Development and Experimental Validation of a Weather-Based Dynamic Line Rating System

D. J. Spoor, *Member, IEEE,* and J. P. Roberts

***Abstract*— TransGrid, Australia, has implemented a dynamic line rating system on several 330kV and 132kV transmission lines in response to emerging thermal limitations. This system produces a more intelligent grid by utilizing weather stations that employ mobile telemetry, where these are installed directly on the steel lattice structures.**

This paper describes the rationale behind the development of the system and provides rationale behind the various decisions made during the implementation. It also presents experimental analysis of conductor temperatures, which is used to validate several internationally recognized overhead conductor rating methodologies. Moreover, these temperature measurements identify the need for simple data filtering strategies and the use of localised weather observations.

***Index Terms*-- Power transmission lines, Power transmission planning, Power system simulation, Temperature measurement**

I. Introduction

TransGrid, Australia, has recently completed an upgrade of the western 330kV network to an operating voltage of 500kV [1]. This project was completed to resolve several emerging thermal and voltage stability limitations. However, this has resulted in increased loading on some 330kV circuits under various network conditions. This paper presents the underlying analysis, rationale and observations from the implementation of an intelligent line rating system for these lines.

A. Deterministic Line Ratings

The rating of overhead circuits may be calculated using a variety of methods specified in international standards [2],[3],[4] or local working group papers, such as [5],[6] which are often used in Australia. The application of each method incorporates a variety of assumptions, such as the ambient temperature and an effective transverse wind speed, along with direct and indirect solar radiation, emissivity and absorptivity coefficients. Some documents provide guidance on which parameters should be used in these calculations. For instance, [7] recommends a default effective wind speed of 0.6 m/s, an ambient temperature equal to the maximum annual value along the line route and a solar radiation of 1000 Watts per metre with an assumed conductor absorptivity of no less than 0.8.

B. Probabilistic Line Ratings

The use of probabilistic ratings can provide significant advantages when compared with the conservative assumptions incorporated with deterministic rating calculations [8]. These approaches rely on the analysis of historical weather parameters in order to quantify the likelihood of the transmission line design temperature being exceeded. Moreover, the probabilistic analysis can be co-aligned with the risk profile adopted by the network service provider.

TransGrid currently utilises probabilistic line ratings on its transmission circuits, which are calculated from historical parameters such as the wind speed, observed solar radiation and ambient temperature. However, moderately conservative assumptions are generally applied in order to minimise the likelihood of conductor temperatures being exceeded on any particular day. It is also noted that rating conditions in certain areas or locations can be more favourable and that the use of monitoring equipment and data analysis may be used to justify the application of higher ratings if these favourable conditions exist [7]. For this reason, TransGrid has developed a real-time line rating system for use on several overhead transmission lines within the New South Wales transmission network.

C. Dynamic Line Ratings

The use of dynamic ratings has become more popular in recent years as it provides Network Service Providers with the opportunity to quantify their compliance with probabilistic planning criteria. In many situations, this also provides an opportunity to defer the need for additional capital expenditure. Moreover, these systems provide operational flexibility due to the ability to utilise significantly higher ratings when favourable weather conditions exist [9],[10],[11]. This increase is achieved without adversely affecting the likelihood of damage or exceeding statutory clearances since monitoring equipment provides a real-time indication of the lines condition and capability. The use of these systems can also provide additional flexibility within electricity markets as constraints are less likely to bind.

For instance, some Aluminium Conductor Steel Reinforced (ACSR) conductors can sag at a rate of up to 10-15 cm with an increased current of 100 amperes. Since this additional current can correspond with a temperature change of 10 degrees Celsius, the ampere rating can be significantly increased by accurately quantifying the actual clearances or conductor

D. J. Spoor is employed by Transgrid, Sydney, New South Wales, Australia (e-mail: darren.spoor@transgrid.com.au).

J. P. Roberts is with Transgrid, Sydney, New South Wales, Australia (e-mail: john.roberts@transgrid.com.au).

978-1-4577-0875-6/11/$26.00©2011 IEEE

temperatures [8].

In some situations, clearances have been increased through mid-span civil works in conjunction with dynamic line ratings [10]. Additional benefits can sometimes be obtained by addressing constraints imposed by primary or secondary equipment, such as line droppers, current transformers, secondary wiring, and circuit breakers [8],[11].

