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Smart Algorithms to Accommodate Distributed Generation in the Grid

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1 INTRODUCTION

The future electricity networks will have to accommodate large scale distributed generation (DG) with renewable energy resources such as windfarms. One of the problems facing the electricity utilities is the thermal ratings of components in the networks. The networks were designed in the past to transport power from centralised power stations to consumers, now they have to accommodate additional in-feeds from distributed generation. The utilities are under pressure to maximise the utilisation of their network to increase power flow.

The overhead line conductors form the backbone of the power transmission and distribution systems. In order to maximise the power transfer capability, it is necessary to fully utilise the thermal ratings of the lines. This cannot be achieved by using the traditional static summer and winter line ratings as defined for example by the UK's Engineering Recommendation P27, which are based on worst case weather conditions. Dynamic line rating (DLR) which takes into account the actual weather and environmental conditions is therefore gaining importance.

This paper provides details of a protection relay that has been developed which is able to compute the dynamic line rating based on real-time weather conditions including ambient temperature, wind speed, wind direction and solar radiation. By comparing the maximum of the three phase line currents with this dynamic line rating, the relay is able to determine whether the rating of the line is about to be exceeded. The paper describes all the innovative features of this relay. It also discusses the different applications of this new technology.

Another particular concern for distribution network operators who must now manage integration of DG into the network is that of reliably detecting the islanding of DG from the main network. The term islanding or loss of mains (LOM) refers to the condition in which a generator is accidentally isolated from the mains supply and continues to feed local demand. This condition is highly undesirable for a number of reasons, including: risk to utility staff, provision of a poor quality supply to demand and the risk of out of synchronism re-closing.

The condition is currently detected using a range of different passive protection elements including: over/under frequency and voltage, rate-of-change-of-frequency and voltage vector shift. Unfortunately, there is a widespread view that these techniques do not offer the levels of sensitivity to near balance conditions and stability during network faults that will enable the reliable integration of distributed generation.

This paper also describes a protection relay incorporating a novel islanding detection method that is based on an accumulated phase angle drift measurement. No additional invasive hardware is required and so the method retains the passive characteristic that is valued by network operators. The method has been tested extensively using a Real Time Digital Simulator (RTDS). The results obtained

indicate that the method possesses good sensitivity whilst at the same time giving highly stable operation for even electrically close three-phase faults.

2 DLR 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.

3 LINE MONITORING METHODS

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, whichever 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.

There are fundamentally two different ways to derive ampacity dynamically. One is by direct measurement using sensors to determine the tension, conductor temperature, or sag. Alternatively, an indirect method can be used, by measuring ambient weather conditions, from which the ampacity can be calculated by solving standard equations in real time as described below.

4 AMPACITY CALCULATIONS AND USAGE

Various computational methods have been developed in the past to calculate the heat transfer and ampacities of the conductors. Engineering Recommendation P27 [1] which is based on Price's experimental work and statistical method [2] has been applied commonly in the UK to calculate fixed line ratings for winter or summer. The two most commonly used international standards are the CIGRE 207 standard [3] and the IEEE standard [4] for the current-temperature relationship of the line.

Both the CIGRE and IEEE standard equations for calculating the line rating in real time have been implemented in a protection relay which is described below.

5 PROTECTION RELAY DETAILS

The relay design is based on an existing multi-function relay product. The dynamic line rating protection has been added as a new function 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.

