SYNCHROPHASOR APPLICATIONS FOR DISTRIBUTED ENERGY RESOURCE CONNECTION AND EFFICIENT GRID OPERATION

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ABSTRACT

Phasor measurement units (PMUs) can produce synchronised measurements with high accuracy and granularity. Currently the technology is widely deployed on transmission systems for Wide Area Monitoring, but it has generally not been exploited at distribution level. This paper introduces some applications that utilise synchrophasor measurements to actively manage distribution networks and release more capacity for connecting distributed energy resources (DER). These applications are considered as part of future Distributed Energy Resources Management System, which offers a range of functions for improving the operation security and reliability of modern distribution networks with high DER penetration. The paper also outlines how each application can be used in a distributed control structure - an efficient control framework for managing smart grids.

INTRODUCTION

It is well known that the emerging smart grids involves much better utilisation of existing network assets in order to achieve high levels of penetration of distributed energy resources (DER), including distributed generation and energy storage. The introduction of cost-effective Phasor Measurement Units (PMUs) and Distributed Energy Resources Management System (DERMS) in distribution systems can provide greatly improved visibility of the true behaviour of the systems, which is a necessity for more flexible and efficient use of distribution networks [1]. Here, DERMS refers to a collection of different modules of adaptive methodologies and control applications for DER management. Each module can either be a stand-alone application or integrated into an existing distribution management system. This flexibility of DERMS is essential to provide an effective solution tailored for distribution networks with different topologies and DER composition and allocation.

Further, the centralised control approach based on SCADA would become inefficient for handling all the control actions in a smart distribution grid. Instead, distributed control, e.g. Multi-Agent System, is promising control architecture for smart grids [2]. In general, a distributed control hierarchy consists of controllers at different levels, as depicted in Figure 1. The controllers at higher levels are responsible for the integrity of larger part of the network therefore require higher degree of visibility to the network; they are also capable of communicating and issuing control instructions to the controllers underneath. The advantages of such control structure including: (1) better utilisation of communication bandwidth; (2) breakdown of a complex control task into more manageable and maintainable smaller pieces; (3) a more flexible and fault-tolerant management system [3].

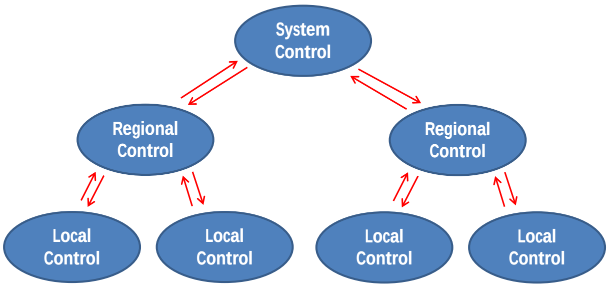

Figure 1: Distributed control and management hierarchy

This paper introduces a range of applications, which are made possible with the visibility provided by PMUs, to actively manage distribution networks as a result to release more capacity for DER connection. The paper will also describe where these applications can be fitted in a distributed control hierarchy.

THREE-PHASE STATE ESTIMATION

To actively manage a distribution network and embedded DER, it is necessary to understand the DER behaviour and impact on the network operation. Such knowledge can be gained by implementing wide area monitoring with state estimation. For imbalanced medium-voltage (or primary) distribution systems, three-phase state estimation must be adopted to produce states of each phase that are accurate to be used for other control applications.

Installing PMUs on distribution networks would improve state estimation in many aspects. Synchrophasor measurements are highly accurate and can be used to improve the three-phase network modelling, which along with angle measurements as inputs would considerably improve the state estimation accuracy. Incorporating angle measurements into state estimation also promote the convergence speed and ability to detect network parameter errors [4, 5]. Moreover, PMUs can be the cost-effective alternatives to RTUs to increase the measurement redundancy. It is also known that to achieve the same degree of network observability, considerably fewer PMUs than RTUs will be required [6].

In a distributed control hierarchy, state estimation can work with controllers at different levels, depending on the type of control applications. However, controllers at lower levels would only require state information within the part of the network concerned. In fact, studies have shown that running multiple state estimations on smaller areas in parallel can significantly improve the convergence speed and robustness than a centralised state estimation [7]. To achieve this, PMUs are installed at the boundaries between the divided networks to synchronise the results for complete network observability.

NETWORK TOPOLOGY MANAGEMENT

A distribution network is normally operated in a radial topology, as depicted in Figure 2. However, it is also possible to change the topology into a meshed network if the switch is closed. In this way the network spare capacity can be utilised for extra demand or distributed generation, and could prevent network overload in the high demand/low generation or high generation/low demand conditions. This strategy has been considered by several UK distribution network operators, and trials have been proposed [8].

