PMU-BASED ANGLE CONSTRAINT ACTIVE MANAGEMENT ON 33KV DISTRIBUTION NETWORK

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ABSTRACT

Active Network Management (ANM) is an effective approach to release more distribution network capacity for connecting renewable generation without expensive network reinforcements. A pilot project is being carried out by ScottishPower Energy Networks in collaboration with Psymetrix new ANM approach on the 33kV distribution network on Isle of Anglesey, North Wales. The new approach is known as Angle Constraint Active Management (ACAM), where a renewable generation is constrained based on voltage angle difference signals produced by Phasor Measurement Units, and a set of angle constraints derived through offline network simulations. ACAM requires fewer measuring devices and simpler control logic than existing ANM solutions, and in this case, 19 potential constraints are managed by 4 angle difference measurements.

The paper describes the concept of ACAM, and the progress of the pilot project, including hardware installation and communication set-up. The results of angle constraints threshold studies using the network model for controlling future wind capacity addition at selected locations are presented. Based on the results, the benefits of ACAM and potential challenges of implementing PMU-based applications in distribution systems are outlined.

INTRODUCTION

There are abundant wind resources on Isle of Anglesey, North Wales. In the past few years ScottishPower Energy Networks (SPEN) has received several enquiries for wind farm connections on the isle. The 33kV network on the isle has almost reached its full capacity. Therefore, it is difficult to accept new connection applications if the conventional ‘fit and forget’ planning approach is used for the connection assessment. One possible solution, to allow more generation to be connected quickly to the network without significant reinforcements, is to adopt an Active Network Management (ANM) scheme. ANM involves curtailment of non-firm generation whenever necessary to prevent the network being operated outside its regulatory limits [1].

A Phasor Measurement Unit (PMU) can measure both magnitudes and angles of three-phase voltages and currents with high accuracy and time definition. PMUs have been widely deployed on transmission networks mainly for wide area stability monitoring and protection [2, 3], while its uses in the distribution system sector are still under exploration [4, 5]. A pilot project is in progress with ScottishPower in collaboration with Psymetrix to trial Angle Constraint Active Management (ACAM), a PMU-based ANM approach using technology developed by Psymetrix. Psymetrix has pending patent applications relating to the ACAM technology [6] developed. The pilot is applied on the 33kV Isle of Anglesey distribution network. In ACAM, renewable generation is constrained using voltage angle difference signals derived from PMUs installed at selected locations. The voltage angle differences act as real-time indicators of loading conditions in different parts of the network [7]. The decision of generation curtailment is made if one of the monitored angle differences is greater than a corresponding angle threshold derived through offline network simulations. As multiple voltage and thermal constraints can be bundled into one angle constraint, ACAM needs fewer measuring devices for managing the same number of constraint locations than other existing ANM approaches which require direct measurements of branch currents and bus voltages. This advantage of ACAM reduces the implementation and testing cost and means that it is versatile to use during network maintenance, and can accommodate network reinforcement with only revision of threshold parameters. As angles are a summary measurement of network loading, ACAM can manage constraints at locations where no measuring device is installed.

In this paper, the concept of ACAM and the progress of the pilot project are described, including PMUs installation and communication hardware set-up. The results of angle thresholds derived from offline network studies for controlling future wind capacity addition at selected locations are also presented and discussed.

ANGLE CONSTRAINT ACTIVE NETWORK MANAGEMENT

The concept of ACAM applied to a radial distribution network is illustrated in Figure 1, where the wind farm at bus E has non-firm access and its output is subject to curtailment. The scheme works without other measurements in the network except voltage phasors at bus A and bus E, denoted $V_A\angle\delta_A$ and $V_E\angle\delta_E$, which are measured by PMUs. The angle difference between the two measurement points is calculated ($\delta_E - \delta_A$) and acts as the real-time indicator of the loading condition between A and E; the angle difference $\delta_E - \delta_A$ becomes more positive with increasing generation and/or decreasing load. The angle difference is continuously compared with a predefined angle constraint threshold. If the angle difference exceeds the threshold, the output of the non-firm wind farm is reduced until the angle difference is brought back within the limit. In practice, the control scheme will logically combine a certain continuously available network capacity defined as local active power, but the power injection can be increased beyond this level when the angle constraint shows that the network can accommodate it.