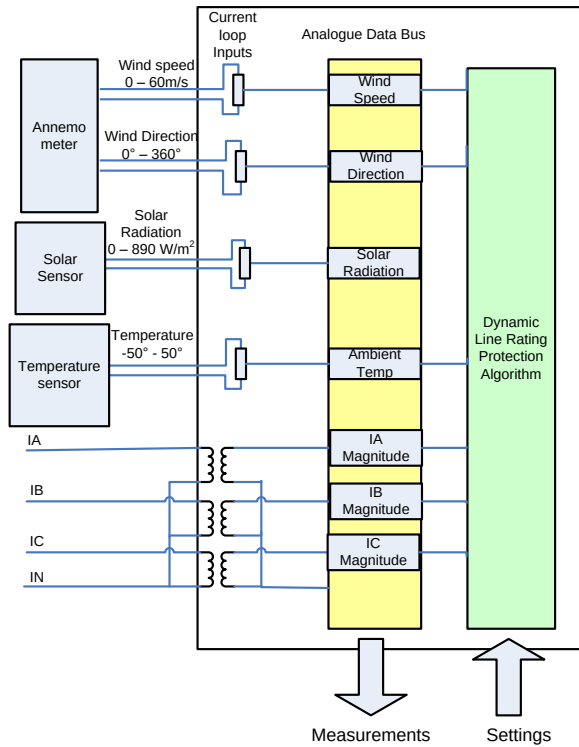


Fig. 1: Inputs to the dynamic line rating protection relay

Variation of the weather parameters along the line is unavoidable and this needs to be considered for each application. The relay includes correction factors which can be applied for each weather parameter to account for variations due to shielding affects and line elevations etc along the length of the line and to provide additional safety margins if required.

6 SKEGNESS-BOSTON DLR SCHEME

One application of DLR is installed by Central Networks at Skegness, North East of England [5]. Due to the proposed additional new wind generation at Skegness and the relatively small local load, there may be an increase of reverse power flow from Skegness to Boston along a 40km, 132kV double-circuit line that could cause the static rating to be exceeded.

Central Networks is applying the dynamic rating algorithms to both their control centre and to the protection relays using the ambient temperature and wind speed measurements. For validation purposes, wind direction and solar radiation are also measured. Two weather stations are connected at Skegness providing redundancy for the relay, and one at Boston, all three feeding into the load management system.

Power donutsTM are installed, one at Skegness, one at Boston and one in the middle of the line to monitor the temperature variations along the line and validate the DLR algorithms.

For the load management and the protection relay system the ampacity is calculated in real time using the CIGRE 207 equations. 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..

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:

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

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

The following assumptions are used in this DLR application. The wind direction is difficult to take into account, because of the way the line changes in direction, and wind direction can be quite

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. Figure 1 shows the details of the inputs to the relay.

Six DLR stages of protection are available, each consists of its own threshold level and time delay settings. In configuring the relay, apart from setting the DLR 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. To assist the user, the relay stores the relevant parameters of 36 types of British conductors. For other conductor types, settings are available for the user to enter the relevant parameters directly.

variable so a wind direction factor of 20° is used. This is based on the assumption that if the actual wind direction is less than 20° , the cooling effect due to wind turbulence is roughly as high as when there is no turbulence with a 20° wind direction. A fixed value of solar radiation (890W/m^2) is assumed. Also, the derived wind speed is limited with a lower limit of 0.5m/s . The dynamically calculated ampacity value is limited with a settable lower limit and upper limit. The upper limit is derived from constraints elsewhere in the circuit, e.g. maximum rating of cables and joints.

7 COMMISSIONING AND DATA ANALYSIS OF SKEGNESS SITE TRIAL

Two relays were installed into wall-mounted cubicles in Skegness in March / April 2008. 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 has since been captured.

The analysis shows good co-ordination between the data from the relay and the data from the power donutTM. As an illustration, the analysis over a 24-hour period on 24/04/2009 is presented in this paper. Figure 2 shows conductor temperature measured by the power donutTM 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 minimum and maximum differences are -1.24°C and 0.96°C respectively and for 90% of the time the absolute difference is less than 1.00°C . This illustrates the accuracy of the environmental measurements and the underlying correctness of the CIGRE equations.