However, one caveat is that, the loop flow after the reconfiguration could cause a limit violation (thermal, voltage, reversed power flow etc.) within the looped network. For a successful network reconfiguration, a method is required to predict the network condition after the topology changes. Using the same example shown in Figure 2, the method proposed here involves in installing a PMU at each Grid Supply Point (GSP). The size of the voltage angle difference between the measurement points prior to the topological change is related to the size and direction of the loop flow introduced after network reconfiguration, as a result of conditions in the external network. An angular difference threshold can be derived from power flow studies, and used to check the feasibility of closing the switch. Moreover, with additional information including network impedance, it is also possible to predict the loop flow in real-time, making the method more adaptive.

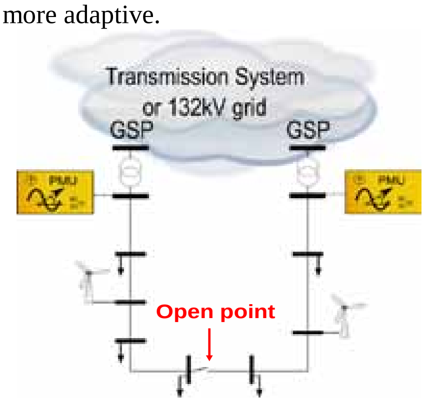

Figure 2: Distribution network example for network topology management

Another caveat is concerned with the fault level exceeding the operating limits of the protection devices after the topology change, especially if the penetration of distributed generation is high. It is possible to calculate equivalent short circuit impedance and fault level in real-time based on the change in current and voltage phasors measured by PMUs triggered by a random disturbance [9], and then regulate the generation output if the calculated fault level exceeds the limit.

A conventional network topology management approach may require a high degree of visibility of the network. If this is the case then the function would be assigned to a controller at high level in a distributed control hierarchy and require a large number of real-time measurements. However, the application proposed only requires the observation of angle difference between two measure points; therefore the task may be assigned to a local controller.

ANGLE CONSTRAINED ACTIVE MANAGEMENT

An active network management usually refers to regulating generation output whenever necessary to prevent a limit violation (thermal, voltage etc.). As renewable generation has a low load factor, it is a cost-effective approach to release extra network capacity for more renewable generation connection within a short time frame.

With synchrophasor measurements, the voltage angle difference between two locations gives an approximate indication on the generation and loading condition of the network between the two measurement points. An angle difference threshold therefore can be derived such that the network remains within its constraints, provided that the angle threshold is not violated.

The concept of Angle Constrained Active Management (ACAM) is illustrated in Figure 3, where the wind farm at bus C has a non-firm access to the network. Under an ACAM scheme, the voltage angle difference between the GSP and bus C is calculated in real-time and compared with a predefined threshold. The output of the wind farm at bus C is regulated such that the measured angle difference would be kept within the angle threshold under all circumstances. More details about ACAM can be found in [10]. The advantages of ACAM compared to other methods include the method requires a simple control logic and few measurements, as well as different types of limits (thermal, voltage and reversed power flow) can be considered simultaneously and bound into one angle difference constraint.

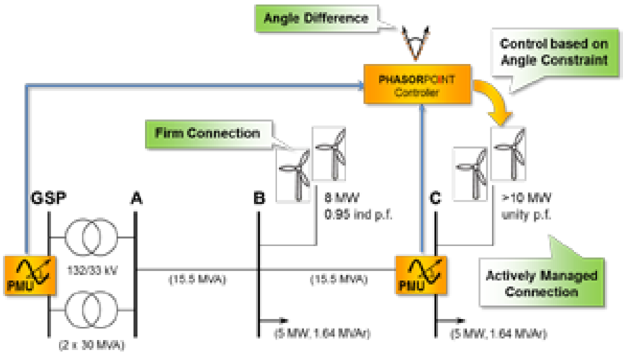

Figure 3: Angle constrained active management concept

ACAM is also a scalable and flexible method. Experience learned from current ACAM design for a meshed network includes finding appropriate locations for PMUs with following considerations:

- Network size and topology complexity
- Locations of distributed generation
- Locations of constraints concerned
- Other engineering considerations such as availability of CTs and VTs

Moreover, the process of deriving angle difference thresholds will take N-1 and N-2 network contingencies into account, so the ACAM would operate correctly even after the network topology changes. Finally, dynamic line rating can be readily integrated into ACAM. Different levels of angle difference thresholds can be adapted depending on the real-time line rating.

