DYNAMIC LINE RATINGS DEPLOYMENT ON THE ORKNEY SMART GRID

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ABSTRACT

This paper presents and discusses initial results from the assessment of the deployment of a dynamic line rating system on the Orkney Isles. The project described in this paper consists of extending the existing Active Network Management scheme through the inclusion of a dynamic line rating device and an accompanying real-time ratings estimation system, with the goal of exploiting the real time rating of the circuits located at constraint locations on the Orkney network.

INTRODUCTION

Power system component ratings are determined by the capacity of a component to dissipate heat, produced by the Joule effect, to the environment whilst remaining below a maximum operating temperature for a continuous period of time. The heat exchange on the component surface is influenced by environmental parameters such as wind speed, wind direction, air temperature and solar radiation. Because of the variability of these parameters, worst case conservative values are used for calculating seasonal ratings as applied to all overhead components. A constant seasonal rating therefore includes a considerable level of security (in line with established standards and practice in the industry). Monitoring weather conditions in real-time permits the calculation of real-time ratings that can result in periods where additional capacity on the network can be safely accessed, particularly in the case of overhead line circuits [1].

An Active Network Management (ANM) scheme has been developed and installed on Orkney to facilitate increased connections to a network previously considered full, while avoiding major network reinforcement works. Several renewable generators have either connected to, or plan to connect to, the operational ANM scheme. The ANM scheme was deployed by the Scottish Hydro Electric Power Distribution (SHEPD) and Smarter Grid Solutions (SGS) in 2009, representing one of the first deployments of an ANM scheme to autonomously manage multiple generators and multiple network constraints. The Orkney Isles are characterised by considerable renewable resources and a rural network that would require expensive reinforcements in order to integrate new distributed generation using conventional methods.

This paper describes a project undertaken by SHEPD and SGS to assess the feasibility of extending the existing ANM deployment with a dynamic line rating system, capable of exploiting the real time rating of the circuits located at a constraint location on the network. This is expected to increase the annual energy yield of the existing actively managed generators and to improve the viability of further generator connections, without physical upgrades to the existing network.

The project is divided into two parts: (a) the deployment of a dynamic line rating (DLR) system based on conductor temperature measurements and (b) the development of a wide area real time rating (RTR) system based on the measurement of meteorological parameters and the subsequent calculation of conductor rating estimations. This paper will report on the anticipated impact of the DLR system and its integration with the ANM scheme, present results of preliminary studies and discuss anticipated outcomes from DLR deployment.

Further reporting of the performance of the installed DLR device and the implementation of the RTR solution will be covered in future work.

DYNAMIC LINE RATINGS

DLR is based on the concept that overhead line component rating is strongly influenced by environmental conditions, such as air temperature or wind speed. The heat produced in the conductor by the Joule effect is dissipated in the environment and the conductor temperature is the result of the energy balance, as described in Equation (1).

$$Qc + Qr - Qs = I^2 \cdot R(Tc) \quad (1)$$

Where,

Qc [W/m] = convective heat exchange
Qr [W/m] = radiative heat exchange
Qs [W/m] = solar gain
Tc [°C] = conductor temperature
I [A] = current flowing in the conductor
R(Tc) [Ω/m] = conductor electrical resistance at specified conductor temperature.

Standards produced by the IEC [2], CIGRE [3] or IEEE [4] can be used to calculate each term in Equation 1. The equations to calculate the parameters used in Equation 1 are given below.

$$Qc = \pi \cdot Nu \cdot \lambda \cdot (Tc-Ta)\ Ka \quad (2)$$

$$Qr = \varepsilon \cdot \sigma S\text{-}B \cdot (Tc4-Ta4) \cdot \pi \cdot D \quad (3)$$

$$Qs = \alpha \cdot D \cdot Sr \quad (4)$$

$$R(Tc) = R0 \cdot [1+a(Tc-T0)] \quad (5)$$

Where,
Nu = Nusselt number
v [$kg \cdot m^{-1} \cdot s^{-1}$] = air kinematic viscosity
D [m] = conductor diameter
λ [$W \cdot K^{-1}$] = air thermal conductivity
Ka = incidence angle correction factor
ε = emission coefficient
σ_{S-B} [$W \cdot M^{-2} \cdot K^{-4}$] = Stefan-Boltzman constant ($5.67 \cdot 10^{-8}$)
α = absorption coefficient
R_0 [$\Omega \cdot m^{-1}$] = conductor resistance at rated temperature T_0
T_0 [K] = conductor resistance rated temperature (20°C)
a [$\Omega \cdot m^{-1} \cdot K^{-1}$] = conductor resistance variation with temperature
Ws [m/s] = wind speed
Wd [°North] = wind direction
Ta [°C] = air temperature
Sr [W/m^2] = solar radiation

An example of calculated overhead line conductor ratings on the Orkney network for different wind speeds and different air temperature values are provided in Figure 1. These values were calculated using the IEC Standard [2].

