Stockholm, 10-13 June 2013

Paper N°0242

## Real-Time thermal rating and active control improved distribution network utilisation

Graeme Lloyd Alstom Grid UK Ltd, UK graeme.lloyd@alstom.com

Li Zou Alstom Grid UK Ltd, UK <u>li.zou@alstom.com</u> Ricardo Gomez Bouchet Alstom Grid UK Ltd, UK ricardo.bouchet@alstom.com

Sharaf Hosseini Alstom Grid UK Ltd, UK sharaf.hosseini@alstom.com Chang An Alstom Grid UK Ltd, UK <u>chang.an@alstom.com</u>

## ABSTRACT

This paper describes work carried out in the UK as part of a collaborative project including Parsons Brinckerhoff, Durham University, Scottish Power Energy Networks (SPEN), ALSTOM Grid and Imass, part-sponsored by the UK Government's Technology Strategy Board (TSB).

The aim of the project is to evaluate the extra thermal capacity available in the critical network components, overhead lines, transformers and cables when the thermal limits are varied many times a day according to the prevailing environmental conditions. This Dynamic Thermal Rating (DTR) technique could enable generators to enhance their energy export or defer network reinforcement.

In 2009 prototype protection relays were installed on SPEN's network to calculate the dynamic thermal rating for an overhead line, transformer and underground cable.

The paper includes an analysis of the field data gathered from site which is used to verify the accuracy and benefits of the real time thermal ratings.

Index Terms- dynamic thermal rating, overhead line, transformer, underground cable, protection, relay design and data analysis.

### 1. INTRODUCTION

Currently the operators of electrical distribution networks face a number of challenges, such as localised load growth, the proliferation of distributed generation and ageing infrastructure. This is drawing attention to techniques which will allow more efficient asset utilisation.

This paper describes work carried out in the UK as part of a collaborative project with partners as described above [1, 2]. The aim of this project is to exploit the extra thermal capacity that is made available with the critical network components (overhead lines, transformers and underground cables) where the thermal limits are varied many times a day according to the prevailing environmental conditions. This technique is known as power system real-time thermal ratings. The electrical and environmental parameters can be measured locally for a component by a protection relay. The protection relays can also calculate the real-time thermal rating of the local component and provide auxiliary tripping

functionality to disconnect DG schemes in case that power outputs are not reduced on command by the substation control system.

The application of continuously changing (rather than seasonal) ratings, which are updated in real-time, could enable DG schemes to enhance their energy export, defer network reinforcement and also allow increased access to distribution networks for weather dependant forms of generation.

In 2009 prototype protection relays were installed in SPEN's network to calculate the dynamic thermal rating for an overhead line, transformer and underground cable. This paper includes an analysis of the field data gathered from site which is used to verify the accuracy and benefits of the real time thermal ratings.

## 2. FIELD TRIAL NETWORK

The section of Scottish Power Energy Networks' distribution network, selected for field trials has a meshed topology with a mixture of overhead line and electric cable infrastructure at 132kV and 33Kv, see Figure 1. Outdoor transformers convert the voltage between these levels. A 60 MW offshore wind farm is connected at the Rhyl Substation and a 90 MW offshore wind farm is teed into the network at St Asaph Substation. With the exception of the 90 MW wind farm connection, each overhead line comprises Lynx 175mm<sup>2</sup> ACSR conductors, with a maximum operating temperature of 50°C and a Autumn static rating of 114.5 MVA (501 A).

In 2008, FMC-Tech<sup>TM</sup> equipment was installed within the field trial network to monitor meteorological conditions local to these components, as well as electrical current flow and conductor temperatures.

# **3. PROTECTION RELAY DYNAMIC RATING FUNCTIONALITY**

The electrical and meteorological parameters are measured locally for a component by a protection relay. The hardware representation and data harvested by each relay in the site trial is shown in Figure 1.

The protection relays calculate, in real-time, the thermal rating of the local components which can be used to reduce the windfarm output or disconnect the windfarms.



**Figure 1:** Hardware representation of prototype installation between Rhyl Substation and St Asaph Substation.

### A. Over-head Lines:

For overhead lines the dynamic ampacity can be calculated taking the weather conditions (wind speed, wind direction, ambient temperature and solar radiation) into consideration. Various algorithms are available to calculate the conductor ampacity such as the CIGRE Standard [3], the IEEE Standard [4], and the IEC Standard [5] which are quite similar. The CIGRE and IEC standard equations are both available to calculate the conductor ampacity and temperature in the trial relays.

### B. Power Transformers:

For power transformers, the dynamic thermal state can be calculated using the hot spot temperature as one of the most critical parameters. The hot spot temperature of the transformer is a function of (1) Ambient temperature (2) Transformer electrical and physical properties (3) Transformer oil cooling method (4) Transformer electrical current.

A high hot spot temperature can cause reduction of the strength of the winding insulation and accelerate the loss of life of the transformer at an exponential rate.