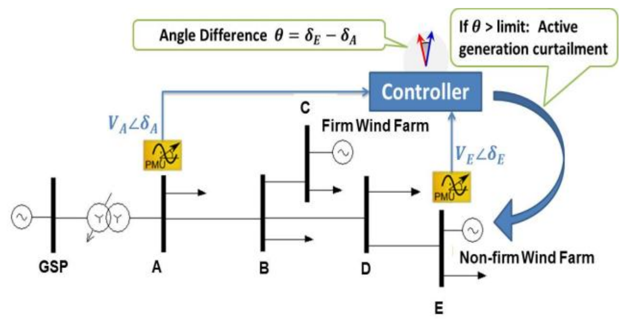

Figure 1: Concept of angle constraint active management

The threshold is derived through a series of offline network simulations. It is crucial that sufficient network loading scenarios are considered in the process, including the limiting scenarios of maximum generation with minimum demand, in order to obtain a threshold value that accurately binds all possible constraints which could be violated when the wind farm output is high.

The general steps towards finding an angle threshold in a network scenario using the example in Figure 1 are described as follows:

Step 1: In a simulated network operating condition, the output of the non-firm wind farm is continuously increased until there is a constraint violation (e.g. thermal, voltage or reversed power flow in the grid transformer). The location where the constraint violation occurs is the *critical constraint location* that limits the wind farm in this particular network operating condition.

Step 2: The size of the angle difference ($\delta_E - \delta_A$) is recorded at the time when the violation occurs. If *n* network operating conditions are considered, then the same process (Step 1+Step 2) is repeated *n* times to find the critical constraint location and corresponding angle difference size in each operating condition considered.

Step 3: The angle threshold is defined as either the lowest or highest value recorded, depending on the convention, among all the network scenarios simulated.

In a larger network with a more meshed topology, it is likely that more than one angle difference measurement and threshold are needed for controlling a wind farm in ACAM by capturing its impact on the loading conditions of different parts of the network.

PHASOR DATA INFRASTRUCTURE

The schematic of the 33kV distribution network on Isle of Anglesey is shown in Figure 2. The meshed network is connected to the 132kV network via grid transformers in Amlwch, Caergeiliog, Caernarfon and Bangor. There are three existing wind farms, with the installed capacity in the range between 5 MW and 20 MW, connected to the network at location A, B and C. These three sites are also regarded as the prospective locations to connect non-firm wind generation in future.

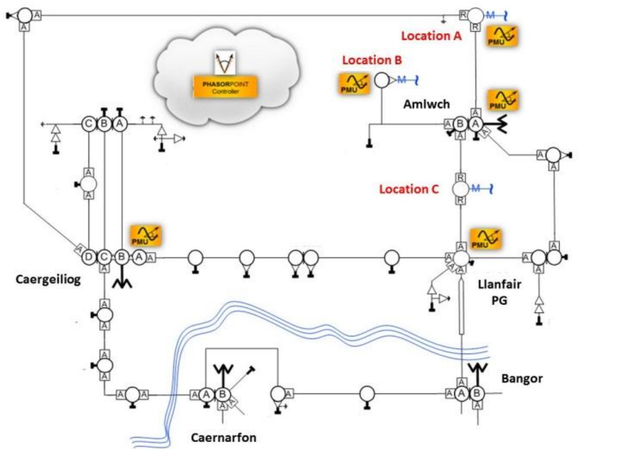

Figure 2: Isle of Anglesey 33 kV distribution network

Five PMUs have been installed at the locations shown in the diagram. The locations were decided based on the following considerations:

- Where new non-firm wind generation is expected;
- where the network is electrically strong, i.e. close to 132/33kV substations;
- where measurement CTs and VTs are available.

There is no internet access at some of the locations where PMUs are installed. Therefore, machine-to-machine (M2M) mobile communication technology is adopted to transmit phasor data to the Psymetrix PhasorPoint platform for phasor-based network wide area monitoring. The phasor data communication diagram is depicted in Figure 3. At each substation, phasor measurements produced by the PMU are passed to a substation phasor data concentrator (PDC), which manages the communications links, and forwards and buffers the data. The data is acquired and stored continuously at 10Hz to analyse both steady-state and dynamic or fault conditions.