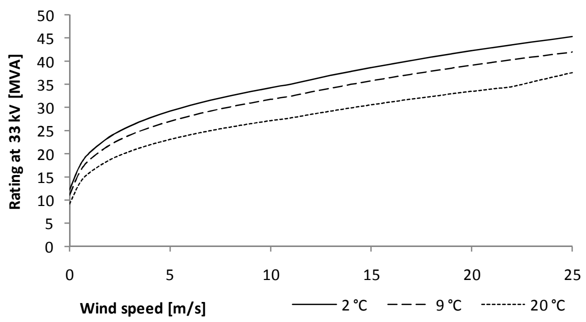

Figure 1: Conductor rating Vs wind speed for different ambient temperature values and a wind incidence angle of 90°

It is normal practice for network operators to apply static seasonal ratings based on assumed seasonal environmental conditions identified in the relevant industrial standards. The environmental parameters currently used in the UK for calculating seasonal ratings are [5]:

- Ws [m/s] = 0.5
- Wd [°] = 0
- Ta [°C] = 2 (Summer), 9 (Spring/Autumn), 20 (Winter)
- Sr [W/m^2] = 0

The choice of the wind speed is particularly conservative, but the choice of the incidence angle and the value for solar radiation, are not so conservative. The air temperature value is altered to calculate the seasonal ratings.

THE DEPLOYED ANM SCHEME

The Orkney network has been the subject of several studies carried out for developing, deploying and validating the ANM scheme. A technical appraisal of the Orkney network and its capabilities and limitations under many scenarios of demand, generation connections, network configuration and reactive compensation can be found in a report by SHEPD and the University of Strathclyde [6].

The Orkney Isles are supplied by two 33 kV feeders from the Scottish Mainland, each with a capacity of around 20 MW. A 33kV network consisting largely of overhead lines and subsea cables supply the Orkney Mainland and surrounding isles. A schematic overview of the network is given in Figure 2.

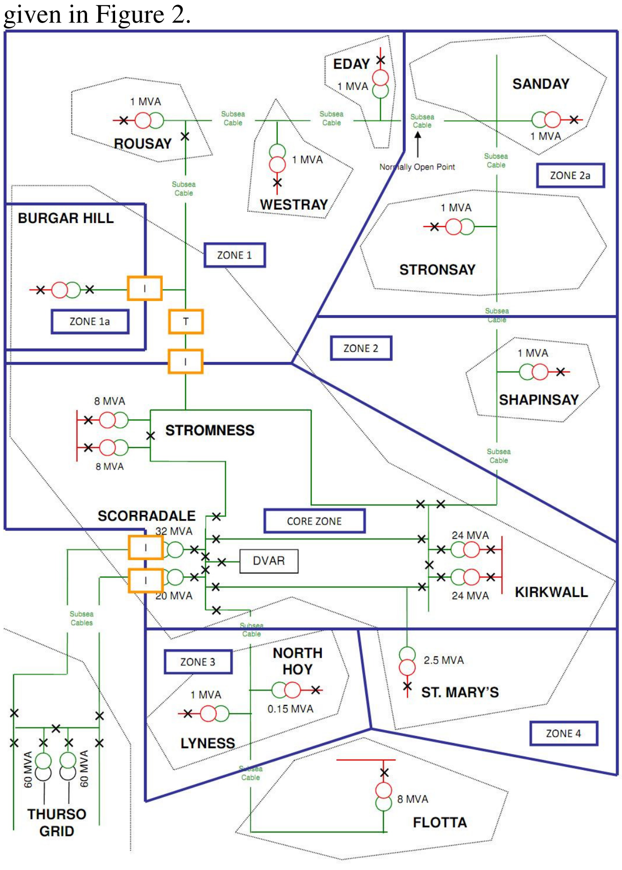

Figure 2: Potential ANM zone topology for the deployment of SGi on the Orkney network. The location of the temperature measurement is marked with a "T"

