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USING SYNCHROPHASOR MEASUREMENTS IN SMART DISTRIBUTION NETWORKS

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ABSTRACT

The transition towards low-carbon electricity systems is reshaping the way distribution networks will be operated in the near future. Distribution Network Operators are facing a future with increasing penetration of utility-scale renewable generation, consumer-scale demand side management, utility-scale storage, and electric vehicles. These new network participants must be integrated without compromising the security and reliability of the distribution network. This work presents a practical introduction to synchrophasor measurement technology and its applications in smart distribution networks. The applications discussed include: control of distributed resources, loss of mains, model validation, and frequency stability.

INTRODUCTION

Distribution circuits, traditionally designed to be passive, are facing increasing penetration of utility-scale renewable generation. In the UK alone, 10GW of additional distributed generation (DG) capacity have been forecast by Distribution Network Operators (DNOs) to connect in the period of 2010-2015 [1]. DNOs are also facing the advent of consumer-scale demand side management, utility-scale storage, and widespread use of electric vehicles. These new network participants should be integrated without degrading security and reliability. It is in this context that the envisaged Smart Distribution Networks, as part of the Smart Grid concept, play a major role providing much greater observability and operational control capabilities than the conventional approach to distribution system management.

In the distribution system, the measured data available for analysis and design involves a relatively long timeframe. It is important to capture a more detailed picture of the operation of the system so that the time-varying characteristics of generation and load are captured. Synchrophasor measurements provide an accurate and detailed source of information to capture both static and dynamic behaviour of the system. Furthermore, phasor measurements are an efficient source of information, as they can be used to identify behaviour at remote locations, and acquiring the same level of detail using conventional measurements would require extensive installation of measurement and communications equipment.

This work presents a practical introduction to synchrophasor measurement technology and its applications in smart distribution networks. Synchrophasor

measurements [2] have been widely deployed in transmission systems over the last decade for measurement, analysis and control of stability [3, 4], and are able to acquire data at a fast speed (up to 50 or 60Hz) with very precise GPS time synchronisation. The deployment of such a technology in distribution networks increases dramatically the observability of the circuits, providing a better understanding of the actual behaviour of the different network participants, both in real-time and for historic analysis, and how their behaviour affects the distribution system and the wider interconnected power system. The applications to be presented and discussed include:

- *Control of Distributed Resources:* Synchronised measurements of voltage magnitude and angle can be used as inputs for simple and robust generation and/or load control schemes.
- *Loss of Mains:* Current islanding detection techniques, typically based on ROCOF devices, might not be the best long term solution in systems with high penetration of distributed generation (DG) as disturbances could result in the disconnection of many distributed generators.
- *Model validation:* The limited observability of typical Distribution-SCADA systems (e.g., 30 minutes) can mislead offline studies when variable sources of generation are in place. By applying synchrophasor measurements it is possible to observe the actual behaviour in detail and replicate it for planning studies.
- *Frequency stability:* By understanding how frequency behaves, high penetration levels of variable renewable generation could be securely operated in islanded distribution systems with demand side management/storage capabilities.
- *State estimation:* With increased observability of the distribution network it is possible to feed downsampled data into state estimation platforms in order to increase their accuracy.

SYNCHROPHASOR MEASUREMENTS

Synchrophasor measurement technology is used extensively at transmission level for system monitoring. The measurement technology developed during the 1990s, and after several large-scale blackouts in North America and Europe it was widely recognised as an important technology to understand and improve the stability of the power system. An IEEE standard for synchrophasor measurement was

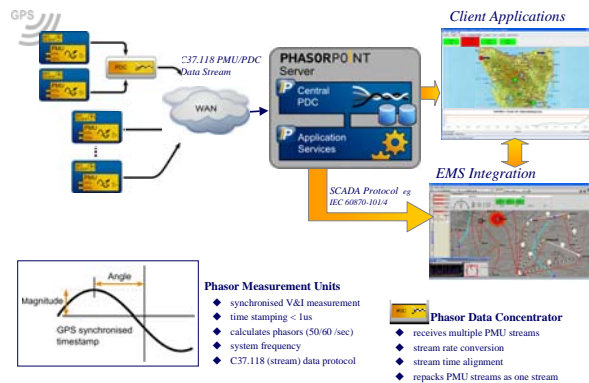


Fig 1. Typical phasor-based Wide Area Monitoring System (WAMS).

released in 2005 [2] that defined requirements for performance and communication. Release of this standard led to widespread deployment of network of Phasor Measurement Units (PMUs) at transmission level.

