DYNAMIC THERMAL RATINGS: THE STATE OF THE ART

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ABSTRACT

Dynamic thermal ratings have the potential to offer a cost-effective alternative to network reinforcement for Distribution Network Operators looking to accommodate load growth or distributed generation connections. A review of the state of the art regarding dynamic thermal rating technologies around the world is presented. Focusing on overhead lines, a survey and evaluation of the various technologies currently available within the industry is given, including planning tools for dynamic thermal rating adoption. A summary is given of various low-carbon projects that demonstrate dynamic thermal rating technology applications and research avenues to facilitate the wide-spread adoption of dynamic thermal ratings are identified.

INTRODUCTION

In the present climate, Distribution Network Operators (DNOs) are faced with pressures such as the accommodation of load growth and the proliferation of distributed generation developers seeking network connections. However, environmental concerns are restricting the building of new electrical infrastructure and in-service network assets are approaching the end of their design lifetime [1]. This is drawing attention to dynamic (also termed 'real-time') thermal rating technologies, which allow more efficient asset utilisation, helping to mitigate the pressures faced by DNOs and facilitate the transition towards lower-carbon distribution networks.

Due to the complexity of monitoring and modelling environmental conditions, static seasonal ratings are used in the planning and operation of distribution networks, at present. Dynamic thermal rating technologies address the above-mentioned challenges by exploiting the latent thermal capacity that is made available within the critical network components of the power system (e.g. overhead lines, electric cables and power transformers) when the thermal limits are varied in real-time according to the prevailing environmental conditions. This could enable DNOs to accommodate increased power flows from consumer load growth or distributed generation connections [2]. Dynamic thermal ratings have the potential to offer a cost-effective alternative to network reinforcement [3]. In addition, the long lead times associated with planning and construction of network reinforcement infrastructure could be avoided.

Focusing on overhead lines, this paper presents a review of the state of the art regarding dynamic thermal rating technologies around the world. A survey and evaluation of the various technologies currently available within the industry is presented, including planning tools for dynamic thermal rating adoption. The various technologies surveyed can be categorised according to direct monitoring and indirect monitoring techniques. Direct monitoring techniques include laser sensors, loading cells and conductor temperature sensors. Indirect techniques use meteorological information together with industrial standard-based component thermal models for indirect component rating estimation. In the latter technology applications, for example, wind speed, wind direction, solar radiation and ambient temperature measurements are input to industrial standards produced by the IEC [4], CIGRE [5] and the IEEE [6] for the dynamic thermal rating of overhead line conductors.

A summary is given of various low-carbon projects that demonstrate dynamic thermal rating technology applications. This includes the application of the technologies by Central Networks in Eastern England, NIE in Northern Ireland and Scottish Power in North Wales for the accommodation of wind farm connections.

In conclusion, the paper identifies future avenues for advancements (such as the development and implementation of proactive dynamic thermal rating technologies for distribution networks, based on forecast meteorological information), which represent the research challenge for academia and equipment manufacturers of dynamic thermal rating technologies.

POWER SYSTEM THERMAL BEHAVIOUR

Whilst dynamic thermal rating technologies have been developed for electric cables and power transformers, it has been demonstrated that overhead line components of the power system exhibit a greater rating variation due to the influence of environmental conditions. Key findings from research at Durham University showed that the average rating of overhead lines, electric cables and power transformers ranged from 1.70 to 2.53, 1.00 to 1.06 and 1.06 to 1.10 times the static rating, respectively [2]. Therefore greater benefits may be captured through the exploitation of overhead line dynamic thermal ratings, particularly as a strong correlation may exist between the power output of wind farms and the cooling of overhead line conductors at high wind speeds.

OVERHEAD LINE THERMAL BEHAVIOUR

Overhead line ratings are constrained by a necessity to maintain statutory clearances between the conductor and other objects [7]. 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 'design' 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, 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 [2]. In order to calculate the maximum current for a given operating temperature, it is necessary to solve 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).

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

OVERVIEW OF OVERHEAD LINE DYNAMIC THERMAL RATING TECHNOLOGIES

Technologies for the exploitation of overhead line dynamic thermal ratings can be broadly categorised into (i) sag-based techniques; (ii) tension-based techniques; (iii) conductor temperature-based techniques; and (iv) current rating-based techniques. Each of the techniques, underpinning overhead line dynamic thermal rating technologies, is described in more detail in the sections that follow:

Sag-based

Technologies that use sag-based techniques monitor the sag of the overhead line conductor either through lasers or radar scans [8]-[9]. This may involve the installation of a monitoring unit on the ground in proximity to the overhead line conductor, or on the conductor span itself. Based on the measurement of the overhead line conductor sag the absolute clearance of the overhead can be quantified.

