Real-time thermal rating reliability enhancement using a graceful degradation methodology

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ABSTRACT

This paper presents a process to increase the reliability of weather-based RTTR systems and sanitise the affected weather parameters to ensure the estimated RTTR is of an acceptable degree of accuracy. As an increasing number of weather station parameters become unavailable or unhealthy, the RTTR values gracefully degrade towards static seasonal ratings and increasingly conservative estimates are made of the RTTR of overhead line assets. Initial study showed that using this methodology for 5% of a year period, when weather parameters are not available to RTTR system, can reliably unlock 823MWh of network annual carrying capacity.

INTRODUCTION

In order to accommodate future demand and increasing connection levels of distributed generators, significant additional network capacity is required. This capacity can be unlocked, in part, if the existing network assets are better utilised. The deployment of real-time thermal rating (RTTR) systems, which have been identified as a key low-carbon transition technology, can release additional capacity for future networks by planning and operating networks to real-time, rather than static, thermal ratings [1]. For example, studies in the UK have shown that an additional 30% capacity, beyond the static rating, can be unlocked in overhead line assets [2].

Scottish Power Energy Networks (SPEN), the UK Distribution Network Operator for South and Central Scotland and North Wales, have trialled the implementation of a Real-Time Thermal Rating (RTTR) system, for two 33 kV overhead line circuits, as part of their Second Tier Low Carbon Networks Fund project "Flexible Networks for a Low Carbon Future". The aim of this project was to enhance the thermal visibility of the distribution network, releasing extra current-carrying capacity from the existing assets.

The methodology used for implementation of SPEN's RTTR system was based on a meshed network of weather stations together with a detailed geographical model of the overhead line to estimate the weather conditions in the vicinity of each span on a real-time basis. One of the key learning points from the implementation of this weather-based RTTR system is that the system is vulnerable to interrupted and erroneous weather parameters. Due to failures in the communication systems or malfunctioning of the sensors the correct values of real-time weather parameters may not be received as an input to the RTTR system. Therefore, there is a requirement for a methodology to enhance the reliability of RTTR calculation [3] for mission-critical network controls.

In this paper, an overview of the RTTR system implemented for the two 33kV circuits located in Scotland is presented. The graceful degradation (GD) algorithm will also be explained in detail and the effectiveness of the algorithm will be demonstrated for different operational scenarios, using actual monitored real-time weather parameters.

SUMMARY OF IMPLEMENTED RTTR SYSTEM

SPEN have implemented an RTTR system for two 33kV overhead line circuits which are located between Cupar and St Andrews in Scotland. In this system, six weather stations allocated along the Cupar-St Andrews circuits monitor the real-time variations of weather parameters (wind speed, wind direction, ambient temperature and solar radiation), see Figure 1.

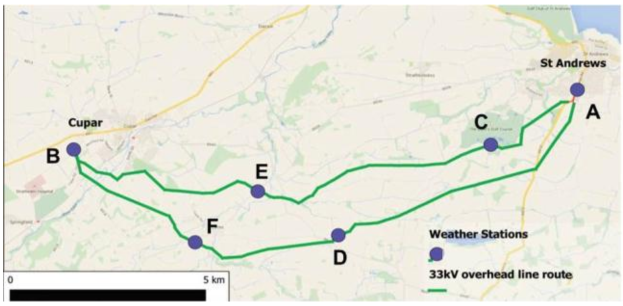

Figure 1: Locations of weather stations in Cupar-St Andrews circuits

An interpolation technique [4] was deployed to estimate the weather conditions in the vicinity of each span taking into account the monitored weather parameters at the six weather stations. The RTTR values of each span within the Cupar – St Andrews circuits are then calculated using the estimated weather parameters, maximum operating temperature of the circuits (50°C) and a detailed geographical model of the overhead line circuits. The RTTR calculations are based on thermodynamic behaviour of the overhead line conductors which is explained in detail in IEC TR61597 [5] and CIGRÉ WG22.12 [6] standards.

