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Islanding Detection Using an Accumulated Phase Angle Drift Measurement

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SUMMARY

Distributed generation is increasingly likely to play a major role in electricity supply systems as recognition is made of its low carbon credentials. However, the integration of these units at distribution voltages is a major challenge for utilities. One particular issue is that generators may, unintentionally, continue to supply local demand when areas of the network are isolated from the main system. Reliably detecting this condition is regarded by many as an ongoing challenge as existing methods are not entirely satisfactory. This paper proposes a novel method based on accumulated phase angle drift that provides inherently enhanced stability without unduly sacrificing sensitivity. It is passive and thus requires no additional invasive hardware. Transient simulations are used to demonstrate its performance.

KEYWORDS

Protection Relay - Loss of Grid - Islanding - Transient Simulation - Distributed Generation

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1. INTRODUCTION

The connection of generation at distribution voltages is seen as one of the most important challenges facing modern electricity supply systems. These units offer the potential to take advantage of local renewable or sustainable energy sources, whilst avoiding the high carbon emissions and losses associated with large fossil fuel thermal stations and long distance transmission respectively. However, distribution networks were originally designed to support unidirectional power flows from high to low voltages meeting the demands of different consumers. Moreover, voltage regulation and operational practices were developed based on the specific assumption that the overwhelming majority of customers simply consume electrical energy and so do not possess their own parallel generating equipment. With ambitious and sometimes binding government connection targets in place [1], this passive nature is almost certainly likely to be challenged. Although the eventual capacity installed is open to debate, there is strong consensus that many issues need to be tackled before distributed generation can play a safe, reliable and profitable role in modern electricity supply systems.

A specific area of concern for utilities is that distributed generation (DG) may continue to supply local demand when areas of the network are isolated from the main system [2]. 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.

This paper firstly reviews the loss of grid problem in section 2 and, importantly, highlights the potential for growing utility concern surrounding the ever greater levels of generation being connected at distribution voltages. Leading on from this, section 3 discusses previously reported protection methods that can be used to detect a loss of grid condition. Comment is made on the effectiveness of both existing passive and several proposed active methods. The use of accumulated phase angle drift is introduced in section 4 and is followed by the reporting of a range of transient simulation tests in section 5. These are used to demonstrate the performance of this novel loss of grid method in terms of sensitivity to near balance conditions and stability during network faults.

2. 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 1 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. It is informative to note that as levels of automated network reconfiguration increase alongside DG connections, a similarly increased likelihood exists for the formation of unplanned islands in the future.

An islanded condition is unacceptable for a number of reasons [3], 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.

However, the comments made above are reflective of current practices with regard to islanded operation and the viability (and indeed usefulness) of this condition has received much attention in the research literature. Many authors have proposed that, under controlled circumstances, islanded operation may be permitted as a means of improving the quality of supply for consumers. Although a thorough discussion of this topic is outside the scope of this paper, it is nonetheless appropriate to highlight the potentially changing role for loss of grid protection. If islanding is permitted, then an important aspect of loss of grid protection will be to detect when an area should be electrically isolated at a specified boundary (e.g. circuit breaker), and then to initiate the changes in control system mode necessary to ensure stable frequency and voltage (e.g. moving from P/pf to V/f control).

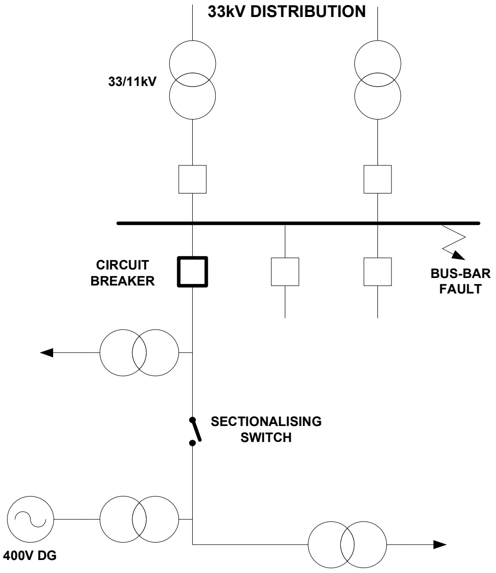


Figure 1: An illustration of the loss of grid problem.

3. EXISTING 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. Details of the assessment criteria used for loss of grid protection performance and a brief discussion of the passive and active classifications are given in the following sections.