Tension-based

Technologies that use tension-based techniques monitor the tension of the overhead line conductor either through loading cells or strain gauges attached to the conductor surface. Loading cells may be installed at overhead line tension towers on the tower-side of the insulation string [10]. The loading cells or strain gauges tend to be powered by local battery sources that are recharged through solar panels. The monitored tension of the line allows the line sag to be calculated (1) and the absolute clearance of the overhead line to be quantified.

Temperature-based

Technologies that use temperature-based techniques monitor the operating temperature of the overhead line conductor. This can then be directly compared to the maximum operating temperature (design temperature) of the overhead line to ensure statutory clearances are maintained. Retro-fitting temperature sensors to the existing conductor may involve clamping the monitoring equipment to the overhead line or taping a fibre wrap to the exterior of the conductor. In the case of newly-commissioned overhead line infrastructure, a fibre optic cable may be incorporated within the overhead line conductor to provide distributed temperature sensing functionality.

Current rating-based

Technologies that use current rating-based techniques monitor or estimate the environmental conditions (wind speed, wind direction, solar radiation and ambient temperature) in the vicinity of the overhead line. Using environmental conditions monitored in real-time, together with fixed parameters (such as the conductor diameter) the maximum current rating of the overhead line conductor may be calculated (2) that corresponds to the maximum operating (design) temperature. Three widely-used standards for modelling overhead line current limits have been produced by the IEC [4], CIGRE [5] and the IEEE [6].

Planning tools

In order to plan for the adoption of dynamic thermal rating technologies it is necessary to (i) identify the location of thermally vulnerable components within the power system; (ii) quantify the influence of environmental conditions on power system ratings; (iii) identify equipment suppliers for the various aspects of the dynamic thermal rating system (such as sensors, telecommunications and control software); and (iv) develop an equipment maintenance schedule.

The identification of thermally vulnerable components within the power system may be achieved through (i) offline power system studies (such as the assessment of thermal vulnerability factors [11]); (ii) physical assessment and monitoring of the power system (such as line surveys and Thermo-vision imaging); and (iii) DNO operational experience. The influence of environmental conditions on power system ratings may be quantified through the development of component thermal models and the population of the models with offline meteorological data relating to the site [2].

OVERHEAD LINE DYNAMIC THERMAL RATING TECHNOLOGIES DISCUSSION

The four techniques, upon which dynamic thermal rating technologies are based, are discussed from the perspective of distribution system planning and operation.

Planning and installation

Overhead line dynamic thermal rating technology that utilises the sag-based technique has the potential to be installed with minimal disruption to the power system, particularly if, in the case of the laser technology, the unit is installed on the ground and not on the conductor itself. The tension-based and conductor temperature-based techniques involve the installation of monitoring equipment directly onto the overhead line conductor. Multiple outages may be required for equipment installation and maintenance, which could entail lengthy downtimes for the network depending on the coverage required by the sensors. In addition, these techniques place an inherent risk on the conductor since damage caused by friction or the build up of dirt could create a hotspot in the conductor. The current rating-based technique involves the indirect monitoring of the overhead line through measurement or state estimation of environmental conditions (e.g. weather conditions) local to the overhead line. Therefore this technique does not require system outages for installation or maintenance.