This approach identifies the span within each circuit that has the lowest rating, and this critical span is used to provide the rating for the entire circuit. By modelling the entire system, complete real-time thermal visibility of the overhead line network is provided and the most frequently limiting spans within the overhead lines can be identified.

In addition to weather stations, there are line-powered sensors co-located with weather stations and mounted directly on the conductors. These line sensors monitor phase currents and conductor temperatures on a real-time basis, see Figure 2. The direct measurement of the conductor temperature is a complementary method to the weather-based RTTR system and boosts the confidence in deploying this system for the real-time operating of the network.

The RTTR system has been developed and integrated into SPEN’s network management system (NMS) through which the real-time RTTR values of each circuit are available to the control engineers. Figure 3 shows a high-level architecture of the RTTR system. The monitored data, weather parameters and direct conductor measurements, are transmitted via GPRS communication to iHost. This dataset is concentrated and transferred to the NMS Server hosting the RTTR processor. The results of the calculation are then available in the control room and through a web interface. The measured and calculated parameters from the RTTR system are also recorded to SPEN’s data historian.

INTERRUPTION IN REAL-TIME DATA

The developed RTTR system relies heavily on real-time weather parameters i.e. the accuracy of the calculated RTTRs can be affected when real-time weather parameters are interrupted. The real-time weather parameters inputted to the RTTR processor may be interrupted due to sensors becoming faulty or interruption in the GPRS communication between weather stations and iHost.

One of the solutions to alleviate the impact of losing weather data on the accuracy of the calculated RTTRs is to increase the number of weather stations and provide redundancy. Therefore, in the event of losing weather inputs from one of weather stations, the remaining weather stations could provide acceptable visibility of the weather conditions across the network. Increasing network instrumentation can be costly. Instead, intelligent algorithms can be deployed to sanitise the “unhealthy” weather data before RTTR calculation. SPEN have now developed and trialled a GD methodology to process the input data to RTTR and gracefully degrade the RTTR values to seasonal thermal rating when increasing number of weather stations become unavailable.

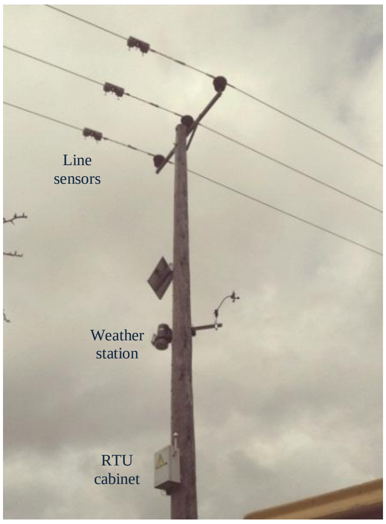

Figure 2: RTTR monitoring system equipment – weather station, line sensors and RTU

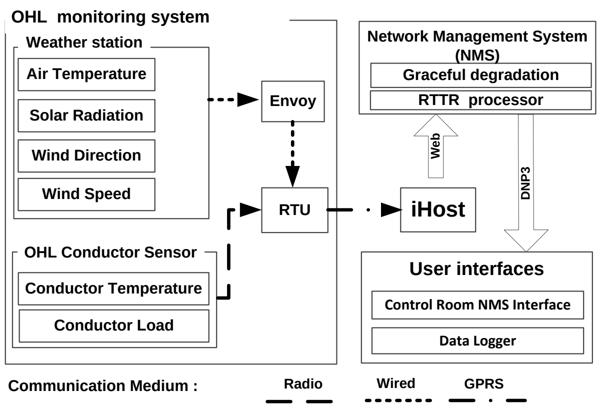

Figure 3: RTTR system architecture

GRACEFUL DEGRADATION METHODOLOGY

The GD’s functionalities are outlined below:

- Identification of “unhealthy” sensors;
- Provision of conservative estimated values for the sensors that have been identified as unhealthy;
- Switching to the seasonal rating values when the number of available healthy sensors falls below an acceptable number;

- Recording estimated values and health status of the sensors in SPEN's data historian.

The GD process is shown in Figure 4.

