DE-RISKING THE IMPLEMENTATION OF REAL-TIME THERMAL RATINGS

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ABSTRACT

This paper addresses the de-risking of real-time thermal ratings (RTTRs) for overhead lines to help build DNO business confidence in the adoption of the technology. Through the use of thermal state estimation with integrated sensors and graceful degradation algorithms, a cost-effective RTTR system is being implemented across the 132kV network in North Wales. The system unlocks significant energy yields (up to 14,358 MWh in November 2012 for a single overhead line circuit) whilst minimising the risk of line temperature profile exceedence to a suitably low value.

INTRODUCTION

Environmental barriers and cost of investment inhibit the building of new overhead lines for the connection of distributed generation (for example wind farms) to the distribution network. Real-time thermal rating (RTTR) systems address this challenge by monitoring weather conditions, conductor operating temperatures and enhancing visibility of the thermal status of the electricity network. RTTRs are time-variant ratings that can be practically exploited without damaging components or reducing their life expectancy [1].

However, for wider business adoption, the risks and uncertainties associated with the implementation of RTTR technology need to be managed and reduced. Also, for the scheme to be utilised operationally, there needs to be a robust system in place that provides clear justification for the constraint of wind farm power output at times of limited network capacity.

This paper disseminates the outcomes from the field trials of an innovative RTTR deployment project, financed by the UK electricity network regulator, Ofgem, through the Low Carbon Networks Fund.

Scottish Power Energy Networks (SPEN), the UK DNO, is working with Parsons Brinckerhoff, GE Energy, Nortech Management Ltd and Skye Instruments to deploy a real-time thermal rating scheme that covers >90km of the existing North Wales distribution network, providing the connection point for several prospective wind farm developments [2].

Focusing on lessons learnt during the system development, this paper should provide useful points of reference for any network operators looking to develop and deploy a real-time thermal rating system.

BACKGROUND

Thermal behaviour of overhead line conductors

Overhead line ratings are constrained by a necessity to maintain statutory clearances between the conductor and other objects [3]. The temperature rise causes conductor elongation which, in turn, causes an increase in sag. Overhead lines are tensioned to operate at a maximum conductor temperature (also termed the 'profile' temperature) to ensure that the risk of statutory clearance violation is minimised.

The line sag (S) depends on the tension (H), the weight (mg) applied to the conductor inclusive of the dynamic force of the wind and the length of the span (L). The sag can be calculated as a catenary or its parabolic approximation [1], as given in (1).

$$S = \frac{H}{mg}\left[\cosh\left(\frac{mgL}{2H}\right)-1\right] \approx \frac{mgL^2}{8H} \qquad (1)$$

In order to calculate the overhead line tension, it is necessary to consider the thermal-tensional equilibrium of the conductor. The maximum current, and hence real-time thermal rating, for a given operating temperature is calculated by solving the energy balance between the heat generated in the conductor by the Joule effect (I^2R) and the thermal exchange on its surface. The thermal exchange of the overhead line is dependent on the heat transferred to the conductor by solar radiation (Q_S) and dissipated to the environment through convective (Q_C) and radiative (Q_R) mechanisms, as given in (2).

$$I^2R + Q_S = Q_C + Q_R \qquad (2)$$

Risk basis of standard overhead line ratings

Standard overhead line ratings, utilised by distribution network operators in the UK, are calculated on a probabilistic basis derived from the research work carried out at the Central Electricity Research Laboratories (CERL) [4], and summarised in Engineering Recommendation P27 [5]. The approach accepts that, because of the random variations in wind speed, wind direction, ambient temperature and solar radiation, the actual temperature of the line may exceed the temperature for which it was profiled. The proportion of time for which the line exceeds its profile temperature is termed 'exceedence'. The choice of exceedence is based on considerations of the statistical occurrence of rated post-fault continuous or short-term loading, reinforced by the tendency for the weather conditions to provide greater cooling during times of high load and high risk of fault. Following consideration and weather statistical analysis, a 12% exceedence has been applied to the post-fault rating of overhead lines. Therefore, if the full post-fault rating is used on a continuous basis (restricted to a maximum 24-hour period), the line temperature will exceed its profiled temperature for approximately 12% of the time.

