DYNAMIC LINE RATING PROTECTION FOR WIND FARM CONNECTIONS

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ABSTRACT

This paper describes how dynamic line rating is applied for load management and protection of a 132kV double-circuit line between Skegness and Boston (North East of England) thereby enabling a larger penetration of wind generation. The rating of the line is calculated dynamically from local weather measurements to co-ordinate allowed generation automatically. As a back-up system, in case for some reason the wind farm power output is not reduced on command by the control system, a relay is available to initiate tripping of the wind generators. The paper also includes an analysis of the field data gathered from site which is used to verify the accuracy of the relay algorithm.

INTRODUCTION

Wind farms tend to be located at the extremes of the distribution system where overhead lines may not be rated to carry the full output of the wind farm in all circumstances. Often a line has been designed originally to supply a relatively small load, and the installation of new wind generation may cause a large reverse power flow, causing the standard winter and summer line ratings to be exceeded. The worst case in this respect is with maximum wind generation and minimum local load.

Rather than applying fixed summer and winter line ratings, load management based on a dynamically derived line rating can be adopted. E.ON Central Networks have proposed to calculate the rating of the Skegness-Boston line dynamically in their control system (ENMAC) from local weather measurements to co-ordinate allowed generation automatically [2]. This takes into account the cooling effect of the wind. It is expected that such a dynamic line rating enhancement can facilitate connection of around 30% more generation as compared to when fixed winter/summer ratings of 539A / 433A (LYNX conductors ER P27 [3]) are applied.

As a back-up system, in case for some reason the wind farm power output is not reduced on command by the control system, it is proposed that a relay will initiate tripping of the wind generators. AREVA has developed this relay as part of an IFI (Innovation Funding Incentive) R&D project, and has commissioned two prototypes for evaluation on the Skegness 132kV substation site. The proposed solution may potentially be replicated in other situations where the thermal ratings of circuits are constraining connection of generation.

LINE MONITORING APPROACH

The thermal rating, also referred to as ampacity, of an overhead line is the maximum current that a circuit can carry without exceeding its sag temperature or the annealing onset temperature of the conductor, which ever is lower. The sag temperature is that temperature at which the legislated height of the phase conductor above ground is met. The present practice in many utilities is to monitor the power flow in overhead lines without knowledge of the actual conductor temperature or the height of the conductor above ground. There are many variables affecting the conductor temperature, such as wind speed and direction, ambient temperature and solar radiation. As these are difficult to predict, conservative assumptions have been made so far in order to always ensure public safety. The main purpose of real time line monitoring is to achieve a better utilisation of the load current capacity of overhead lines whilst ensuring that the regulatory clearances above ground are always met.

In the project described here it was decided that weather stations will be employed to measure the ambient weather conditions, from which the ampacity can be derived in real time by solving standard equations. Two weather stations are connected at the Skegness line end providing redundancy for the relay, and one at the Boston line end, all three feeding into the load management system. The power donut™ supplied by USi Power was selected to directly monitor the conductor temperature. This will provide an independent direct measurement to be compared with the conductor temperature derived by calculation and weather measurements. For validation purposes, wind direction and solar radiation are also measured. Figure 1 shows a power donut™ connected to an overhead line conductor. It was decided to install four power donuts, two at the Skegness line end on each circuit, one at the Boston line end and one midway, so that the effect of local wind conditions (speed and direction) can be observed.

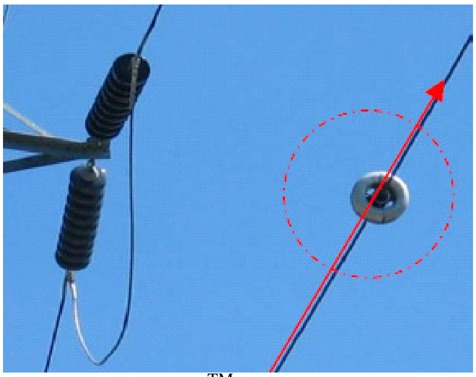

Figure 1: Power Donut™ (supplied by USi Power) measuring the conductor temperature.