II. Real Time Rating Calculations

The primary objective of all real-time rating methods is to estimate or measure the conductor temperature and quantify the clearance to ground. This can be achieved through a variety of approaches, such as the physical measurement of on-line temperature, the measurement of conductor tension or even local weather parameters. Some less commonly used approaches include the use of a conductor replica, conductor position tracking and vibration monitoring, which relies on the correlation between frequency of vibrations and tension [8],[12].

TransGrid conducted a trial on a 330kV transmission line in Western Sydney to examine the viability of these options. This included the use of an on-line temperature probe, tension monitors and a weather station comprising an ultrasonic wind speed transducer.

A. The use of On-Line Temperature Measurements

On-line temperature measurements appear to provide useful information from which to rate a transmission line. There are a variety of commercially available transducers which can provide these measurements using radio or mobile phone telemetry. Fig. 1 shows two of these probes which have been installed on each conductor of the centre phase on a 330kV line in Sydney.

Fig. 1. Two on-line temperature probes installed on the two ACSR/GZ Olive (54/7/3.50) conductor of a single phase from a 330kV transmission line in Sydney.

Most on-line devices rely on current in the phase conductors in order to power the internal processors. Consequently, both congestion at the mobile cell tower and the presence of a lightly loaded circuit will result in a loss of telemetry information. Interestingly, this arrangement also produced inconsistent conductor current measurements from the two on-line devices and could not be configured to provide telemetry information with the required sampling rate.

B. The use of On-Line Tension Monitoring

Tension monitoring has been regularly used for the last twenty years and is most prevalent in the USA [8]. It is also noted in [10] that tension-based monitoring systems are the most common method for implementing dynamic line ratings. However, these systems are also generally more expensive to install, maintain and operate [13]. As shown in Fig. 2, tension monitoring usually involves the installation of load cells at ground potential between a tension structure and the dead-end insulator string [14].

Tension monitoring has been found to be a highly accurate method of determining the conductor sag. In one study, 200 tension monitoring sites were examined and it was found the sag could be predicted within 5-10 cm at distance even 10 spans from the tension monitoring site [10]. The same study found the line temperature could be determined within a resolution of around 1.5 Degrees Celsius.

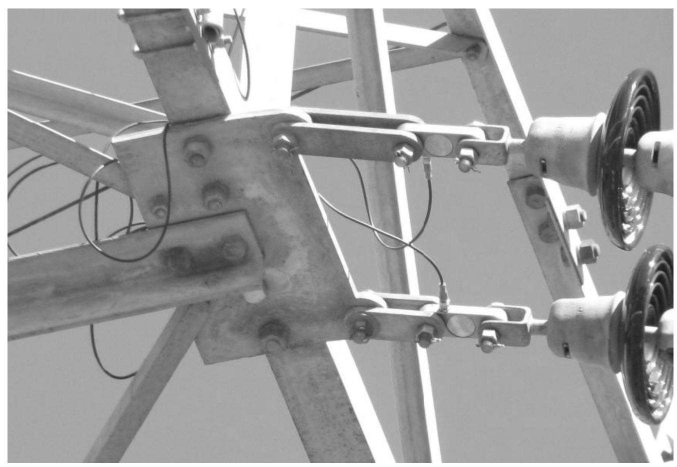

Fig. 2. Installation of load cells on each conductor from the same phase and span as the on-line temperature probes.

The primary advantage is that the tension correlates directly with the conductor sag, and provides more accurate calculations than those obtained from weather stations [14]. The measurements are also the most accurate at lower tensions, when accurate ratings are more critical. Nevertheless, tension monitoring equipment can only be used to monitor a single section of line and requires careful calibration of the system to determine the relationship between tension, temperature and clearance for each span [14].

The tension monitors shown in Fig 2, were installed on the same span as the on-line temperature probes, shown in Fig 1. This provided an opportunity to directly correlate the tension of this twin conductor span against the conductor temperature using the following simple relationship, which assumes a linear correlation between tension and temperature:

$$T = 2K/(t_A + t_B) \tag{1}$$

where, T is the computed conductor temperature (Kelvin), while t_A and t_B is the respective tension in the two insulator strings (Newtons).