Planning and operational continuous ratings have been specified for summer, spring/autumn and winter seasons as given in Engineering Recommendation P27 [5]. These ratings use a pre-fault ratio of 84% of the post-fault continuous rating in order to restrict the risk of exceeding line temperature to a suitably low value. For example 132kV Lynx 175mm^2 ACSR overhead lines with a profile temperature of 50^{o}C (equivalent to the overhead line conductors considered in later sections of this paper) have a pre-fault summer rating of 390 A (89 MVA), based on a post-fault rating of 465 A (106 MVA). This ensures the risk of exceeding the line temperature is minimised to approximately 1 in 1000 (8.76 hours / annum) but the risk of exceeding it by more than 5^{o}C, when sag increases start to become more significant, is less than 1 in 10,000 (52 minutes / annum).

Description of real-time thermal ratings

Real-time thermal ratings (RTTRs) are defined as a time-variant rating that can be practically exploited without damaging components or reducing their life expectancy. Actual measurements of environmental conditions (wind speed, wind direction, ambient temperature and solar radiation) are used as the input to steady-state thermal models. In order to calculate and exploit the RTTR, it is assumed that local environmental condition measurements are available. Short term transients, taking into account the thermal capacitance of power system components, are not included within the RTTR assessment. This is termed a 'dynamic thermal rating' and it is felt that this would not materially affect the GWh/annum throughput of energy within the electrical power system.

RTTR deployments could be particularly beneficial for wind farm connections since there is a correlation between the power output of wind farms at times of high wind speed and the cooling effect of the wind on overhead line conductors.

RISKS AND MITIGATION

The RTTR system development process is described below with a discussion of the cautious approach to mitigate risks and uncertainties, in order to demonstrate the same level of risk (or, indeed reduced risk) when compared to the static ratings utilised at present in the UK.

Real-time thermal rating system risks

Key risks were identified in the RTTR system design phase through a failure modes and effects analysis (FMEA). For each failure mode, as shown in Table 1, the pre-mitigation risk, R, has been quantified through multiplying the probability of occurrence, P (1=low, 5=high) by the magnitude of impact if the failure mode occurred in practice, I (1=low, 5=high). The residual (post-mitigation) probability, impact and risk are given in **bold**:

Failure mode	**Effect**	**P**	**I**	**R**
Information technology / Telecommunications failure	Reduction in thermal visibility	4 ↓ **4**	5 ↓ **1**	20 ↓ **4**
Too many additional planned outages required to install and maintain system	Reduction in power system reliability and security of supply to customers	3 ↓ **2**	5 ↓ **2**	15 ↓ **4**
Uncontrolled thermal excursion	Conductor degradation and failure	3 ↓ **3**	5 ↓ **1**	15 ↓ **3**
Lack of sufficient thermal visibility of overhead line network after RTTR system deployment	DNO business does not have confidence to adopt system	3 ↓ **1**	5 ↓ **3**	15 ↓ **3**
RTTR system is too expensive (comparative investment with network reinforcement)	RTTR system not adopted on an economic basis	2 ↓ **1**	5 ↓ **3**	10 ↓ **3**
Change in line construction, land use and vegetation growing near conductors	Conductor clearance infringement	4 ↓ **3**	2 ↓ **1**	8 ↓ **3**

Table 1: FMEA of RTTR system

In addition to the risks identified in Table 1, there are also RTTR system uncertainties that need to be considered:

Accuracy of instrumentation: In order to reduce uncertainties and systematic errors relating to the accuracy of monitoring instrumentation, a correction factor is applied to each sensor to ensure that the most conservative RTTR is calculated. The correction factor is selected using suppliers' equipment specification sheets. On this basis, the wind speed value is reduced, the wind direction value brings the angle of incidence closer to parallel, the ambient temperature value is increased and the solar radiation value is increased.

Drift of signals with time: In order to mitigate the drift of monitoring signals with time, the system is recalibrated after a maximum period of two years.

Mitigation and benefits

In order to mitigate the above mentioned risks, SPEN's RTTR system utilises a thermal state estimation with integrated sensors approach. This cost-effective approach uses a meshed network of weather stations together with a detailed geographical model that allows the weather conditions at every span within the 90km overhead line network to be interpolated. The real-time thermal rating and operating temperature of each span of the overhead line network is calculated. The system identifies the span within each circuit that has the lowest rating and this is used to provide the rating for the entire circuit. The operating conditions of the identified critical spans are validated against a limited number of conductor temperature sensors, carefully selected to minimise the number and duration of outages required for equipment installation.