Orkney has experienced higher than average activity in the connection and operation of distributed generation (DG). There is a mix of wind, wave, tidal and gas generators connected to the existing grid. DG connections fall into three main categories:

- Firm Generation (FG)
- Non-Firm Generation (NFG)
- New Non-Firm Generation (NNFG)

The total installed FG capacity is 26 MW; FG can freely operate with an intact network and in N-1 conditions. A NFG capacity of 21 MW can operate freely with an intact network, but are inter-tripped if necessary for the case of an outage on one of the two submarine cables connecting the islands to the Scottish Mainland. NNFG units are connected in addition to FG and NFG. NNFG units are actively managed in real-time, with export levels dependent on the actual Orkney demand (between 8 and 32MW for the entire group) and the diversity between the outputs of other online DG units.

NNFG units are autonomously managed by SGi, the ANM system deployed in 2009, which curtails (i.e. reduces generator output) NNFG units when constraints at one or more locations on the Orkney network are breached. The NNFG units are placed in a priority stack for access to capacity; the first to connect has the highest priority. A discussion of different commercial principles of access is presented in another CIRED paper by SGS [7].

DYNAMIC LINE RATING APPLICATION

The DLR device considered for deployment on Orkney is a conductor temperature measurement device, the PowerDonut2^{TM} manufactured by USi. The DLR sends readings in real time to the SGi ANM system via a low power radio link. SGi can then compare the actual conductor temperature with the maximum design temperature and in effect curtail generators on the basis of this parameter rather than on the comparison between measured current and conductor rating.

The main advantage of this method is the availability of a direct measurement of the thermal state of the conductor. A disadvantage is that the rating is only calculated at a single point on the line and may not be representative of the state of the whole line, where different sections can experience different wind directions and speeds.

REAL TIME RATING APPLICATION

In order to overcome the limitations of deploying an individual DLR device, SGS has developed a RTR system which is able to estimate real time circuit ratings for all the overhead circuits of the network. The RTR system provides estimates of circuit ratings using the thermal model described in Equation (1) and a number of state estimation techniques in order to take into account weather variability and the effect of measurement and communication failures. The initial deployment of the RTR system will be used in an off-line mode to provide information to the control room, without interacting directly with SGi. After a test period, the RTR system may be fully integrated into SGi to provide automatic constraint management using estimated real time ratings.

A single weather station, installed at the same location as the DLR device, will be used to provide weather parameters; however, SHEPD and SGS are investigating the possibility of integrating existing weather stations to improve system accuracy and reliability.

DLR FEASIBILITY STUDY

In order to quantify the benefits of the DLR device in terms of increased energy output from existing NNFG units and capacity of additional NNFG units that could be enabled, a series of curtailment assessment studies were carried out. Ratings values used in the study were calculated using historical meteorological readings from Kirkwall Airport on the main Orkney Island. Historical values for the year 2008 are shown in Figure 3. Weather data is presented in months in order to facilitate a comparison with the assumed environmental conditions used for conductor ratings in existing industry standards, such as [5]. For wind speed, a value of 0.5m/s is applied throughout the year, whilst for air temperature, values of 2°C, 9°C and 20°C are applied for winter, spring/autumn and summer respectively.

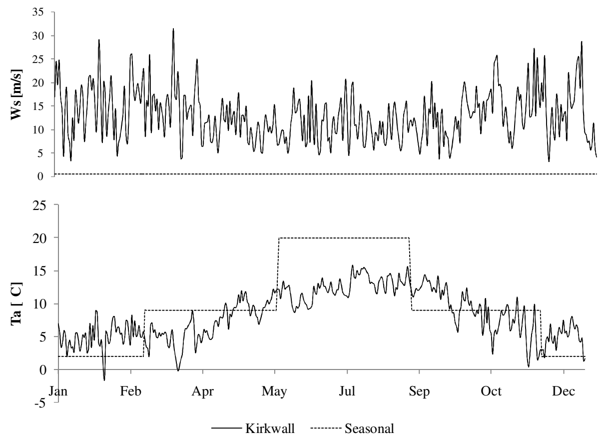

Figure 3: Comparison between average daily weather parameters and static seasonal values used for seasonal rating for (a) wind speed and (b) air temperature

As can be seen, the temperature is often above that assumed in the standard, which highlights the potential for a DLR implementation to reduce operational risk. However, it is the case that for most of the year air temperature is below and wind speed is significantly above the seasonal value. The rating at any particular time is dependent on both of these weather parameters. This means that for a significant period of time, circuits could have a dynamic line rating higher than the presently applied seasonal rating.