The coefficient K was subsequently calculated by minimising the error between the calculated and observed conductor temperatures. As shown in Fig 3, the use of tension monitoring can provide a good estimate of the conductor temperature. However, the requirement to calibrate these tension measurements, combined with the distributed nature of most line clearance issues, dictated the use of weather parameters within the TransGrid network.

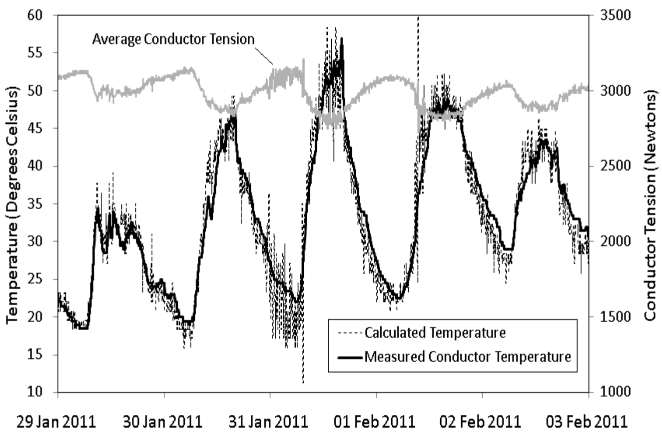

Fig. 3. Comparison between the measured and computed conductor temperature based on conductor tension measurements.

C. The use of Weather Parameters

The rating of an overhead conductor can be determined from the local weather conditions. The most favourable conditions include low ambient temperatures, high wind speeds, a transverse wind direction and low solar heat radiation [15]. Of these, the wind speed and wind direction are generally the most significant variables [7], but these can also be the most difficult parameters to measure or predict. Some reports observe that the hotter part of the day can coincide well with higher wind speeds which partially cancel the effect of high solar heating and high ambient temperatures [7],[16]. Similarly, night-time ratings can be less than those experienced during the day.

The primary objective of weather-based rating techniques is the calculation of the conductor heat gain and heat loss. Sources of heat gain include the joule heating imposed by the conductor resistance, as well as solar, corona and magnetic heating. Corona heating is usually ignored due to its minimal effects on most lines, while magnetic heating is generally only included for ACSR conductors where there are an odd number of aluminium layers [5], and it may be overlooked under some situations [3],[4]. The primary sources of cooling include the forced cooling introduced by transverse winds, as well as other cooling mechanisms such as radiative and natural convective cooling, while evaporative cooling is often ignored.

Once these parameters are known, it is possible to derive the conductor current which results in an equilibrium between the heating and cooling mechanisms. This current corresponds with the 'normal' or 'continuous' rating.

Two internationally accepted methods for calculating conductor ratings using weather data are the IEEE standard 738-2006 [3] and the Cigre approach [4], while [5] is commonly used as a local Australian standard. The equations contained in these documents calculate the heat gains and heat losses, and then use the heat balance equation to calculate the conductor ratings and predict the conductor temperature.

D. Comparative Analysis of Rating Methods

Consider a single ACSR/GZ Olive (54/7/3.50) conductor installed near Sydney, with a design temperature of 90°C. This hypothetical line is subjected to an ambient temperature of 30°C and it is assumed that the conductor absorptivity and emissivity are both 0.8 and that the albedo (ground reflectance) is approximately 0.2. Under these conditions, Fig. 4 shows the sensitivity of the IEEE, Cigre and Australian Transmission Network Service Provider (TNSP) methods to a wind speed applied at 20 degrees to the conductor on the 1st January.

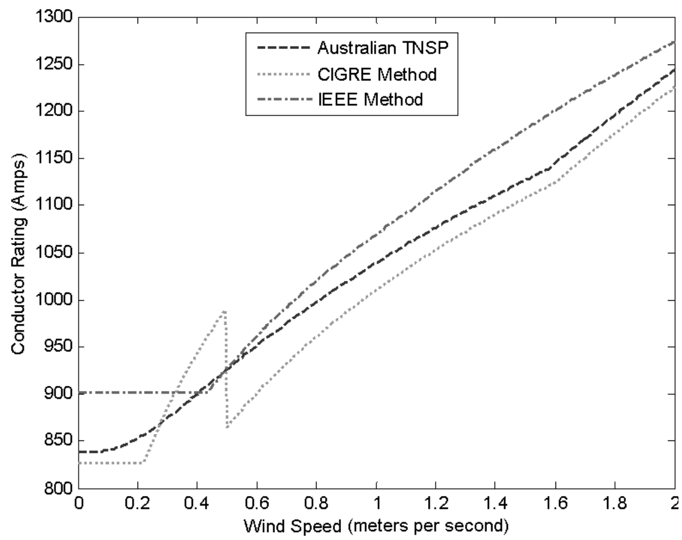

Fig. 4. Sensitivity of computed conductor ratings to variations in wind speed. Conditions include an ambient temperature of 30°C where the wind speed is applied at 20 degrees to the conductor on the 1st January.