By modelling the entire system, the DNO is provided with complete thermal visibility of the overhead line network. The meshing of weather stations allows the system to degrade, gracefully, thereby making increasingly conservative estimates of the overhead line thermal ratings as an increasing number of input signals are lost. Furthermore, the integration of the RTTR system with an active network management (ANM) system mitigates the risk of excessive thermal excursions at times of low thermal rating through power flow control techniques [6]. This functionality is vital for the future integration of low carbon generation sources such as wind farms.

RESULTS

Field trial network

The field trial network used for developing the RTTR system and demonstrating the de-risking process is given in Figure 1. Throughout 2012, weather stations have been installed within the field trial network. Each weather station has a 10 km 'zone of influence' whereby the monitored weather conditions are taken into account through weighted distance interpolation to each span within the 'zone of influence' [1].

Results and discussion

The results of the RTTR deployment, for the St Asaph – Dolgarrog circuit, are given in Figure 2. At present, the full potential to exploit the energy yield headroom, unlocked by the RTTR system, would be constrained at 550A by a cable section in the circuit.

Figure 3 shows the cumulative bar chart of additional energy (MWh) which can be transferred through the St Asaph-Dolgarrog overhead line during November when different levels of uplift are assumed. The different levels of constraint on the uplift could be due to a cable section in the overhead line circuit or a protection setting that cannot be violated. Alternatively, the upper constraint levels could represent the cautious relaxation of the constraint.

As shown in Figure 3, an additional 4,335 MWh can be transferred if the real-time thermal rating is limited to 10% uplift of the autumn rating (450 A). By relaxing the maximum uplift limit the additional available energy transfer capacity reaches a total of 14,358 MWh. The results show that the increment rate of additional headroom gradually decreases whilst the maximum allowed uplift increases. For operating the network at a high uplift limit the protection system needs to be correspondingly adapted. Moreover, the total system risk is likely to increase by allowing a high uplift. Therefore, there will be a trade-off between the benefit accruing from increasing the level of allowed uplift and the complication and risk involved with this practice.

Increased thermal visibility of the system allows the system operator to reduce the risk of overstressing the network when the actual thermal rating of the system is below the seasonal thermal rating. Considering the St Asaph – Dolgarrog overhead line, there are some cases when the real time thermal rating is below the autumn rating.