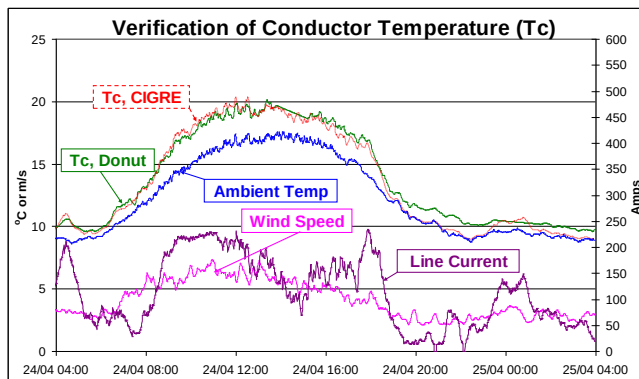


Fig. 2: Comparisons between measured and derived Conductor temperature on 24/04/2009 at Skegness

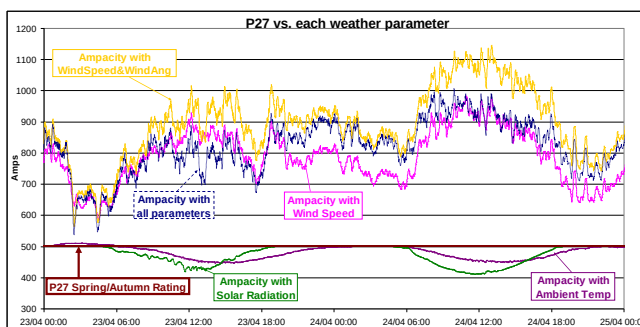


Fig. 3: P27 vs each weather parameters on 20, 21/04/09

Figure 3 shows the ampacity calculated by the relay on the 20 and 21/04/09 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 recommendations. The analysis shows that the weather parameters having a significant impact on the line rating, are in the order from lowest to highest: solar radiation (407-501A, max +0% compared to P27), ambient temperature (438-526A, max +5%), wind speed (501-960A, max +92%) and wind speed + wind angle (491-1161A, max +132%). Note that P27 assumes zero solar radiation which is why the solar radiation ampacity is always below the P27 ampacity. The P27 Spring rating for the Skegness-Boston line is 501A.

8 LOSS OF GRID INTRODUCTION

A specific area of concern for utilities connecting generation at distribution voltages is that distributed generation (DG) may continue to supply local demand when areas of the network are isolated from the main system. This is a particularly undesirable condition and therefore protection is required for its detection and the subsequent tripping of DG.

Although many protection methods have been developed for this task, concern still exists with regard to their performance in terms of the highly interrelated criteria of sensitivity and stability. This paper proposes the use of a method based on accumulated phase angle drift that provides inherently

enhanced stability without unduly sacrificing sensitivity. This method continues with the prevailing practice of using only passive techniques and thus requires no additional invasive hardware.

9 THE LOSS OF GRID PROBLEM

The term loss of grid (or islanding) is used to describe the condition wherein a generator is inadvertently isolated from the grid and continues to supply local demand. Such an undesirable eventuality could potentially occur due to circuit tripping by protection operation or, perhaps more rarely, accidentally due to network reconfiguration.

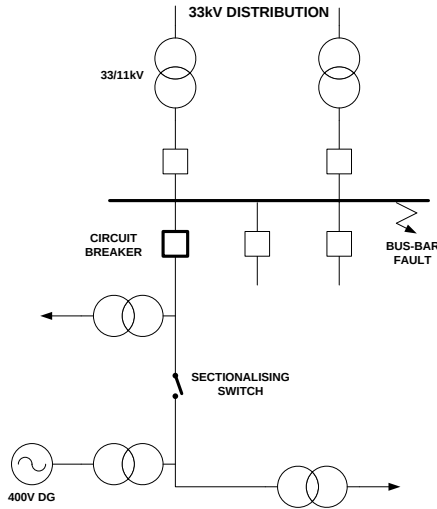


Figure 4 illustrates these two possibilities: both a fault as shown on the substation busbar (circuit breaker opening) and the erroneous operation of the indicated switch would isolate the generator and local demand from the system. An islanded condition is unacceptable for a number of reasons, including: the risk to utility operatives whilst reconfiguring a network that would formerly have not been energized; exposure to the stresses caused by out of synchronism re-closure; loss of the system earth where the system earth is on the star winding of a network transformer, and the provision of a poor quality supply to local demand. In all cases the burden of commercial together with the health and safety responsibilities will rest with the utility. Consequently, their connection arrangements will require that generator operators install suitable protection with which to detect this condition.