The Australian TNSP method assumes that convection is a mixture of the natural and forced convection, which leads to a smoother response at lower wind speeds. However the Cigre and IEEE methods assume the convection is either natural or forced depending on the wind speed. This can create discontinuities in the rating versus wind speed relationship. For instance, the Cigre methodology assumes a default 45 Degree wind angle of attack when the wind speed falls below 0.5 meters per second.

Similarly, Fig. 5 shows the sensitivity of these methods to variations in the 'angle of attack' between the wind and the conductor, assuming a wind speed of 0.5 meters per second.

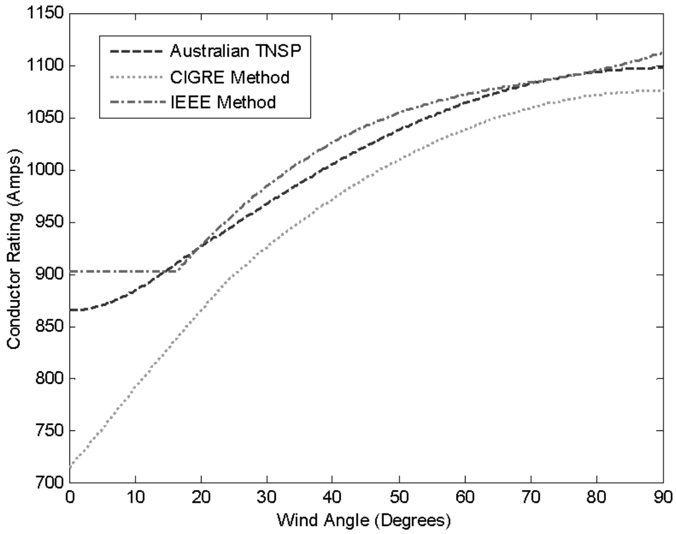

Fig. 5. Sensitivity of computed conductor ratings to variations in wind angle. Conditions include an ambient temperature of 30°C on the 1st January and a wind speed of 0.5 meters per second.

Similar sensitivity analysis in Fig. 6, reveals that the Australian TNSP method produces a slightly higher rating during the night in this particular scenario. This appears to be due to the inclusion of a term for the sky and ground temperature, whereas the Cigre and IEEE methods use the background ambient temperature for radiation calculations.

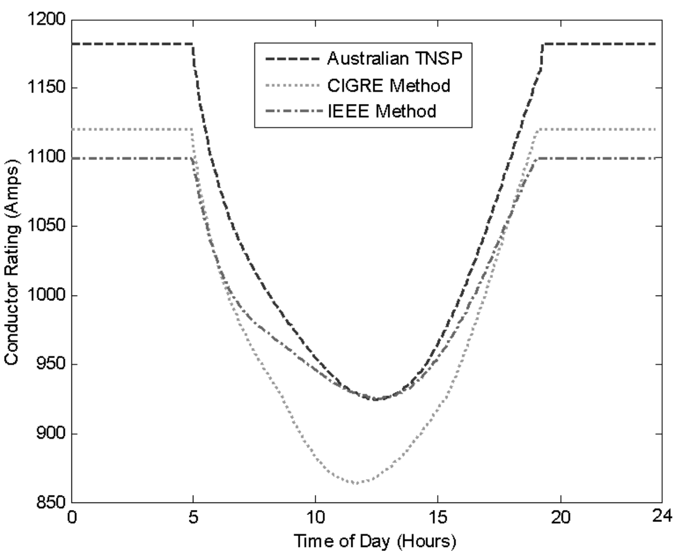

Fig. 6. Sensitivity of computed conductor ratings to the time of day on the 1st January. Conditions include an ambient temperature of 30°C and a wind speed of 0.5 meters per second at an angle of 20 degrees to the conductor.