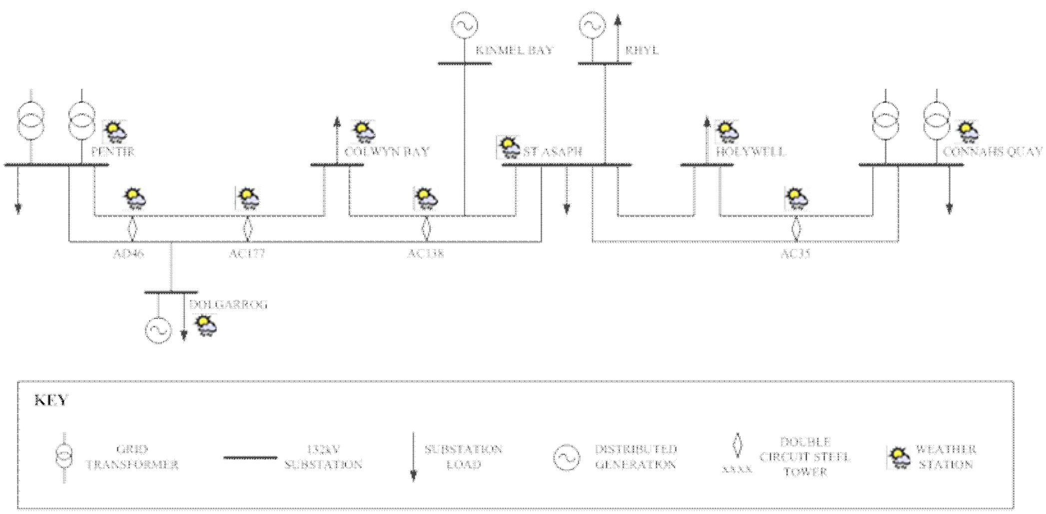

Figure 1: Field Trial Network

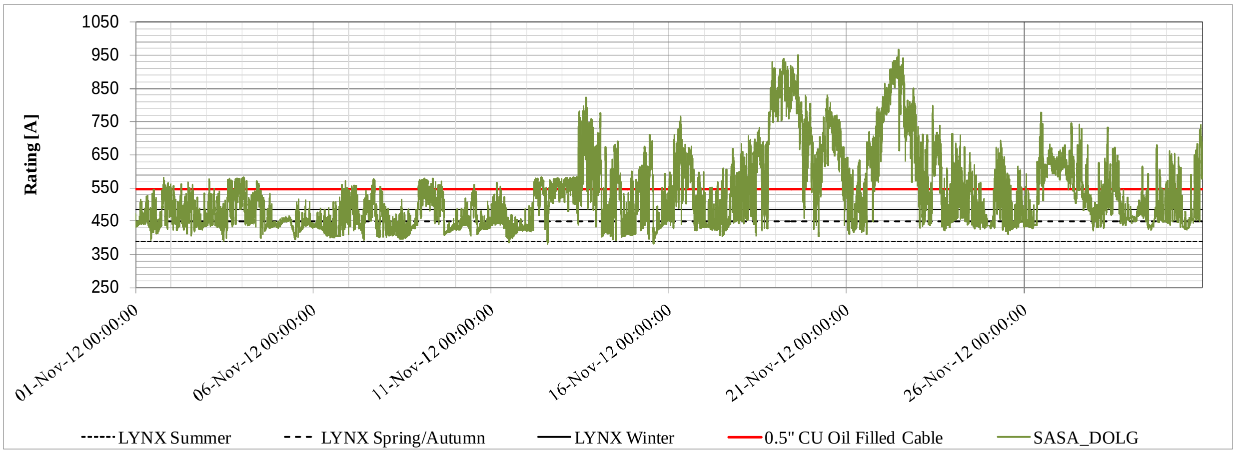

Figure 2: Real-time thermal rating of the 132kV circuit from St Asaph – Dolgarrog during November 2012

The energy transfer capacity under the autumn seasonal thermal rating is around 925 MWh, which represents the energy yield value that would need to be constrained in order to retain the integrity of the system. Since this energy yield occurs in the band between the static summer and autumn ratings, if the RTTR system gains were compared to the static summer rating, the energy yield gains could be significantly greater.

CONCLUSIONS AND FURTHER WORK

This paper has presented the risks and mitigating actions that support the implementation of a real-time thermal rating system for DNO businesses. Through the use of thermal state estimation with integrated sensors and graceful degradation algorithms, significant energy yields can be unlocked (for example 14,358 MWh in November for a single overhead line circuit) whilst minimising the risk of line temperature profile exceedence to 1 in 10,000 (52 minutes / annum). An important conclusion from this work is that early engagement with key decision makers within the DNO business is vital.

The following work is planned to develop the real-time thermal rating system further: (i) temperature sensor deployment, followed by validation; (ii) development and deployment of a graceful degradation algorithm;

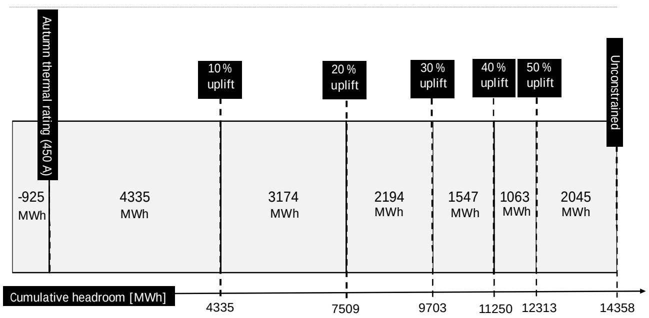

Figure 3: Energy yield accruing from deploying RTTR on the St Asaph – Dolgarrog circuit in November 2012

(iii) forecasting real-time thermal ratings (up to 8 hours ahead for the emergency return to service plan); (iv) quantification of uplifts in different seasons; (v) quantification of additional capacity to accommodate wind farm connections; (vi) design of an ANM scheme to control the power output of wind farms utilising the SCADA-based RTTR for each circuit; and (vii) exploring RTTRs for contingency (N-1 and N-2) operation.

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