Fig. 4: An illustration of the loss of grid problem

10 EXISTING LOSS OF GRID DETECTION METHODS

10.1 Performance Assessment

The performance of loss of grid protection can be assessed in terms of sensitivity and stability. For the former criterion, this relates to the smallest possible mismatch between local generation and demand at the instant of islanding. Some authors use the term non-detection zone to quantify this as a percentage imbalance based on the generator rating. For stability, the criterion can be defined in terms of fault types, duration and retained voltage at the point of measurement [6]. Thus, the objective for designing a loss of grid method is to provide a small non-detection zone whilst ensuring that stability is maintained for as many fault characteristics as is practically possible. As would be expected, the designs and their settings are inevitably a difficult compromise between these two criteria.

10.2 Loss of Grid Detection Methods

A range of methods are currently used in practice to detect loss of grid and many more have been proposed in the research literature. Passive protection elements commonly used for loss of grid detection include: over/under frequency and voltage, rate-of-change-of-frequency and voltage vector shift. Unfortunately, there is a widespread view that these techniques do not offer the levels of sensitivity to near balance conditions and stability during network faults that will enable the reliable integration of distributed generation.

A further method is to use direct inter-trips from possible points of isolation. Some utilities will specify this as part of their connection arrangements should they assess the likelihood of near balance conditions to be unacceptably high. This risk has to be balanced against the risk of failure of the inter-trip communications channels. This method evidently suffers from a high capital cost and a single inter-trip would only provide protection from islanding at a single location. Extending a scheme's scope is costly and will lead to complex signalling and marshalling arrangements.

Active methods including active frequency drift and current injection to date have shown the potential for possessing very small non-detection zones, however, their acceptability from a utility viewpoint remains limited since generator controllers are not subject to the same levels of rigorous

testing as would be expected of protection. There is also some evidence that several of the proposed methods may have a detrimental impact on power quality for surrounding loads. With these in mind, the preferred nature is still, at present, passive for loss of grid protection.

11 ACCUMULATED PHASE ANGLE DRIFT (PAD)

The proposed method is dependent on only passive principles with a tripping threshold being applied to an accumulated phase angle drift calculated from measured frequency values.

When a loss of grid event occurs, the measured frequency will deviate from its nominal rated value and thus a difference will exist with respect to the estimated grid value. This difference in frequency will lead to changes in the phase angle that will increase (drift) with time. The nature of this increase is complex and is dependent upon a range of factors, including: generator inertia, initial power imbalance and the parameters of the method used for frequency estimation.

The detection method is based on a threshold comparison of an accumulated phase angle drift derived from the difference between the current measured local frequency and the estimated grid frequency using historical data. A linear extrapolation technique is used to provide the estimated grid frequency, as illustrated in Figure 5.

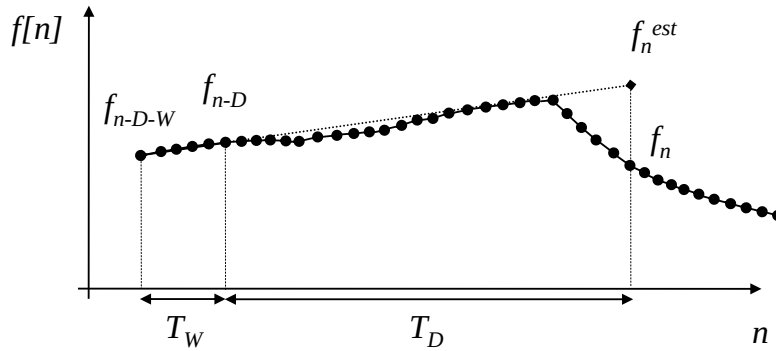


Fig. 5: An illustration of frequency estimation using linear extrapolation based on historical data.

(TD = Historical Time Delay, TW = Estimation Window, f_n = Measured frequency
 f_n^{est} = Estimated frequency)

12 TRANSIENT PERFORMANCE ANALYSIS

The transient performance of the proposed method has been assessed using a Real Time Digital Simulator (RTDS) simulating a combination of idealized disturbances and full islanding simulations using rotating machine models. All tests have been performed using a 50Hz system.