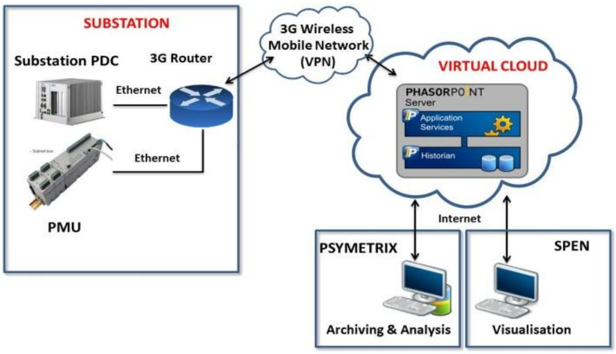

Figure 3: Phasor data communication based on machine-to-machine technology

The phasor data streams are then transferred into PhasorPoint in a virtual cloud via a 3G mobile network. Authorised Psymetrix and SPEN staff can access PhasorPoint from local machines for phasor data visualisation and analysis. A continuous record of data is retained by Psymetrix for analysis. The equipment in the substations is assigned with fixed IP addresses, which enables the configuration of input and output phasor data streams to be done remotely.

The M2M communication arrangement avoids the need to upgrade SPEN's own communications network in the pilot stage. As a result it accelerates the installation progress and reduces the cost. The reliability of phasor data transfer via the 3G network depends on the strength of 3G signals covering the isle, which will be evaluated.

CALCULATION OF ANGLE THRESHOLDS

Angle thresholds were derived for controlling non-firm wind farms at the three locations (A, B and C) indicated in Figure 2. In total more than 1000 network scenarios were simulated in the process to exercise all of the potential network constraints in various operating scenarios. N-1 and N-2 contingencies were considered, accommodating conditions where, for example, the system is under maintenance and experiences a fault. Constraints such as voltage, thermal and reverse power flow in the 132/33kV transformers were considered to derive the angle threshold values in each network scenario. The network simulations were automated using Python with the power systems software, IPSA.

<u>Simulation Results</u>

The wind farm outputs recorded when a constraint violation happens in all network scenarios simulated are summarised in Figure 4. The results show that in the worst scenarios the outputs are all equal to zero at all three locations, which implies that no additional wind farm can be connected if the conventional 'fit and forget' approach is adopted. Moreover, it seems that under an ANM scheme the network can accommodate much more generation at location C than A and B. Note that the result should not be interpreted as the additional generation capacity that is economically viable under an ACAM scheme, as the scenarios are defined to identify the constraint boundaries, and do not represent all of the normal operating scenarios or the probability of occurrence. A future goal of the pilot project is to investigate the energy that could be delivered for each additional 1MW installed capacity, evaluated over a year of continuous recording.

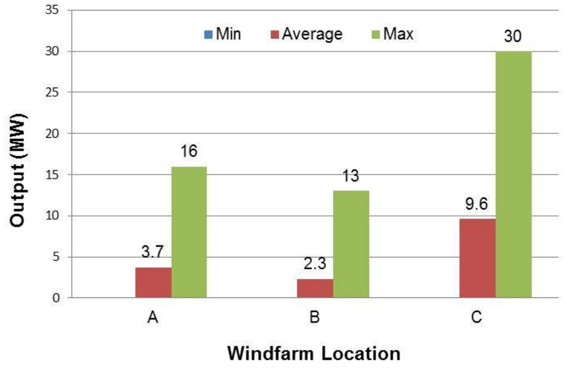

Figure 4: Summary of windfarm outputs recorded that trigger a constraint violation in different network scenarios

The number of constraint locations found that could limit the wind farm output at each of the locations is depicted in Figure 5. It appears that voltage rise in the distribution system would be the more dominant problem than thermal overload.

For an ANM scheme to work reliably all the constraint locations need to be managed. The benefits of adopting ACAM compared to other ANM methods are also clearly presented in Figure 5. If other ANM methods are applied, at least 19 voltage and current measurements will be needed to monitor directly for controlling the wind farm at each site. However, in ACAM the voltage and thermal constraints can be bundled into only four angle constraints, hence greatly reducing the number of measuring devices and communication channels required with lower installation cost and simpler control logic.