3.1 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 [4]. For stability, the criterion can be defined in terms of fault types, duration and retained voltage at the point of measurement [5]. 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.

3.2 Passive Methods

Passive methods of detecting loss of grid rely on direct measurements and some derived quantities. The most basic example being the application of simple under/over frequency and voltage elements set with parameters at the boundary of normal statutory limits. Although these will perform satisfactory in cases where the mismatch between local generation and demand is always known to be large, they suffer from a comparatively large non-detection zone leading to possible delays in tripping.

Alternatively, derived quantities such as the rate-of-change-of-frequency (ROCOF) or voltage vector shift (VVS) can be used. These offer superior sensitivity as their settings allow detection to take place within statutory limits, but their settings must be carefully selected to avoid mal-operation during network faults. The trade-off between the two performance criteria is especially difficult for these methods.

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.

3.3 Active Methods

The basis for many of the proposed active loss of grid methods is the use of a modified generator control scheme that, when islanded, will make the changes in frequency or voltage more easily detectible. A positive feedback loop that inherently destabilizes the output (when islanded) of the generator is commonly added to achieve this and the actual protection is based on simple over/under frequency and voltage elements. Examples of methods include active frequency drift and current injection [6].

Although the results presented to date have shown the potential for possessing very small non-detection zones, 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.

4. 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 [7]. A block diagram for the method is given in Figure 2.

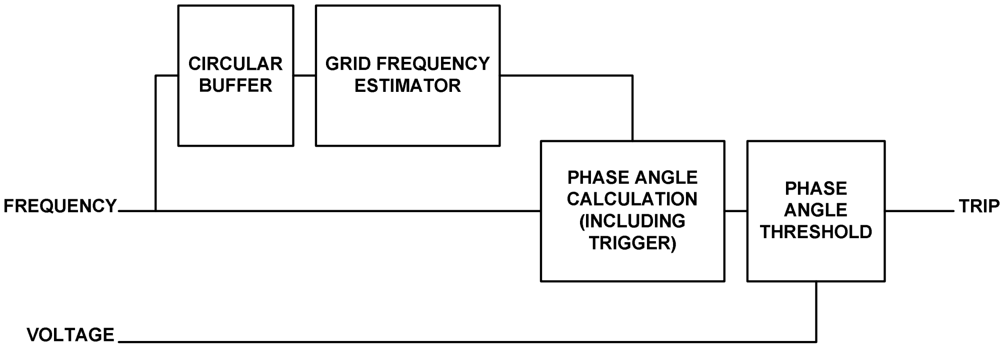


Figure 2: PAD loss of grid protection block diagram.

4.1 Basic Principle

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 3. Equation (1) below forms the basis of the method for deriving the phase angle using both the current measured value from the tracking algorithm and an estimated frequency calculated using linear extrapolation from stored historical frequency values. It is evaluated every half cycle of the fundamental waveform, based on 24 samples per cycle.

$$\alpha_n = \alpha_{n-12} + 2\pi(f_n^{est} - f_n)T_{12samples} \qquad (1)$$

Where:

n	Sample index	α_{n-12}	Previous phase angle
α_n	Updated phase angle	f_n	Measured frequency
f_n^{est}	Estimated frequency	$T_{12samples}$	Time interval between algorithm executions

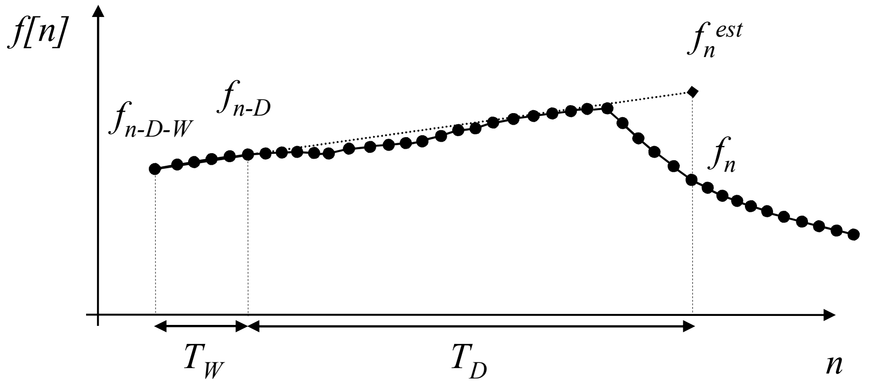
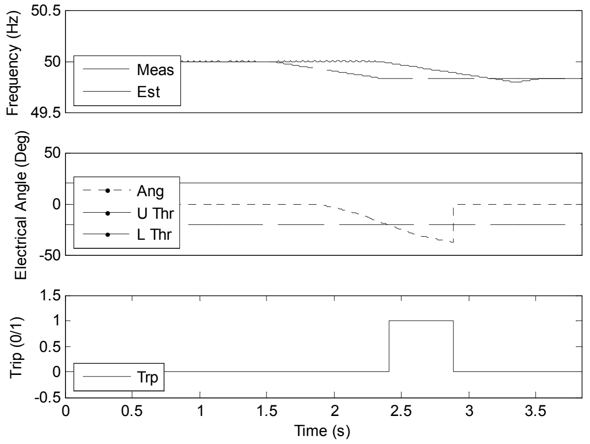