The dynamic response of a synchronous machine to loss of grid connection is primarily determined by the inertia constant of the machine. The controller parameters although important do not significantly impact on the dynamic response in the first few hundred milliseconds of the transient. On the other hand, the behaviour of a Double Fed Induction Generator (DFIG) depends mostly on the control, e.g., a Phase-Locked Loop (PLL) controller. Shortly after disconnection from the grid and the loss of the reference signal the controller becomes unstable. Identification of the islanding event is therefore relatively easy in such cases [7]. For this reason only synchronous machines were tested in the simulations.

12.1 Simulation Model

Two main network case studies have been used. The first scenario tests the relay operation protecting a synchronous generator (SM) connected to a 33kV network. For the second scenario, a synchronous generator connected to an 11kV network is used. These models are simplified versions of the full network supplied by an UK Distribution Network Operator (DNO) with appropriate aggregations made to reduce their complexity where necessary.

Each scenario consists of a grid source, simplified network, point of isolation, local trapped load and generator (including a step-up transformer where appropriate). In the new model, for simplicity the control is using P+V. The important controller for loss of grid is that of the governor and this is

modelled appropriately. For the AVR, basic voltage control is enabled which is satisfactory (provided that the resultant power factor is within normal acceptable bounds).

12.2 RTDS Sensitivity Tests

Loss of mains test cases using a synchronous machine at 0%, 2.5%, 5% and 10% power imbalance (active or reactive) were carried out to check the sensitivity of the protection. Figure 6 shows the response of PAD with a 2.5% real power imbalance between the pre-islanding output and captured demand.

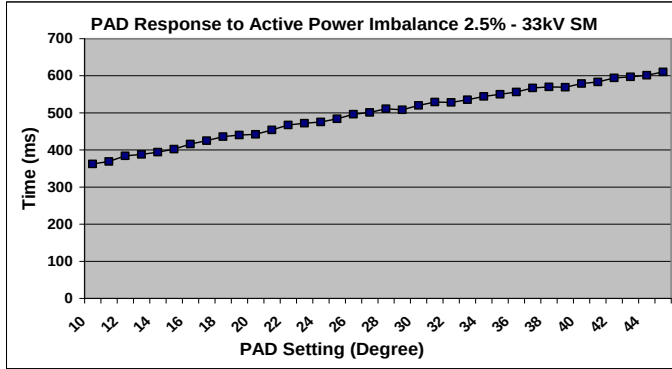


Fig. 6: 33kV SM Sensitivity Active Power Imbalance 2.5%

The algorithm is able to detect the loss of mains in all test cases, except 0% imbalance. The trip time increases linearly with PAD angle setting. To assess the performance it was decided to use 500ms trip time as the criterion to determine the maximum settings for sensitivity. To detect all imbalances a suitable setting of 10° is sufficient. This setting can be further increased if the operating time criterion is relaxed.

12.3 RTDS Stability Tests for Network Fault Scenarios

To test the stability, test cases were created with various fault types causing voltages to be reduced (retained voltage) to 20%, 50% and 80%. For the 33kV network model the protection is stable for all fault types except close-up three-phase faults. The trip time also increases in an approximately linear function with setting values.

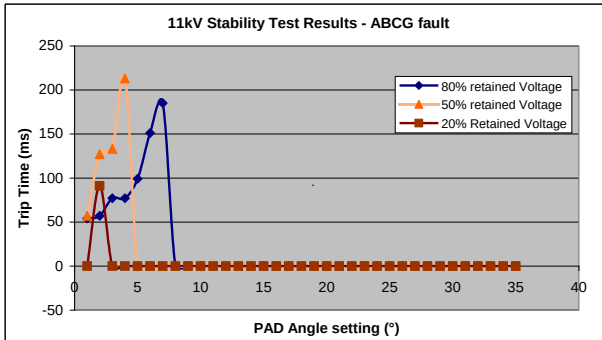


Fig. 7: 11kV SM Stability
(Retained Voltage 80%, Three-phase fault)