There is the possibility that during the year studied the DLR value could be below the seasonal rating value. It is conceivable that weather events and local environmental factors could cause this. The probability of this occurring is low; but, the identification of such events through the application of DLR and the corresponding management of NNFG output will provide additional network safety.

Curtailment analysis was carried out using GenCAT, the Generation Curtailment Analysis Tool developed by SGS to assess NNFG unit connections. The impact of weather on zone export capacity was estimated; circuits with sections of underground or subsea cables were given fixed ratings. The rating of a circuit consisting only of overhead lines was calculated using the method outlined in Equation (1) and the weather data described previously. At each time step, the export capacity of each zone was calculated as the minimum value between the minimum calculated overhead line real time rating and the minimum rating of an underground/ subsea cable present in the same group of circuits at the zone boundary. Curtailment analysis without considering the influence of weather conditions on zone export capacity was carried out to provide a benchmark. Curtailment analysis was then carried out with the effect of the weather on the export capacity included.

Studies showed that the implementation of DLR on the network could reduce the cumulative curtailment for NNFG units by 48% on average, with differences depending on the connection location of the NNFG unit. NNFG connected behind the DLR device benefit the most, with reduction in curtailment in the region between 47% and 81%. NNFG units external to the zone of DLR location were found in some cases to suffer an increase in curtailment. This is due to the increased export of generators with higher priority resulting in greater core zone constraints for lower priority NNFG units. This is a significant learning outcome from this project, demonstrating some potential technical and commercial impacts of Smart grid technology adoption. To overcome this and to maintain fair access according to the Last In First Out principle, modifications to the operation of the SGi ANM scheme will be implemented. This is possible due to the modular and flexible nature of the ANM scheme, which is a key design featuret.

A second analysis was carried out, increasing the NNFG capacity in the zone of DLR location (assuming new NNFG unit capacity to be wind generation) in steps of 1 MW while keeping the existing FG, NFG and NNFG at their current level. This was continued until curtailment with DLR installed exceeded 10% of annual unconstrained energy production.

The results of this second analysis are reported in Table 1 showing that it is possible to connect an additional 4 MW of generation whilst maintaining curtailment at 10% of possible energy output. Based on this criteria, 4 MW of additional capacity would experience 9.7% curtailment with DLR and 38.5% without DLR.

Table 1: results of curtailment analysis of additional NNFG capacity with and without DLR

Additional NNFG [MW]	Unconstrained production [MWh]	Curtailment [MWh]	
		No DLR	With DLR
1	4154	1287 / 30.9%	303 / 7.3%
2	8308	2787 / 33.5%	662 / 8%
3	12462	4490 / 36%	1099 / 8.8%
4	16615	6400 / 38.5%	1614 / 9.7%

This demonstrates the potential for the deployment of DLR devices to facilitate further NNFG unit connections to the Orkney network. However, it should be noted that the results presented are based on a single annual period of data and would be subject to change throughout the lifetime of the wind farms.

CONCLUSION

This paper described the project undertaken by SHEPD and SGS to implement a DLR device as part of the ANM scheme deployed on the Orkney isles. The paper presented an introduction to DLR and to the existing ANM scheme including key findings from a feasibility assessment of DLR deployment. It was found that the addition of DLR to the existing ANM scheme had the potential to reduce the average curtailment of NNFG units by 48% and allow the connection of an additional 4 MW of NNFG units. These results are estimates based on a single annual period of data and further analysis and results from field trials are required.

One key finding in this work is the impact of DLR deployment on the technical and commercial performance of Smart Grids. It has been demonstrated that DLR deployment may require modifications to ANM algorithms to ensure operation in accordance with commercial contracts and Principles of Access. This type of flexibility is necessary if ANM schemes are to facilitate the connection and operation of different forms of low carbon technologies.

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