Figure 3: An illustration of frequency estimation using linear extrapolation based on historical data. (T_D = Historical Time Delay, T_W = Estimation Window)

4.2 Sensitivity - Ideal Ramp Frequency Inputs

The response of the method to ideal frequency ramp inputs of -200mHzs^{-1} and -800mHzs^{-1} beginning at 1.5s are given in Figures 4 and 5 respectively. In both examples the estimated frequency can be seen to remain at nominal until the extrapolation method has reached the stored data corresponding to the ramp. Detection of the ramp change can be seen in both examples. In the -200mHzs^{-1} case, reset action in the algorithm occurs after tripping as the rate of increase in angle falls below the trigger setting.



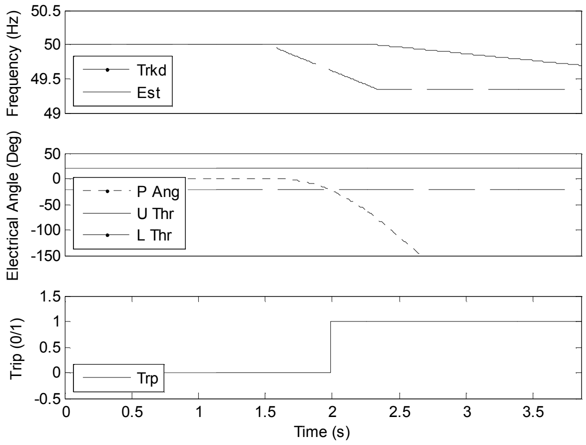


Figure 4: Response to a -200mHzs^{-1} ideal ramp input. (U/L Thr – Upper/Lower angle thresholds)

Figure 5: Response to a -800mHzs^{-1} ideal ramp input. (U/L Thr – Upper/Lower angle thresholds)

4.3 Stability - Voltage Phase Step Changes

The response of the method to an ideal voltage phase step change of -10° is given in Figure 6 and it is clear that it remains practically immune to the effects of the disturbance.

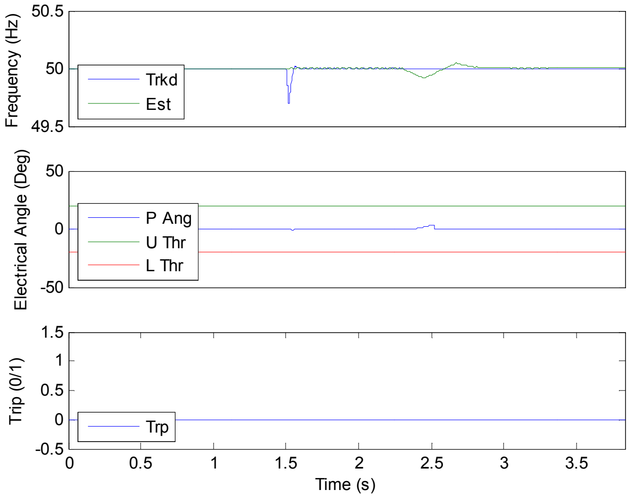


Figure 6: Response to a -10º ideal voltage phase step change.

5. 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.

5.1 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.