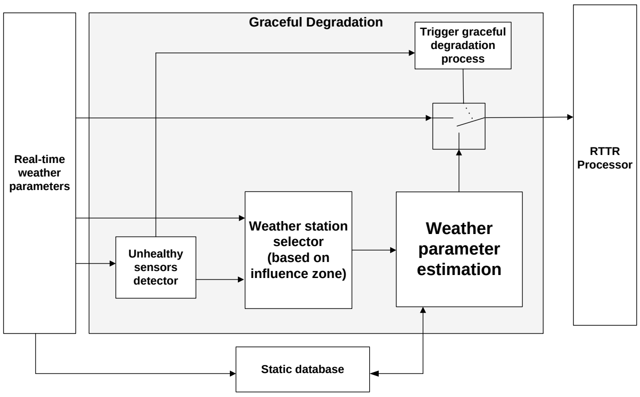

Figure 4: Graceful degradation process

Triggering graceful degradation process

A "quality value" is associated with each of the weather parameters transmitted to the iHost. This "quality value" indicates whether the weather data is healthy. The GD process will be triggered with a delay when the status of at least one weather sensor is identified as unhealthy or unavailable. This delay is considered to avoid unnecessary computational burden and repeatedly triggering the GD process in the event when the weather data is unavailable only for a short period e.g. 10 minutes. The temperature of the conductor changes gradually based on the conductor's heat capacity, hence, this delay would not comprise the RTTR system. During the delay period the latest healthy weather parameter will be considered for the RTTR calculation.

Correlation analysis

Real-time variation of a weather parameter may not necessarily follow the same pattern at all weather stations. This may be due to distance between weather stations or different geographical conditions. In order to enhance the accuracy of the estimated weather parameters only correlated weather stations should participate in the estimation process. A correlation analysis, using MATLAB correlation function, was carried out on a four-month period of historic weather parameters. The results of the correlation analysis identify the weather stations that should participate in estimating the data at an unhealthy weather station. Table 1 shows the results of correlation analysis.

Table 1: Correlated weather stations

	Participating weather station					
Unhealthy weather station	**A**	**B**	**C**	**D**	**E**	**F**
A	×	×	√	√	√	√
B	×	×	×	√	√	√
C	√	×	×	√	√	√
D	√	√	√	×	√	×
E	√	√	√	√		√
F	√	√	√	×	√	×

Estimation of unavailable weather parameters

The GD process estimates the weather parameters identified as unavailable to avoid the risk of significant overestimation or underestimation of RTTRs of the overhead lines. In particular, it is important to reduce the risk of asset damage due to overstressing the network. Therefore, the proposed GD methodology provides a real-time conservative estimation for weather parameters.

The approach used to estimat the missing weather parameters relies on the historic data of other weather stations. The GD process retrieves a historic period called "backward window" from SPEN's data historian. Figure 5 shows an example of a backward window indicating a historic period ending at the current time.

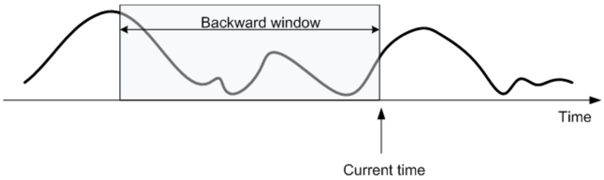

Figure 5: Backward window concept used in GD methodology

The length of the "backward window" and the computation steps for estimating each weather parameter is different. The approach used for estimating each weather parameter (ambient temperature, solar radiation, wind speed, wind direction) is outlined in the following sections.

Ambient temperature

Ambient temperature variation patterns are usually similar at different weather stations installed along an overhead line. Nonetheless, an average ambient temperature difference can be envisaged between two locations. The approach for estimating the real-time ambient temperature is outlined as follows:

- *Calculate correction factor:* This is the average difference (positive or negative) between the ambient temperatures recorded by correlated sensors during the four hours before a sensor is detected as unhealthy;
- *Retrieve historic data:* maximum ambient temperatures recorded for a one hour backward window by healthy sensors correlated with the unhealthy sensor;
- *Add the correction factor:* Add the corresponding correction factors to the maximum values retrieved in the previous step;
- *Calculate the estimated values:* Maximum of the resultant values in the previous step represents the estimated ambient temperature.