AMPACITY CALCULATION AND USAGE

The CIGRE 207 standard equations [1] have been chosen to derive ampacity from weather measurements. When the measured line current reaches a certain percentage of dynamically calculated ampacity, the first action is for the load management system to send a signal to the generators to reduce their power output. Figure 2 shows a simplified diagram of the measurements and outputs of the combined load management and protection system.

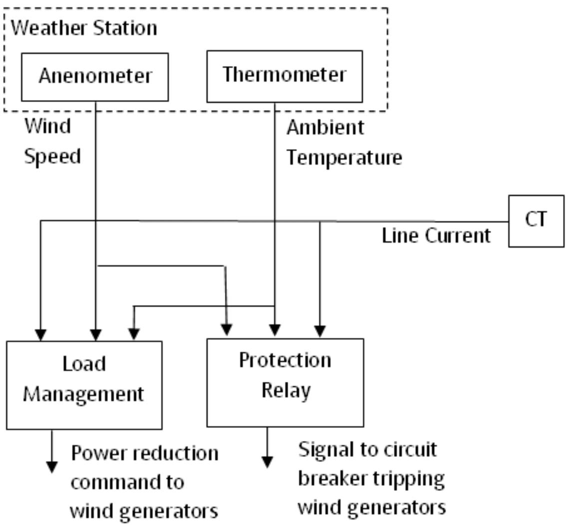

Figure 2: Overview of weather station measurements feeding the load management and protection system.

As a back-up to the load management system, the protection relay will issue a signal to trip a circuit breaker connecting a wind farm to the 132kV Skegness-Boston line on the following condition, subject to a threshold time delay:

$$I_{measured} \geq Trip_{level} * Ampacity \qquad (1)$$

The threshold time delay and $Trip_{level}$ are settable in the relay to provide flexibility for co-ordination with the load management system.

The ampacity is calculated in real time using the CIGRE 207 equations with following assumptions and conditions:

1. Wind direction is difficult to take into account, because (i) the line changes in direction from Skegness to Boston and (ii) wind direction can be quite variable. A simplified approach may be taken, which is to multiply the wind speed measurement with a wind direction factor of sin (20°) = 0.34 to take into account wind direction. This is based on the assumption that if the actual wind is less than 20°, the cooling effect due to wind turbulence is roughly as high as assuming that there is no turbulence but assuming 20° wind direction.
2. Solar radiation is taken into account by taking a conservative approach assuming no clouds, but taking into account day/night and seasons.
3. After multiplication by the direction factor, the derived wind speed is limited with a lower limit of 0.5m/s. The resulting limited wind value is used for calculating the convective cooling.

The dynamically calculated ampacity value is limited with a settable lower limit and upper limit. The upper limit may be derived from constraints elsewhere in the circuit, for example the maximum rating of the cable, joints or other circuit components.

CIGRE EQUATIONS TO CALCULATE AMPACITY

The basic heat balance equation (heat gain = heat loss) is given in the CIGRE standard as follows:

$$P_J + P_M + P_S + P_i = P_C + P_r + P_w \qquad (2)$$

where
P_J = Joule heating (due to current flow)
P_M = magnetic heating
P_S = solar heating
P_i = corona heating
P_c = convective cooling
P_r = radiative cooling
P_w = evaporative cooling

P_i and P_w are commonly neglected, and P_M can be neglected for the Lynx conductor in the Skegness-Boston line because the two layers of aluminium strand spiral in opposite directions around the steel core, and the magnetic fields largely cancel out.

The current heat effects for steel cored conductors are calculated by first considering the heating as a result of an equivalent dc current [1]:

$$P_J = I_{dc}^{\ 2} R_{dc} \left[1 + \alpha \left(T_{av} - 20\right)\right] \qquad (3)$$

where
α = Temperature coefficient of resistance
T_{av} = average conductor temperature, (assumed at the maximum of 50°C for Skegness-Boston line by design)
I_{dc}, R_{dc} = equivalent dc current and dc resistance.

Rearranging Equation (2) and substitution of Equation (3) gives

$$I_{dc} = \sqrt{\frac{P_C + P_r - P_S}{R_{dc}\left[1 + \alpha\left(T_{av} - 20\right)\right]}} \qquad (4)$$

Calculation of P_C, P_r and P_s can be found in [1].