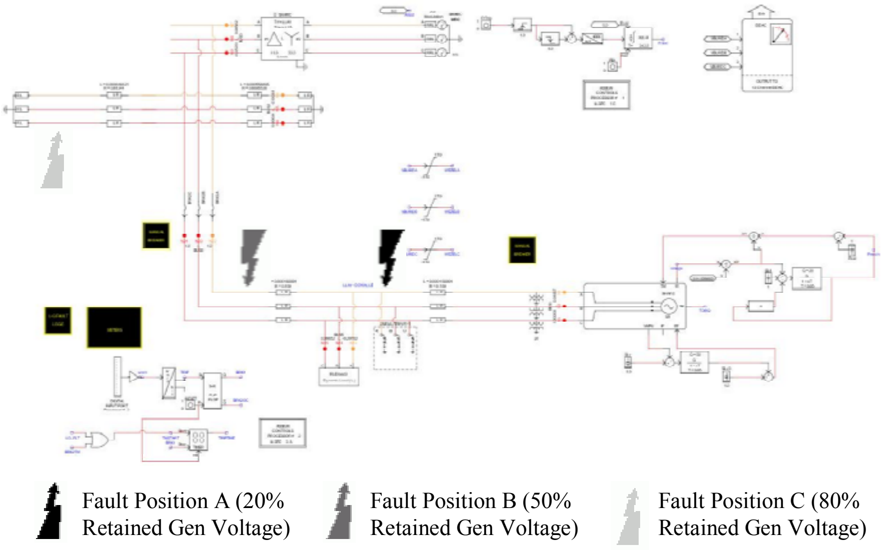


Figure 7: 11kV network model and fault locations.

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).

A circuit diagram for the 11kV network model and fault locations is shown in Figure 7.

5.3 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 8 shows the response of PAD with a 2.5% real power imbalance between the pre-islanding output and captured demand. 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.

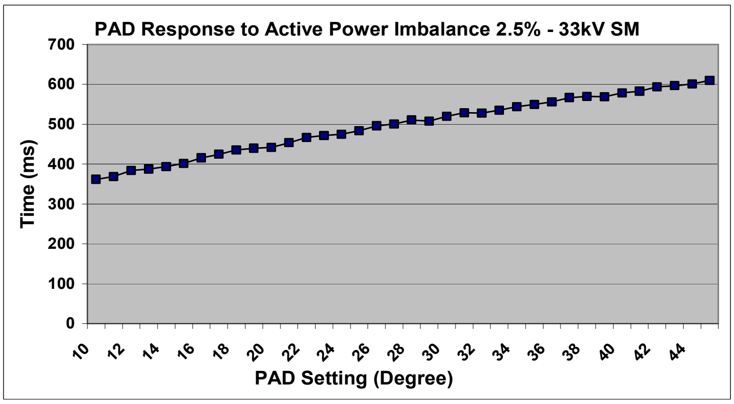


Figure 8:33kV SM Sensitivity Active Power Imbalance 2.5%

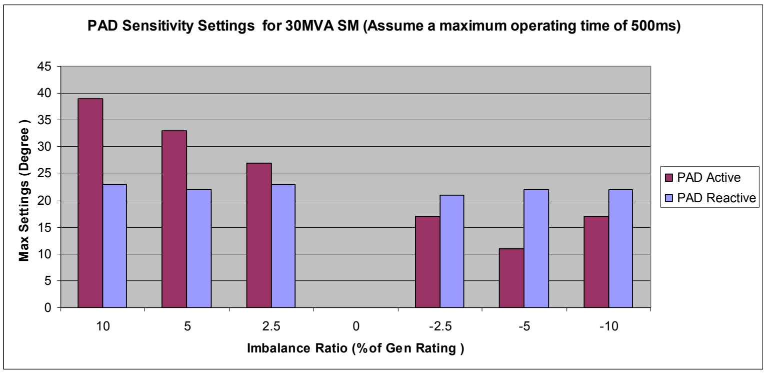


Figure 9: 33kV SM Maximum Sensitivity Setting for PAD

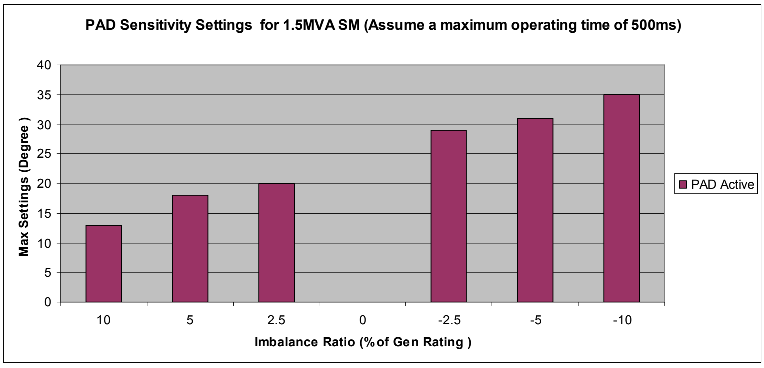


Figure 10: 11kV SM Maximum Sensitivity Setting for PAD

Figures 9 and 10 show the maximum PAD settings to detect various power imbalances. To detect all imbalances a setting of 10° is sufficient. This setting can be further increased if the operating time criterion is relaxed.

