	1.82	2.20	2.45
Current	0.01 A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Variable	**Accuracy**	**60 A**	**574 A**	**623 A**	**651 A**	**60 A**	**574 A**	**623 A**	**651 A**
Solar radiation	90 W/m^2	0.37	0.41	0.42	0.43	0.34	0.42	0.43	0.43
Ambient temperature	0.5 °C	0.51	0.56	0.58	0.59	0.50	0.55	0.56	0.56
Wind direction	4°	0.00	1.02	1.25	1.40	0.01	1.04	1.26	1.40
Wind speed	1 m/s	0.04	4.27	5.77	6.45	0.03	4.19	4.37	4.86
Current	1%	0.00	0.40	0.52	0.54	0.00	0.16	0.20	0.20

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