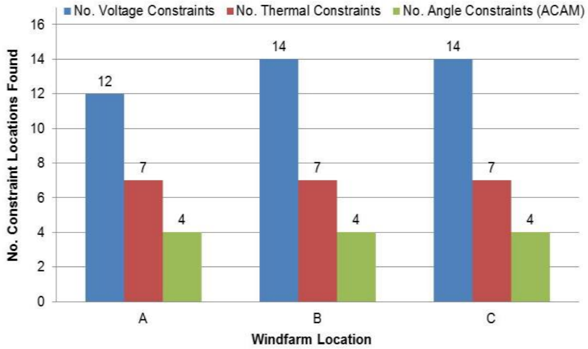

Figure 5: Number of constraint locations found caused by non-firm wind farm at different locations

The angle thresholds derived for managing non-firm wind generation at the three locations in normal, N-1 and N-2 contingency scenarios are indicated in Table 1. As expected, the threshold values for the same angle difference measurement tend to decrease with more severe network outages. The sign of the thresholds depends on the convention used to calculate an angle difference, i.e. whether it is voltage angle A minus voltage angle B, or vice versa.

Angle Difference Measurement	Angle Difference Threhold(deg)		
	Normal	N-1	N-2
Angle Difference A1		≥ -3.3	≥ -3.2
Angle Difference A2	≥ -1.3	≥ -0.7	≥ -0.4
Angle Difference A3		≤ 7.1	≤ 6.9
Angle Difference A4		≥ -2.6	≥ -2

(a) Windfarm Location A

Angle Difference Measurement	Angle Difference Threhold(deg)		
	Normal	N-1	N-2
Angle Difference B1		≤ 5.1	≤ 4
Angle Difference B2	≥ -1.2	≥ -1.1	≥ -1.1
Angle Difference B3		≤ 7.5	≤ 7
Angle Difference B4			≥ -1.6

(b) Windfarm Location B

Angle Difference Measurement	Angle Difference Threhold(deg)		
	Normal	N-1	N-2
Angle Difference C1		≤ 3	≤ 2.8
Angle Difference C2	≤ 5.3	≤ 3.6	≤ 0.1
Angle Difference C3		≤ 5.4	≤ 4.6
Angle Difference C4			≤ 7

(c) Windfarm Location C

Table 1: Angle threholds derived for managing windarms at locations A, B and C

The operation of ACAM can be further divided into multiple layers classified by the number of circuit outages. For instance, in the normal network operation condition the threshold values derived from N-1 scenarios are used to control the non-firm generation. Similarly, when there is an outage, the threshold values are updated to those obtained from the N-2 scenarios. Such multi-layer operation in ACAM should further increase the maximum wind farm penetration compared with continuous application of the more conservative N-2 thresholds.

It can be noted in the table that there are thresholds with small values, especially those below 1 degree. The thresholds apply in one direction, for example, where $\delta_1 - \delta_2 \leq 1°$ all negative angle difference values are unconstrained. A margin should be applied to deal with measurement accuracy. At present PMUs complying with the IEEE C37.118 standard [8] should produce synchrophasor measurements with equal or less than 1% of Total Vector Error (TVE). The project includes PMU testing that has shown that in near-nominal voltage conditions in which the ACAM scheme will operate, much better PMU accuracy is obtained. However, one must also consider other errors such as those introduced in the VTs. The project will involve validating the derived thresholds against the data obtained from real-time monitoring, and more definite conclusions can be made regarding the minimum acceptable threshold values and potentially the PMU specification required for monitoring and control applications in distribution systems. Nevertheless, the analysis results show that the small thresholds would only become the binding limits in very few N-1 and N-2 network scenarios. Therefore one potential solution is to add an additional operation layer in ACAM. Once one of these scenarios is detected in a real operation condition, the non-firm wind generation will be curtailed either below a more conservative angle constraint or below a predefined MW level that is enough to ensure secure network operation.

CONCLUSIONS

The paper describes a new Active Network Management (ANM) approach to constrain wind generation based on voltage angle difference measurements produced by phasor measurement units (PMUs). The Angle Constraint Active Management (ACAM) is currently implemented at pilot stage on the 33kV distribution network on Isle of Anglesey. Five PMUs have been installed at selected network locations. The phasor data is transferred to Psymetrix's PhasorPoint in the virtual cloud via a 3G mobile network. The phasor data is visualised through PhasorPoint and downloaded to perform analysis of the performance and potential economic benefit of the scheme over an annual weather and loading cycle. Offline network simulations were conducted to obtain the angle difference thresholds that will be used to control future non-firm generation in ACAM. The benefits of adopting ACAM compared to other ANM solutions can be assessed, including the requirement of fewer measuring devices and communication channels, simpler control logic, lower installation cost with adaptability to outages.

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