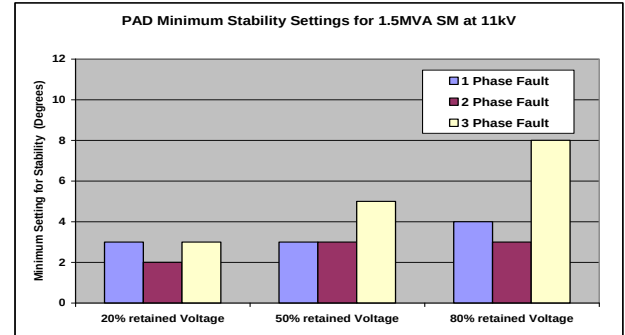


Fig. 8: 11kV SM Minimum Stability Settings for PAD

For the 11kV network model the protection is stable for all fault types if the angle setting is set at or above 10° . Stability is actually improved significantly for close-up faults, due to one of the stability enhancement measures which increase the PAD angle setting dynamically with low retained voltages. The responses to a remote three-phase network fault at 20%, 50% and 80% retained voltages are shown in Figure 7. The minimum PAD setting to achieve stability for all fault types is shown in Figure 8.

12.4 Performance assessment

The results clearly demonstrate the advantages of the proposed method. It has been shown that the relay is sensitive to a very small (2.5% on the generator base) mismatch in power with a setting above 10° . With the same setting the protection is stable for the vast majority of simulated fault scenarios. Therefore, significant stability gains are evident while a high level of sensitivity is preserved.

13 CONCLUSION

Dynamic line ratings have been shown to enable more wind generation to be connected to the grid by taking into account the real time weather parameters. A protective relay has been developed to provide control commands and 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 analysis also shows that the weather parameters having a significant impact on the line are in the order from lowest to highest – solar radiation, ambient temperature, wind speed and wind speed + wind angle. The ampacity analysis also shows that compared to the static ratings dynamic line ratings can enable up to 30% or more wind generation to be connected to the grid by taking into account the weather parameters.

The use of an accumulated phase angle drift has been demonstrated in this paper to be an effective means of detecting the loss of grid condition. It was shown to possess good levels of sensitivity at near balance conditions whilst maintaining a high degree of stability under severe fault disturbances. An open loop trial of the method is planned for the near future to confirm its performance under practical conditions.

The above described protection relay algorithms will help to overcome some of the major problems facing utilities connecting DG into their network, so encouraging higher penetration of DG.

Acknowledgements

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REFERENCES

- [1] Electricity Association, Engineering Recommendation P27, Current Rating Guide for High Voltage Overhead Lines Operating in the UK Distribution System, 1986.
- [2] C.F. Price, R.R. Gibson, “Statistical approach to thermal rating of overhead lines for power transmission and distribution”, IEE Proceedings, Vol. 130, Pt. C, No. 5, September 1983, pp 245-256.
- [3] CIGRE Technical Brochure Ref. 207, Thermal Behaviour of Overhead Conductors, Working Group 22.12, August 2002.
- [4] IEEE Standard for Calculating the Current-Temperature Relationship for Bare Overhead Conductors, IEEE Std 738-1993.
- [5] T. Yip, M. Aten, B. Ferris, G Lloyd, C. An, 8-11 June 2009, "Dynamic line rating protection for wind farm connections", *CIGRE 20th International Conference on Electricity Distribution*, Paper 0733.
- [6] A. Dysko, C. Booth, O. Anaya-Lara, and G.M. Burt, “Reducing unnecessary disconnection of renewable generation from the power system,” IET Journal of Renewable Power Generation, vol. 1, issue 1, pp 41-48, Mar. 2007.
- [7] A. Dysko, G.M. Burt, and R. Bugdal, Annual Report (Novel Protection Methods) Year II, DTI\CDGSEE\TR\2006-007, Centre for Distributed Generation & Sustainable Electrical Energy, 2006. [Available online: www.sedg.ac.uk]