5.5 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. The response to a three-phase fault with 20% retained voltage is shown in Figure 11.

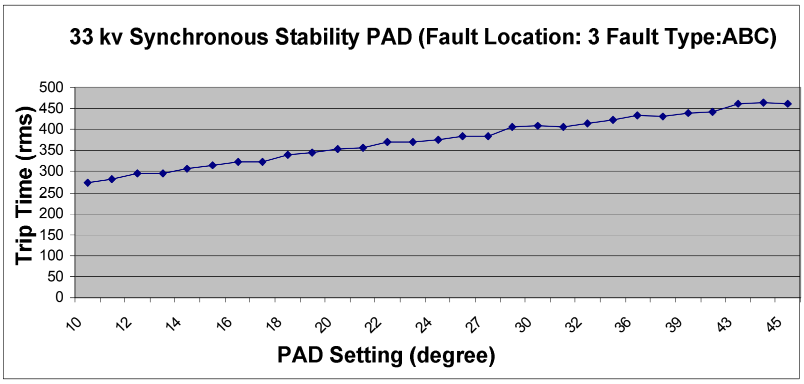


Figure 11: 33kV SM Stability (Retained Voltage 20%, Three-phase fault)

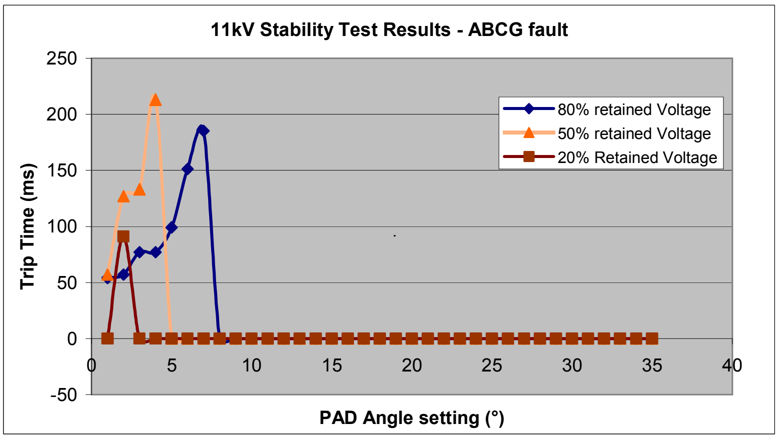


Figure 12: 11kV SM Stability (Retained Voltage 80%, Three-phase fault).

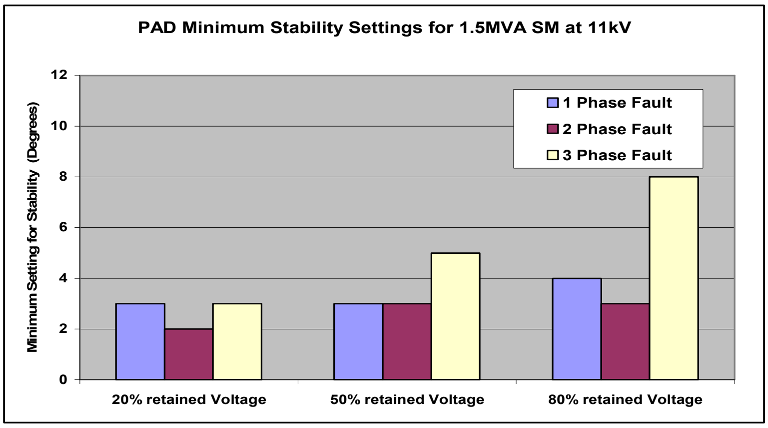


Figure 13: 11kV SM Minimum Stability Settings for PAD

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 12. The minimum PAD setting to achieve stability for all fault types is shown in Figure 13.

5.6 Performance assessment

The results presented 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 active or reactive power with a setting above 10°. With the same setting the protection is stable for the vast majority of simulated fault scenarios with the exclusion of the 33kV system three phase fault with a retained voltage of $20\%V_n$. Therefore, significant stability gains are evident while a high level of sensitivity is preserved.

6. CONCLUSIONS

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.

ACKNOWLEDGMENT

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