Figure 6 shows the estimated versus actual ambient temperature for a 24-hour period at weather station A. As can be seen, GD methodology has provided a conservative estimate for ambient temperature that is higher than the actual ambient temperature but follows the actual ambient temperature variation.

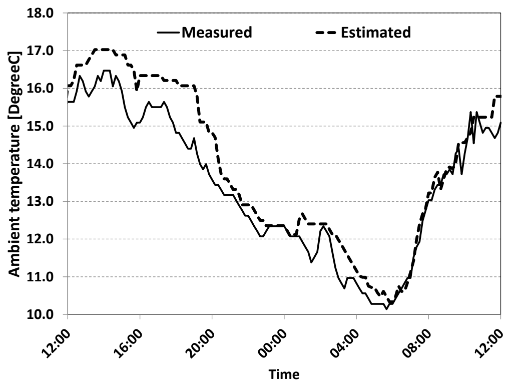

Figure 6: Estimated and actual ambient temperature

Solar radiation

Solar radiation follows a bell-shaped curve during a 24-hour period. Data analysis also showed that there is a strong correlation between variations in solar radiations at different locations along the overhead line. The approach for estimating the real-time solar radiation is outlined as follows:

- *Retrieve historic data:* maximum solar radiation recorded for a one hour backward window by the healthy sensor correlated with the unhealthy sensor;
- *Calculate the estimated values:* Maximum of the values retrieved in the previous step represents the estimated solar radiation.

Figure 7 shows the estimated and actual solar radiation for a 24-hour period at weather station A. The estimated solar radiation is higher than actual solar radiation and that can provide conservative RTTR values.

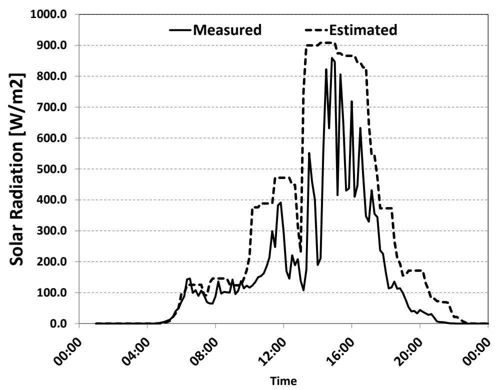

Figure 7: Estimated and actual solar radiation

Wind speed

Wind speed has a stochastic nature and its variation, apart from metrological conditions, depends on the ground roughness and the height from the ground which is expressed by exponent Kshear [7], see equation (1).

$$Ws_{z1} = Ws_{z2}.\left({}^{H_{z1}}/_{H_{z2}}\right)^{Kshear} \tag{1}$$

Where Ws_{z1} and Ws_{z2} are wind speeds at H_{z1} and H_{z2} heights, respectively, and $Kshear$ is the ground roughness factor.

The approach deployed for estimating an unavailable wind speed is outlined as follows:

Retrieve historic data: Retrieve minimum wind speed recorded for a six hour backward window by healthy sensors correlated with the unhealthy sensors. The six hours backward window is selected to provide a consistent conservative estimated wind speed;

Calculate wind speeds at a reference height: In order to remove the effect of ground roughness the minimum wind speeds retrieved in the previous steps are projected to a height reference (e.g. 200m) using equation (1);

Estimate wind speed at a reference height: Use the inverse distance interpolation technique [4], see equation (2), to estimate minimum wind speed at a reference height at the point where the unhealthy wind sensor is located.

$$Ws_{ref} = \frac{\sum\left({}^{1}/_{di^2}\right).Ws_{iref}}{\sum\left({}^{1}/_{di^2}\right)} \tag{2}$$

Where di is the distance between a healthy wind sensor i and the unhealthy wind sensor, Ws_{iref} is the wind speed at the reference height at healthy wind sensor sensor i.