Some distinct differences can also be seen in the calculation of solar and magnetic heating in these standards. For instance, each method applies a seasonal modulation to the global solar radiation, although there are notable dissimilarities between the implementation of this modulation. The Australian TNSP methods also include correction terms for magnetic heating. Conversely, the Cigre method combines the skin effect and magnetic core losses together in an approximation [4], while the IEEE standard does not mention the effects of magnetic heating and instead recommends the use of engineering judgement.

E. Validation of Weather-Based Ratings

Prior to adopting a particular calculation methodology, TransGrid trialled the use of several weather station sensors. These included various temperature transducers as well as both cup anemometers and ultrasonic wind speed transducers. Since the cup style anemometers resulted in observed stall speeds of approximately 0.5 meters per second, an ultrasonic transducer was ultimately selected for connection to a Remote Terminal Unit (RTU). This RTU and sensor was installed on the steel lattice structures with the intent of measuring wind speeds at conductor elevations and avoiding errors introduced by wind shear.

Fig. 7. Installation of various weather stations and transducers on a 330kV transmission line structure in Sydney, Australia.

To validate the use of the equations contained in [3], [4], [5], an ultrasonic weather station was also installed adjacent to the existing on-line temperature probes and tension load cells.

The observed weather and metering data from the first week in February 2011 was analysed in detail as the ambient temperatures during this period reached 39°C. The calculations in Fig. 8 have considered the thermal inertia of the phase conductors between each measurement interval which produces a reasonable estimate of the conductor temperature. However, the calculations on most days appeared to slightly lead the conductor temperature during the early morning and late afternoon.

By explicitly incorporating the measured solar radiation in this analysis, Fig. 9 confirms that these morning and afternoon temperature offsets are not predominantly due to errors in the solar heating calculations. Rather, it is assumed that thermal capacitance of the ground in this urban location may have introduced additional thermal contributions during the afternoon.

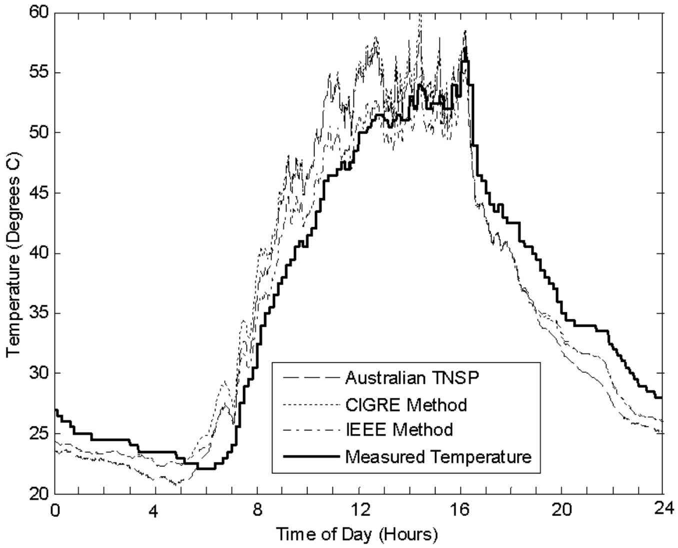

Fig. 8. Comparison of measured and computed conductor temperatures on a 330kV transmission line in Sydney on the 31st January 2011.

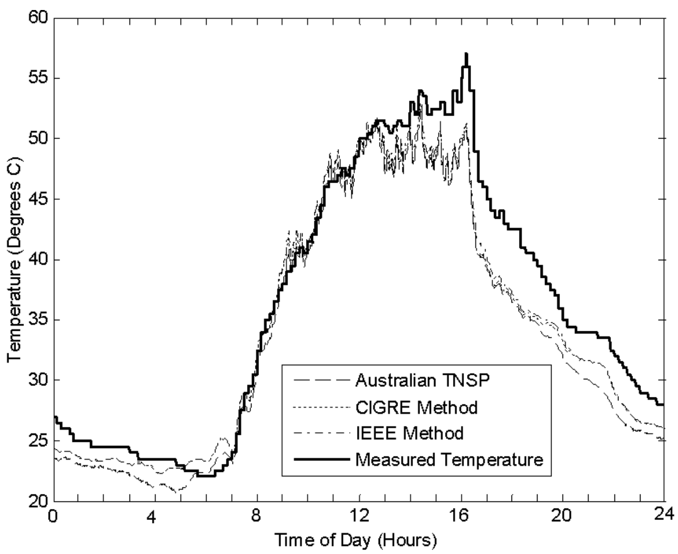

Fig. 9. Comparison between measured and computed conductor temperatures using observed solar radiation measurements.