In a distributed control hierarchy, ACAM is envisaged to mainly work at a local control level. However, if multiple ACAM schemes are present in a distribution network, the operation of one scheme may affect the operation of another. In this case, it may require controllers at higher levels to determine the priority of the schemes considering the existing commercial arrangement.

DYNAMIC LINE RATING

Traditionally, a conservative approach is adopted to calculate the thermal limit of a transmission line. However, it is well known that the physical thermal capability of a line varies with temperature. Calculating the line thermal limit in real-time is regarded as a very effective method to allow more wind generation connections [11], because the output is highest when the cooling effect of wind on the line is also highest.

There are various approaches to calculate the line rating in real-time, either by estimating the temperature or sag of the line, or use ambient weather data, and derive a less conservative thermal limit. A challenge exists in ensuring that the thermal limit is appropriate for the whole line, and that there are no unforeseen critical spans or hot spots. Synchrophasor measurements can be used to determine the average line resistance, and therefore identify any inconsistency between the spot measurements and the overall line condition. The concept is illustrated in Figure 4. The combined approach provides greater confidence in the calculated line rating and release more capacity for wind generation.

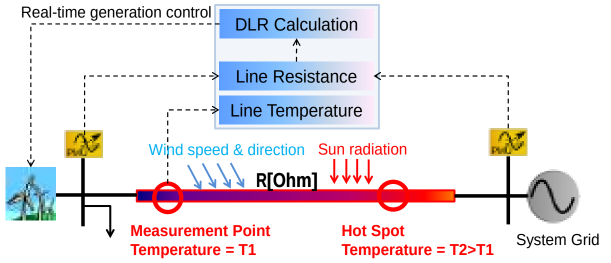

Figure 4: Dynamic line rating

In a distributed control hierarchy, dynamic line rating is regarded as a local solution; therefore this function is embedded to the local controllers and can be used for other distributed generation control applications such as the Angle Constrained Active Management (ACAM) scheme.

MICROGRID ISLANDING AND RESYNCHRONISATION

Over the last decade, microgrid operation has gradually become an acceptable solution to improve the network security and reliability, in measure of decreasing the average duration and number of customer interruption after a contingency. Challenges of microgrid operation include islanding detection, protection, and generation control to regulate frequency and phase of the electrical island for resynchronisation. It is envisaged that synchrophasor measurements will play a critical role in tackling some of the challenges.

Conventional passive approaches such as Rate of Change of Frequency (ROCOF) and Vector Shift are widely adopted for islanding detection and generation tripping. The sensitivities of both methods depend on a large power imbalance in an island. However, for microgrid islanding detection, these methods may become ineffective as the power imbalance could be small. Conversely, they can be over sensitive to large disturbances in the grid, compounding the network problem. The sensitivity of islanding detection can be enhanced by measuring the voltage angle difference between the island and the main grid, therefore reducing the chance of false detection [12]. Moreover, as mentioned previously, with synchrophasor measurements it is possible to calculate the equivalent short circuit impedance in real-time as an alternative approach for islanding detection, as the value could vary greatly before and after the network separation [13].

With PMUs installed on both the main grid and island, the angle difference measure between the separated networks can be adopted for controlling the generators on the island such that the frequency and voltage angle measures of the island match closely to those in the main grid before reconnection [14].

In a distributed control hierarchy, the islanding and resynchronisation application would require regional or system controllers to coordinate the generation controls at local levels.

LOAD PROFILING AND MODELLING FOR DEMAND SIDE MANAGEMENT

A demand side management scheme may involve controlling multiple types of loads. In this situation the scheme would need the knowledge such as the amount of each type of load available for control during different periods of time. This information can be obtained by monitoring the total demand and disaggregate the demand into different types, provided that accurate models for different types of loads are available and their characteristics are fully understood. While the penetration of modern types of loads to distribution networks is increasing, e.g. adjustable speed drives, compact fluorescent lamps and electrical vehicle chargers, there is still work to be done to understand the characteristics of different types of modern loads and their aggregated behaviour.

PMUs can provide three-phase, accurate measurements, therefore are ideal for load monitoring and waveform capture. The captured waveforms can be used for studying load characteristics, load modelling and model validation for each type of load. Finally, an aggregated load model can then be built for analysing the overall behaviour of the demand consisting of different types of loads with different proportions.

CONCLUSION

This paper has explored some innovative uses of synchrophasor measurements for better management of distribution networks incorporating distributed energy resources. By utilising highly accurate synchronised measurements, the applications introduced in this paper offer some clear advantages over other conventional approaches; this includes simpler control logic, using fewer measurement signals and accuracy improvement. The concept of distributed control architecture and how each application can be fitted into the structure were also described.

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