Various computational methods are available to calculate the hot spot temperature of the transformer, such as the IEEE Standard and the IEC Standard. These standards are similar and have algorithms to estimate the real-time state of the transformer, for example, top oil temperature, bottom oil temperature, and aging ratio.

The IEC standard, IEC60354 [6], which is the most conservative method, is used to calculate the transformer's real-time hot spot temperature.

## C. Under-ground cables:

For underground cables the dynamic rating can be calculated considering the soil conditions, consisting of soil temperature and soil thermal resistivity, (soil thermal resistivity is derived from the soil moisture). The soil temperature, has a direct effect on the cable temperature. The soil thermal resistivity affects the heat exchange rate between the cable and the external environment. Various computational methods have been developed to estimate the current rating of an underground cable, such as the IEC Standard and an ENA engineering recommendation (ENA P17 [8]).

The site trial relay is using a linearised model based on ENA P17. This is because other standards have many parameters such as the number of layers, layer thickness and layer physical properties to be input to the cable model which are difficult to obtain for a practical installation.

The algorithm uses the cable static rating and aims to estimate the cable's real-time current rating based on a linearised function of (1) Soil temperature and (2) Soil thermal resistivity.

## 4. PROTECTION RELAY DESIGN

The relay hardware platform and software is based on an existing multi-functional product. The dynamic thermal protection functions for overhead lines, underground cables and power transformers have been added to the existing functions such as overcurrent and earth fault protection. The current loop interface (0-1 mA, 0-10 mA, 0-20 mA or 4-20 mA) is used to integrate the meteorological sensors into the relays. The relay allows the user to select the type and the current loop channels to be used for the sensors, as required. Three-phase currents and three-phase voltages are also measured by the relay and used to calculate real and reactive power flows.

In the relay, six stages of percentage ampacity protection are available for the overhead line, two for the underground cable and two hot spot temperature stages for the power transformer. Each consists of its own threshold level and time delay settings.

# 5. DATA ANALYSIS OF ST-ASAPH AND RHYL SITE TRIAL

Three relays were installed at St Asaph and Rhyl as shown in figure 1 in 2009. Each relay captures the data from the weather sensors and power system and data is logged in a computer via an IEC61850 communication link.

### A. Over-head Lines:

The data analysis is based on using the CIGRE 207 standard equations. Figure 2 shows the direct conductor temperature measured by the FMC Tech sensors at the St Asaph line end compared to ones calculated from the weather measurements and CIGRE equations. The results over a continuous one week period (from 28/09/2010 at 11:58:06

### Paper N°0242

to 05/10/2010 at 10:09:26) show the largest positive and negative differences are  $-5.73^{\circ}$ C and  $+6.28^{\circ}$ C respectively. Removing the largest 10% maximum positive and 10%maximum negative differences shows that for 80% of the results over 7 days the temperature differences are between  $-1.31^{\circ}$ C and  $1.43^{\circ}$ C. This illustrates the good accuracy of the environmental measurements and the underlying correctness of the CIGRE equations. During this week it can be seen that the line load current is lower than 100A, note the CT ratio is 600/1 for the line. It also shows how the conductor temperature is following the ambient temperature and increases as the solar radiation increases. It shows that when the solar radiation is high there is a bigger difference between the conductor and ambient temperature due to the heating affect of the solar radiation.



Figure 2 - Comparison between measured conductor temperature (Tc) via FMC Tech sensor and calculated conductor temperature (Tc) from CIGRE at St Asaph line end, during one week period, Autumn 2010

Figure 3 shows the ampacity calculated by the relay at St Asaph on the 28/09/2010 to 05/10/2010 for variations in one weather measurement at a time for ambient temperature, solar radiation, wind speed, wind speed + wind angle, with the other parameters set at the P27 static rating recommendations. The analysis shows that the weather parameters having a significant impact on the static rating, are in the order from lowest to highest: Solar Radiation (462A - 501A, max 0% compared to P27), Ambient Temperature (430A - 512A, max +2.3%), Wind Speed (450A - 670A, max +33.8%) and Wind Speed + Wind Angle (450A - 770A, max +55.1%).



**Figure 3:** P27 vs Ampacity with each weather parameter at St Asaph on 28/09/2010 to 05/10/2010.



**Figure 4:** Theoretical Uprated Power on 28/09/2010 to 05/10/2010 at Rhyl.

Figure 4 shows the theoretical up-rated power based on the data gathered from one weather station located at the Rhyl line end during the autumn period from 28/09 to 05/10/2010. The theoretical power takes into account all weather parameters as varying quantities. It clearly illustrates the potential line up-rating using dynamic rating. The theoretical up-rated power ratings are continuously calculated at twenty seconds intervals during the 7-day period, and they are statistically measured at every 10% increment of the power rating. Considering all of the weather parameters at Rhyl, the theoretical up-rated power results in an increased line rating of at least 20% for 78% of the analysed time and 40% for 22% of the time comparing to the static P27 spring/autumn rating. The average ampacity ratings of the analysed 7-day period, based on twenty seconds calculations, is 653A, which is equal to an increase in the rating of 30% compared to the P27 spring/autumn rating of 501A. On the other side, for 1.45% of the analysed period the rating is lower than the P27 rating, which is illustrated in the '-10%~0%' band in Figure 4. This is clearly specified in P27 as the 'Percentage Excursion Time', which is defined as 'The percentage of time in any particular season (with an assumed mix of ambient conditions) that a continuously loaded conductor may exceed the line design maximum temperature' and is recognized as a significant factor in the application of line rating. Thus, dynamic rating is not only able to increase the line's thermal rating but is also able to detect the over rating of static ratings in some extreme weather conditions. This hazard will have a more significant impact in future networks as more and more renewable energy is brought online, and so the transmission lines become more fully utilized, potentially exceeding the design conductor temperature if the static rating is used to rate the overhead lines.