System operation

From an operational perspective, the current flow in overhead line conductors is a key parameter for controlling the distribution network. From a statutory perspective, the critical parameter is the conductor clearance from the ground. It has already been stated that complex physical systems relate the current flow in the overhead line to its sag. Therefore, the provision of sag measurements directly back to the DNO control room, whilst giving an absolute indication of the proximity the power system to its operational limit, may be of limited use for control purposes. Whereas the acceptable sag or sag angle varies from span to span, the acceptable conductor operating temperature remains constant for the entire component. Moreover, ground-based laser sensing technologies, which offer the advantage of minimising disruption to the power system operation for installation of the equipment, entail the possibility that the overhead line conductor may be blown out of the sensor scanning range in high winds. For the tension-based techniques to be of benefit to system operations, the overhead line tension needs to be combined with the conductor operating temperature to assess the overhead line current carrying capacity. Clearly, this technique would require the installation of load cells or strain gauges in each thermally vulnerable set of overhead line spans. This is likely to be a cost-intensive solution from an equipment investment point-of-view. For the temperature-based techniques to be of benefit to system operations, the difference between the actual and maximum conductor operating temperatures would need to be used to calculate the headroom in current carrying capacity of the conductor. Similarly to the tension-based techniques, this technique would require the installation of temperature monitoring sensors in each thermally vulnerable set of overhead line spans and is therefore likely to be a cost-intensive solution. Current rating-based techniques are likely to be of most practical use to network operators for controlling the power system. The installation of the system may be less obtrusive to power system operation compared to the other techniques. Furthermore, the cost of this type of system may be reduced by the adoption of thermal state estimation techniques whereby limited meteorological station installations are used to determine the thermal rating of wide areas of the power system [12]. Thermal state estimation techniques also allow power system continued operation and graceful degradation in the presence of communications failures. As an increasing number of communications signals are lost the system makes increasingly conservative estimations of the overhead line thermal rating. The downside of this type of system is that the modelling software needs to be maintained for changes to the power system topology and a weather station maintenance regime is required. In the early stages of dynamic thermal rating system deployment, as the technology is cautiously adopted, it is recommended that the current rating-based technique is deployed with sag-, tension- or temperature-based techniques for validation purposes.

Conflicting drivers

Within the DNO itself, conflicting drivers may exist in different parts of the business and arbitration is needed to facilitate the adoption of dynamic thermal rating technologies. For example, enough equipment would need to be installed within the distribution network to provide power system operators with a sufficient level of confidence to utilise dynamic thermal ratings. However, the system planners and asset managers who are responsible for equipment installation and maintenance will look to minimise the amount of equipment needed and the therefore minimise the potential disruption to the power system.

CASE STUDY PROJECTS

Significant activity is being carried out in the UK to demonstrate the value and viability of dynamic thermal ratings as a technology to enable lower-carbon distribution networks.

Central Networks, in conjunction with Alstom Grid (formerly AREVA T&D), are trialling dynamic thermal rating technology on the 132kV double circuit line from Skegness to Boston in Eastern England [13]. Due to increased penetrations of wind generation in the Skegness region, there is the possibility that reverse power flows may be experienced in the 132kV circuits leading to thermal limit violations. In order to mitigate thermal overloads, the current rating-based technique is being deployed both centrally within the Central Networks control room and in a distributed architecture, embedded in protection relays local to the overhead lines. Both CIGRE and IEEE standards are being used and the ratings of the overhead lines are varied in real-time according to wind speed and ambient temperature, with fixed parameters assumed for wind direction and solar radiation. Validation measurements of the overhead line operating temperature are harvested using Power Donut™ technology.

NIE, in conjunction with Alstom Grid, are trialling dynamic thermal rating technology on the 110kV line from Omagh to Dungannon in Northern Ireland [13]. Thermal overloads may be experienced on this line due to the loss of transmission circuits in other parts of the network and, as a result, a 30 MW wind farm can be constrained. In this case, the current rating-based technique is being deployed to vary the rating of the overhead line in real-time according to the ambient temperature measured at Omagh substation. Other weather parameters are fixed, based on Engineering Recommendation P27 assumptions.

Scottish Power Energy Networks, in consortium with Parsons Brinckerhoff (now part of the Balfour Beatty Group), Alstom Grid, Durham University and Infoterra, recently completed a three-year Research and Development project that developed dynamic thermal rating technology on multiple 132kV circuits, due to planned increased penetrations of wind generation, both onshore and offshore in North Wales. Weather data from a limited number of meteorological station installations is used, together with thermal state estimation techniques and the IEC standard, to determine thermal ratings for wide areas of the distribution network. In this project the algorithms have been validated through the use of conductor temperature monitoring sensors [12].

Dynamic thermal ratings have been identified by the UK regulator, Ofgem, as a key enabling technology for the transition towards low carbon distribution networks. This is embodied in the Low Carbon Networks funding support provided to CE Electric and Scottish Power to implement dynamic thermal rating system projects over the next three years [14].

FUTURE RESEARCH AVENUES

A number of potential research avenues are identified below to facilitate the wide-spread adoption of dynamic thermal rating technologies:

- The evolution of planning standards and how the power system is operated in contingency scenarios;
- The voltage level of deployment;
- Adequate network thermal visibility for power system operation;
- Training of planning and operational personnel;
- ‘Proactive’ dynamic thermal ratings based on weather forecast data;
- Suitably reliable sensors and communication links within the dynamic thermal rating system; and
- Suitably responsive generator output control to ‘turn down’ signals from the network operator.

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