For aluminium-steel conductors with 1 or 2 layers of aluminium wires and a nominal cross section A = 175mm^2 or more, as is the case for the Lynx conductor, the ampacity, I_{ac} is then calculated as follows [1]:

$$I_{ac} = \frac{I_{dc}}{\sqrt{1.0045 + 0.09 \cdot 10^{-6} I_{dc}}} \qquad (5)$$

This empirical formula converting the equivalent DC to an AC current takes into account the skin effect.

AMPACITY AS A FUNCTION OF WIND AND AMBIENT TEMPERATURE

The dynamic ampacity as a function of wind speed is shown in Figure 3 for four different ambient temperatures, which has been calculated using the CIGRE equations with the assumptions described above. For most wind speeds and ambient temperatures, the ampacity is larger than the ER P27 [3] summer/winter ratings, however with higher ambient temperature and lower wind speeds the calculated ampacity is actually lower. The ampacity exhibits very high values, but in practice limitations in the rating due to other components (e.g. cables, joints, switchgear) in the circuit need to be taken into account, which is shown by the grey area. At the time of writing, it is expected that the circuit can take up to 650A as a maximum current. Note that ER P27 recommends the following weather conditions to be applied:

- Wind speed 0.5m/s
- Ambient temperature
  - Winter: 2°C
  - Summer: 20°C
- Solar radiation: nil (on the basis that in the presence of sun there will always be a minimum amount of wind.)

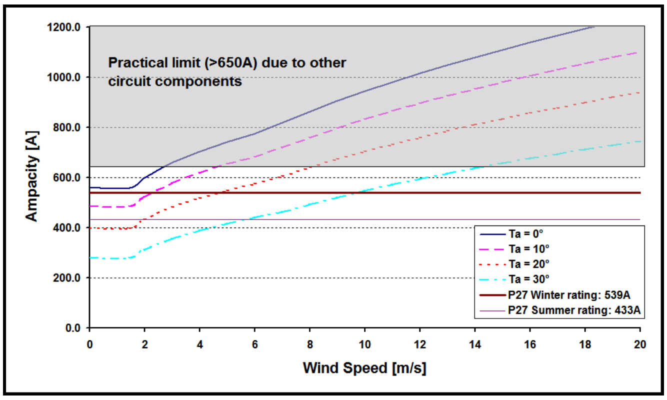

Figure 3: Dynamic ampacity as a function of wind speed for different ambient temperatures (Ta). P27 winter and summer ratings are also included.

The difference between the summer rating of 433A according to ER P27 and the dynamic rating of 397A calculated at 20°C and 0.5m/s is due to the following reasons:

- The dynamic rating is calculated according to CIGRE 207 equations with a conservative maximum solar rating of 890W/m^2, whereas ER P27 applies zero.
- The wind direction has been taken into account in a different way. In ER P27 the Nusselt number is multiplied by a Yaw factor of 0.55 [3], which relates to a wind direction of 17° for wind speeds lower than about 2.7m/s and 26° for higher wind speeds.
- No statistical excursion factor of 3% is applied here, unlike in ER P27 where an excursion factor is chosen for continuous loading conditions with low risk of the likely conductor design temperature being exceeded when the circuit is supplying distribution type load cycles.

PROTECTION RELAY DETAILS

The relay development is based on an existing product. The dynamic line rating protection has been added as an enhancement to the existing functions such as overcurrent and earth fault protection. The current loop interface (0-1mA, 0-10mA, 0-20mA or 4-20mA) is an analogue electrical transmission standard for instruments and transducers, therefore, it is the most suitable form of communications between the weather station and the relay. The relay allows the user to select the type and the current loop input channels to be used for the wind speed, wind direction, solar radiation and the ambient temperature monitoring as required. The results are fed into the algorithm which implements the dynamic line rating calculations.

Three phase currents are measured. The maximum phase current magnitude is selected as the relaying quantity for the alarm and tripping criteria. The current magnitudes, the sensor measurements together with the calculated ampacity are available from the relay as measuring quantities.

A number of alarm and trip elements are available, each consists of its own threshold level and time delay settings. In configuring the relay, apart from setting the alarm/trip thresholds and time delays, it is also necessary to enter a range of conductor data parameters, which are required for the heating and cooling calculations (P_J, P_C, P_r and P_s). To assist the user, the relay stores the relevant parameters of 35 types of British conductors. For other conductor types, settings are available for the user to enter the relevant parameters directly.