III. Application of Dynamic Line Ratings

TransGrid has historically used a probabilistic line rating approach that aims to control conductor sags and thereby maintain required clearances. Calculations have been produced for both day and night in summer, winter, and spring/autumn. The rating methodology also applies further limitations for conductors with a 120 Degrees Celcius design temperature to avoid excessive annealing of the aluminium conductor strands and to avoid the loss of lubricating grease.

A. Dynamic Line Rating Implementation

Tension-based line rating systems are generally noted as being the preferred dynamic line rating application as significant uncertainties can be introduced within weather-based systems [17]. However, it is also noted that a combination of weather and tension measurements can result in a more robust methodology [13]. Nevertheless, TransGrid has restricted the scope of its line rating system to the use of weather parameters due to data availability and calibration issues associated with the tension measurements.

These weather measurements are applied to the Australian TNSP equations [5], where the documented recommendations are also adopted. Additional conservatism is applied by assuming that the sun is located perpendicular to the conductor and that the wind flows along the conductor with a shielding factor of 0.8.

B. Weather Station Locations

Weather stations have been installed on the transmission structures at a similar elevation to the lowest phase conductors. In some situations, this has resulted in installations at various elevations within steel lattice towers near spans with poor conductor clearances. Steel structures have been selected where possible due to the good shielding from lightning and the additional security provided by anti-climbing protection. In some locations, this has resulted in measurements from steel towers that are significantly offset from the dynamically rated transmission line.

Fig. 10. Example of a weather station installation above the anti-climbing protective device on a steel lattice transmission structure.

The installation of weather stations has also been restricted to locations where mobile coverage is available for data telemetry and where there is adequate access for an elevated work platform to assist with the installation. Consideration was specifically given to locations that are more likely to experience lower than normal wind speeds. On long lines, this has resulted in the approximate installation of one weather station every ten kilometres.

C. Results and Observations

The application of the dynamic line rating system has provided notable benefits. For instance, Fig. 11 compares the average daily dynamic and probabilistic ratings of a 330kV line south of Sydney during the summer months of 2010/11.

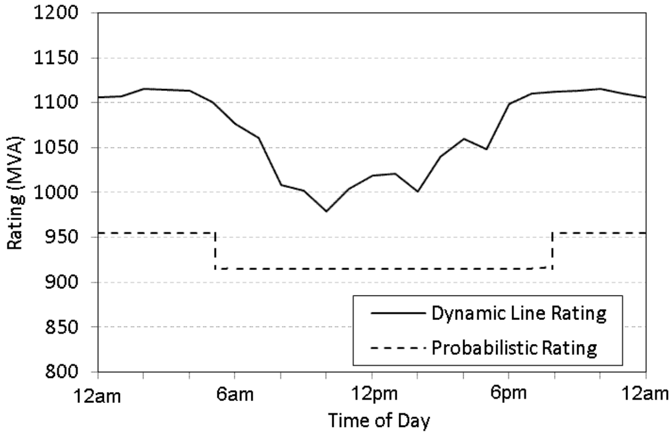

Fig. 11. Comparison between the average daily dynamic and probabilistic rating during summer 2010/11 for a 330kV transmission line south of Sydney.

Interestingly, the most notable benefits from the use of this system are generally observed during the afternoon on hot days. As suggested by the Fig. 12, the correlation between temperature and wind speed in Sydney can provide significant advantages when supporting high summer afternoon demands.

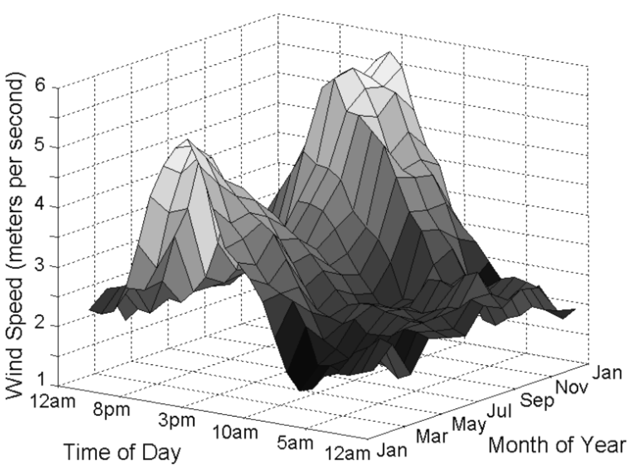

Fig. 12. Distribution of average wind speeds observed in Western Sydney, Australia, during the 2009 calendar year.