### B. Power Transformers:

Figure 5 shows the maximum phase current from the three phases and ambient temperature directly measured by the relay for the transformer T2 during a 7-day period. The trend of the hot spot, bottom and top oil temperatures follows the ambient temperature trend. The transformer rated life is based on a hot spot temperature of 98°C. The

Paper N°0242

hot spot temperature varies between a minimum of  $21.6^{\circ}$ C and a maximum of  $52.5^{\circ}$ C. It shows the ampacity calculated from the rated hot spot temperature, varies between 1596A and 1743A, average is 1667A (+5.9% above 1574.5A rated current).



Figure 5 - Power Transformer Temperatures vs Ampacity and Rated Current at Rhyl T2 on 28/09/2010 to 04/10/2010

#### C. Under-ground Cables:

Figure 6 shows the maximum phase current from the 3 phases, soil moisture and soil temperature directly measured by the relay for the cable. The soil temperature varies between  $13.2^{\circ}$ C and  $14.5^{\circ}$ C.

It also shows the ampacity, varies between 1704A and 1920A, average is 1732A (+10.0% above 1574.5A rated current).



Figure 6 - Underground cable, Dynamic Rating versus Static Rating on 28/09/2010 to 04/10/2010

Figure 7 shows how a large soil moisture rise increases the ampacity in more detail on 03/10/10. The soil moisture starts picking up at 7:35 BST, reaching the sensor's limit of 35.7% at 12:30 which lasts for 4 hours until 16:30 and then starts decreasing. This sharp rise in soil moisture measurement is backed up by rainfall data from the UK Met office for a weather station in Rhyl which shows a large accumulation of rainfall to 20.8mm from GMT 5:00 to 12:00 on 3/10/2010 (BST6:00 to 13:00).



**Figure 7** - Underground cable, Dynamic Rating vs Static Rating on 03/10/2010.

## 6. CONCLUSION

Prototype protection relays were installed in SPEN's network in 2009 to gather electrical and meteorological data locally for an overhead line, transformer and underground cable.

Analysis of the data from the St Asaph - Rhyl line shows a close co-ordination between the actual and the theoretical calculations of the conductor temperatures on the overhead lines. The analysis also shows that the weather parameters having a significant impact on the line rating are in the order from lowest to highest - solar radiation, ambient temperature, wind-speed and wind-speed + wind angle. Variation of the weather parameters along the line is unavoidable and this needs to be considered for each application.

The analysis at Rhyl also shows an increased line rating of at least 20% for 78% of the analysed time and 40% for 22% of the time compared to the static P27 spring/autumn rating of 501A. The average ampacity rating over a 7-day period is 653A = 30% increase in rating compared to the static P27 rating.

The ampacity calculated for the transformer and cable is less variable than for the overhead line due to a lower cooling effect under constrained weather conditions. However, the dynamic rating for the transformer and the cable still can be beneficial to the network operator as both can be up-rated by 5%-10% on average if the weather conditions are favourable.

In future networks with renewable energy, the transmission system will become more fully utilized exceeding the component static ratings more often. The use of dynamic thermal ratings could help to overcome these problems.

### 7. ACKNOWLEDGEMENTS

The authors wish to thank all the consortium members that have contributed to this project as listed in the Abstract section.

#### REFERENCES

- H. T. Yip, C. An, G. Lloyd , P. C. Taylor, A. Michiorri, S. C. E. Jupe and M. Bartlett "Real-time thermal rating and active control for improved distribution network utilisation", PACWorld, Dublin, 2010
- [2] S. C. E. Jupe, P. C. Taylor and A. Michiorri, "Coordinated output control of multiple distributed generation schemes", IET Proc. Renew. Power Gener., In Press, 2010
- [3] CIGRE 207 Thermal Behavior of Overhead Conductors, August 2002
- [4] IEEE Std 738TM IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors, 2006
- [5] IEC TR 1597 Overhead line conductors calculation methods for stranded bare conductors, 1995
- [6] IEEE Standard C57.91:1995 IEEE Guide for Loading Mineral-Oil-Immersed Transformers
- [7] IEC 60354 Loading Guide for Oil-Immersed Power Transformers, 1991
- [8] IEC 60287 Electric cables calculation of the current rating, 1994
  [9] Energy Networks Association, "Engineering Recommendation P17 Current rating for distribution cables", 2004Units