COMMISSIONING AND DATA ANALYSIS

Two relays have been commissioned in Skegness in March / April 2008. The relays were installed into wall-mounted cubicles. Each cubicle has also a data logger installed which captures the data from the weather station and outputs from the relay. Data over several months have since been captured. The analysis shows good co-ordination between the data from the relay and the data from the power donut™. As an illustration, the analysis over a 24-hour period on 20/10/2008 is presented in this paper. Figure 4 shows conductor temperature measured by the power donut™ at the Skegness line end as compared to that derived from the weather stations. The derived temperature is an iterative calculation based on the measurements of ambient temperature, average wind speed, wind direction, solar radiation and line current. The results show a very good match, the differences are mostly less than 1°C, with the maximum at 1.4°C. This illustrates the accuracy of the environmental measurements and the underlying correctness of the CIGRE equations.

Figure 5 shows the real-time ampacity calculations captured from the relay as compared to the ampacities calculated off-line, based on the inputs (average wind speed and ambient temperature) applied to the relay. Again the two results closely match one another, the highest difference is 0.81%. The plot also shows the actual ampacity if all the environmental conditions, including wind direction and solar radiation, are taken into consideration. The actual ampacity is always higher than the ampacity calculated from the relay, with a margin of at least 6.2%. This illustrates that the conservative assumptions made (wind direction is 20°, solar radiation is 890W/m^2) are reasonable in providing a good safety margin.

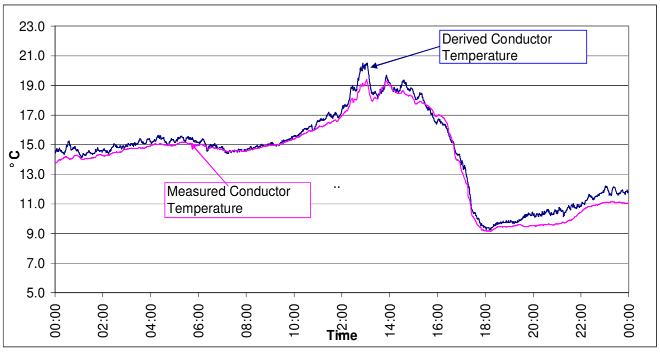

Figure 4: Comparisons between measured and derived conductor temperature on 20/10/2008

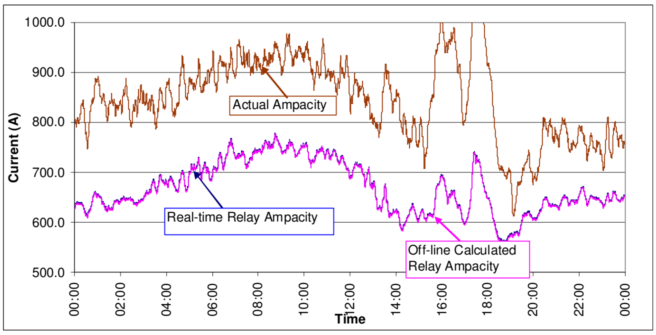

Figure 5: Comparisons between the relay ampacities (both real-time and off-line calculations) and the actual ampacity (by taking all environmental conditions into consideration) on 20/10/2008

CONCLUSIONS

Dynamic line ratings are applied to the 132kV line between Skegness and Boston to enable up to 30% more wind generation to be connected to the grid by taking into account the cooling effect of the wind. A protective relay has been developed which co-ordinates with E.ON Central Networks' control system and provides backup in case the latter fails. Analysis of the data obtained from site shows a close co-ordination between the actual and the theoretical calculations of the conductor temperatures. The conservative assumptions made about wind direction and solar radiation are also shown to provide a good safety margin.

REFERENCES

[1] CIGRE Technical Brochure Ref. 207, August 2002, Thermal Behaviour of Overhead Conductors, Working Group 22.12.

[2] J Douglas, M Orme, April/May 2006, "Time to Connect", *IET Power Engineer*, pages 31– 33.

[3] Electricity Association, Engineering Recommendation P27, 1986, Current Rating Guide for High Voltage Overhead Lines Operating in the UK Distribution System.