Nevertheless, TransGrid's dynamic line rating system has been adversely affected by a combination of adverse weather and poor mobile phone signal strength. Poor mobile coverage has imposed additional loading on some weather station batteries. When combined with lengthy periods of cloud cover, this has resulted in a loss of telemetry due to poor battery voltages.

D. Filtering of Computed Ratings

It is also necessary to apply a filtering algorithm to avoid significant fluctuations in the calculated ratings [13],[16]. This may be applied through the use of time averaging transducers, or by encoding a low-pass filter in the line rating calculation. For instance, Fig 13 shows the impact of using a simple averaging filter on the measured wind speed. One minute averaging of the input data can produce a stochastic response which can introduce problems with generation dispatch. Conversely, the filtering delay associated with a 30 minute filter can produce high transient conductor temperatures following sudden wind speed variations, which necessitates the use of a de-rating factor.

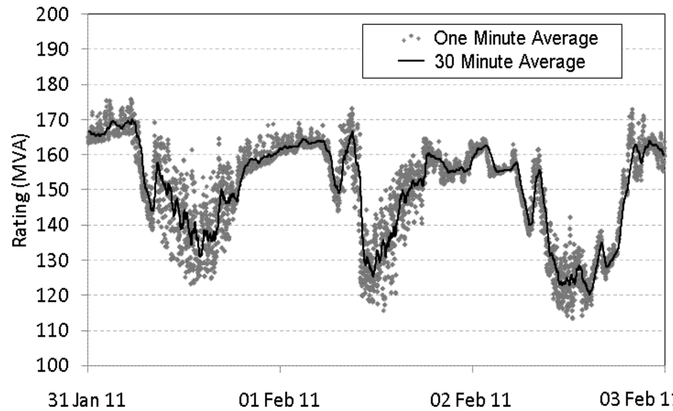

Fig. 13. The rating of a 132kV transmission line calculated using one minute and 30 minute averaging of the input wind speed.

E. Sensitivity to Weather Station Location

It is implicitly assumed within [2],[3],[4] and [5] that line rating calculations should use local weather measurements. However, economic factors can influence the number and location of remote weather stations used within a line rating scheme and there is little guidance available on the accuracy of non-local parameters.

Fig 14 shows the calculated temperature on the same 330kV transmission line in Western Sydney using local measurements, and compares the computed temperature against that obtained using remote measurements. Additional weather observations have been utilised from Dapto and Moss Vale, which are 60km south and 60km south west of the 330kV transmission line span, respectively. The result clearly identifies the need to use local weather measurements in similar line rating schemes.

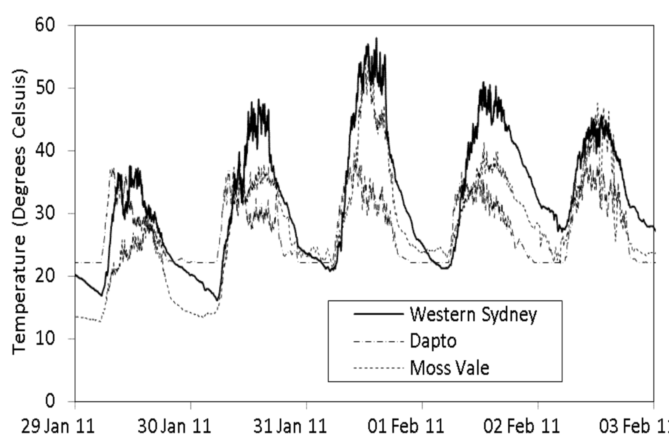

Fig. 14. Computed conductor temperatures using local weather measurements, compared to similar calculations using measurements at Dapto and Moss Vale, which are 60km away from the temperature measurement site.