Estimate the minimum wind speed: Use equation (1) and estimated minimum wind speed at reference height to estimate the wind speed at the unhealthy wind sensor.

Figure 8 shows estimated wind speed and actual wind speed for a 24 hour period. The estimated values are mostly lower than actual wind speeds and that can provide a conservative RTTR values. It should be noted that. This conservative RTTR value would be still higher than the static thermal ratings.

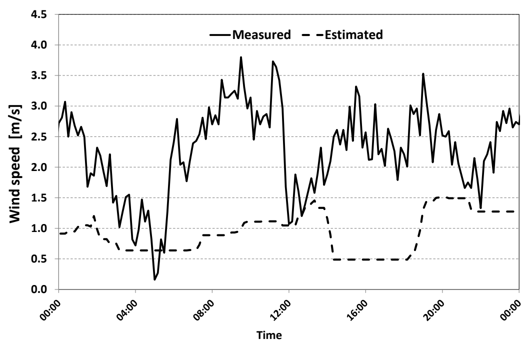

Figure 8: Estimated and actual wind speed

Wind direction

Wind direction and wind speed usually become unavailable at the same time as the sensors for these parameters are usually fitted in the same device. A similar interpolation technique used for wind speed estimation is deployed for estimating wind direction. This methodology is outlined as follows:

Retrieve real-time wind directions: Retrieve the latest healthy wind directions transmitted to the iHost. These are the wind directions recorded at the wind sensors correlated with unhealthy wind sensor.

Estimate the real-time wind direction: Use interpolation technique given by equation (2) and calculate the wind direction at the unhealthy sensor.

As an example, Figure 9 shows the estimated and actual wind direction for a 24-hour period.

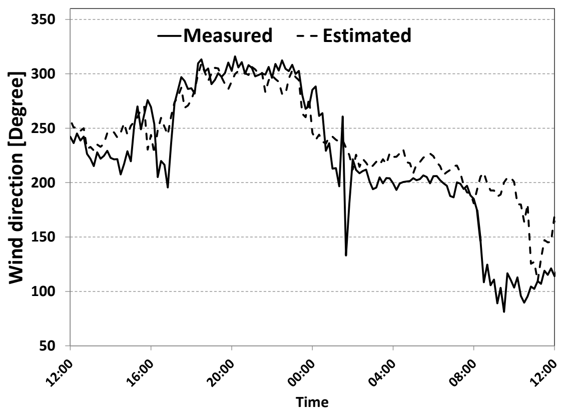

Figure 9: Estimated and actual wind direction

Multi failures

In order to provide reliable RTTR calculations, a “minimum number of healthy weather sensors” should participate in the estimation of the unhealthy weather parameter. For cases where less than the “minimum number of healthy weather stations” is available the estimation is not valid and the unhealthy sensor will be eliminated from RTTR calculation process. This “minimum number of healthy weather sensors” depends on the total number of weather stations and the length of overhead line. As an indicative number, for the Cupar-St Andrews RTTR system, at least two healthy weather sensors should be available for estimation.

Degrading to seasonal rating

In order to provide a reliable RTTR calculation a “minimum number of sensors”, for every weather parameter, should be available for RTTR calculation of a span. This “minimum number of sensors” includes the available healthy sensors and estimated sensors. For the cases where the “minimum number of sensors” are not available the rating of the span will be degraded to the seasonal thermal rating. Seasonal thermal rating depends on the prevailing weather conditions, which may differ for different regions. Engineer recommendation P27 [8] is widely used by UK distribution network operators for evaluating the seasonal thermal rating of overhead lines.

CONCLUSIONS

A GD methodology for enhancing the reliability of a weather-based RTTR system was developed and trialled. The proposed GD methodology estimates unavailable weather parameters and provides conservative RTTR values once at least one weather sensor becomes unavailable. In case of multi-failure GD algorithm instructs the RTTR processor to switch to seasonal thermal rating.

It should be noted that the parameters of the proposed GD e.g. “backward window” period, may be tailored for different RTTR systems based on number of weather stations, overhead line length, and telecoms interruption frequency.

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