IV. CONCLUSION

TransGrid has implemented an intelligent dynamic line rating system on several transmission lines in response to emerging network limitations. Consideration was given to the use of on-line temperature and tension measurements. However, this system utilises remote weather stations on steel lattice structures that transmit wind speed, wind direction and ambient temperature measurements. The Australian TNSP methodology has also been implemented due to the lack of potential discontinuities in the calculated rating and its detailed modelling of solar radiation and magnetic heating.

On average, the system has demonstrated significant benefits over existing probabilistic methods even after the application of appropriate filtering algorithms. Nevertheless, several issues, such as the internal battery capacity, have the potential to affect the reliability of similar systems.

V. REFERENCES

[1] D. Spoor, K Hinkley "TransGrid's Experience with Travelling Wave and Impedance-Based Fault Location on Double Circuit 500kV Lines" CIGRE, South East Asia Protection and Automation Conference, 10-11 March, 2011

[2] IEC Technical Report "Overhead electrical conductors – Calculation methods for stranded bare conductors" IEC/TR 61597:1995

[3] IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors, IEEE Std 738-2006 (Revision of IEEE Std 738-1993), Jan. 30, 2007

[4] R. Stephen, D. Douglass, M. Gaudry et al., "Thermal Behaviour Of Overhead Conductors", CIGRE Working Group 22.12, paper 207, 2002

[5] TNSP Co-operative Charter Plant Rating Working Group. (2007, September). TNSP Operational Line Ratings. [Online]. Available: http://www.aer.gov.au/

[6] "Current Ratings of Bare Overhead Line Conductors" Energy Supply Association of Australia, Tech. Report. D(b)5:2006

[7] "Guide for Selection of Weather Parameters for Bare Overhead Conductor Ratings", CIGRE Working Group B2.12, paper 299, 2006

[8] "Increasing Capacity of Overhead Transmission Lines – Needs and Solutions", CIGRE JWG B2/C1.19, paper 425, 2010

[9] P. M. Callahan, D. A. Douglass, "An experimental evaluation of a thermal line uprating by conductor temperature and weather monitoring," Power Delivery, IEEE Transactions on , vol.3, no.4, pp.1960-1967, Oct 1988

[10] T. O. Seppa, "Increasing transmission capacity by real time monitoring," Power Engineering Society Winter Meeting, 2002. IEEE, vol.2, no., pp. 1208- 1211 vol.2, 2002

[11] "Dynamic Circuit Thermal Line Rating," California Energy Commission, Oct. 1999.

[12] D. C. Lawry, J. R. Daconti, "Overhead line thermal rating calculation based on conductor replica method," Transmission and Distribution Conference and Exposition, 2003 IEEE PES , vol.3, no., pp. 880- 885 vol.3, 7-12 Sept. 2003

[13] A. Dino and A. Ketley, "Dynamic Transmission Line Rating Technology Review," Hydro-Electric Corporation, Cambridge, TAS, July 2009

[14] R. Stephen (on behalf of WG 22.12): "Description of State of the Art Methods to Determine Thermal Rating of Lines in Real – Time and their Application in Optimizing Power Flow". CIGRE 22-304 Session -2000.

[15] S. D. Foss, S. H. Lin, R. A. Maraio, H. Schrayshuen, "Effect of variability in weather conditions on conductor temperature and the dynamic rating of transmission lines", Power Delivery, IEEE Transactions on, vol.3, no.4, pp.1832-1841, Oct 1988

[16] J. S. Engelhardt, S. P. Basu, "Design, installation, and field experience with an overhead transmission dynamic line rating system," Transmission and Distribution Conference, 1996. Proceedings., 1996 IEEE , vol., no., pp.366-370, 15-20 Sep 1996

[17] D. A. Douglass, et al., "IEEE's Approach for Increasing Transmission Line Ratings in North America," CIGRE 2000: 38th Session of the International Conference on Large High-Voltage Electric Systems (CIGRE), Paris, Aug. 27-Sept. 1, 2000.

VI. BIOGRAPHIES

Dr. **Darren Spoor** completed his undergraduate electrical engineering degree in 2002 and is currently employed by TransGrid, Australia. He received his PhD from the University of Technology, Sydney in 2007, with his main interests focussed on the modelling of overhead and underground transmission circuits.

John Roberts is due to complete his Bachelor of Electrical Engineering in 2011 and is currently employed by TransGrid. His main interests are increasing transmission capacity by implementing dynamic line rating systems.