The diagram below (Fig 1) describes a typical phasor-based Wide Area Monitoring System (WAMS). The PMUs acquire voltage and current waveform data at the substation, and using an accurate GPS timestamp, the waveform is referenced to a perfect 50Hz (or 60Hz) waveform. The magnitude and angle of the phasor representation of the signal is produced. The data is then streamed continuously through a wide area network to a central point where applications for real-time monitoring, analysis and control are carried out, and the data is stored for post-event. Nodes known as Phasor Data Concentrators (PDCs) can be used to aggregate several data streams into a single stream and downsample it if necessary.

In contrast with conventional monitoring, the accurate timestamping and fast data rate mean that the information on the dynamic performance of the system can be derived. Also, conventional data sources are not usually accurately time aligned, and the process of using the data for initialising a state estimation or simulation is significantly improved with synchrophasor data.

SYNCHROPHASOR APPLICATIONS

Control of Distributed Resources

Current practice in the UK and, in general, in Europe, is to provide DG operators with a firm connection. Such an approach, also known as 'fit and forget', requires that all technical limitations such as voltage rise, thermal ratings and avoidance of reverse power flows through grid transformers (if necessary) are satisfied in any credible operational scenario (e.g., minimum demand-maximum generation, N-1 or N-2 contingencies, etc.). While this might be considered a secure, reliable and proven approach, it requires expensive traditional reinforcements and neglects the fact that renewable sources, such as wind power, are

inherently variable and hence there will be many periods where assets are not fully utilised. Indeed, these fit-and-forget connections have significantly curtailed the ability of certain networks to integrate more generation capacity as the extra costs are not viable for most DG developers. Although alternative connections based on intertripping schemes that actuate upon the occurrence of a constraint breach or a contingency, known as non-firm connections, allow the integration of more DG capacity, the true potential of distribution networks to accommodate large generation capacities by applying active management has yet to be realised.

In a previous work [5], the authors proposed a scheme coined Angle Constraint Active Management (ACAM). This technique uses synchrophasor measurements to actively manage wind power generation output in congested distribution networks, resulting in the connection of more capacity and, hence, the delivery of more energy as opposed to the fit-and-forget approach. This is achieved by applying an angle-based constraint that is determined according to the network characteristics (i.e., a proxy for thermal and voltage limits, avoidance of reverse power flow through grid transformers, etc.) and using minimal communication (PCT application number PCT/GB2010/052120).

Fig 2 shows a 33kV test feeder with two wind farms connected to it. It is assumed that WF1 has been granted firm connection as no further reinforcements were needed to accommodate it (the N-1 condition for the substation is as restrictive as line A-B). WF2, on the other hand, corresponds to a new potential development (fit-and-forget capacity of approximately 10MW). It is important to highlight that given the firm connection agreement between WF1 and the local DNO, its power production will continue to follow its normal pattern, disregarding the effects that a new generator might have on the network. Consequently, any potential congestion must be managed solely by WF2.

The proposed implementation of the ACAM scheme would include two Phasor Measurement Units (PMUs), one at the substation and one at the connection point of the wind farm whose output will be actively managed. The voltage angle difference between these two PMUs will be constantly compared against the fixed angle constraint (found according to the network characteristics). If the angle difference is above the angle constraint, then the control mechanism is triggered, leading to a reduction of the power output of WF2 in a way that maintains the angle difference within limits, and hence keeps the network secure.

Adopting hourly demand and wind power data for central Scotland in 2003, the ACAM scheme is able to connect 14MW (angle constraint equal to 3.77°), allowing an increase of 37% in terms of capacity compared to the fit-and-forget case [5]. However, generation curtailment of WF2 occasionally occurs, particularly during critical scenarios of minimum demand-maximum generation

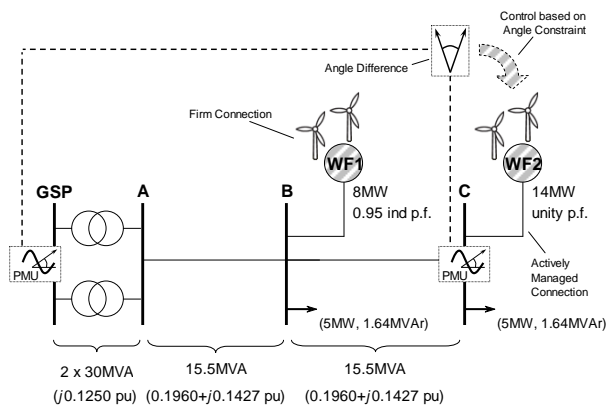


Fig 2. 33kV 4-bus test feeder with two wind farms (WF1 and WF2), including the Phasor Measurement Units (PMUs) for the proposed Angle Constrained Active Management.

scenarios. The resulting volume of energy exported increases by 35%. From the capacity factor perspective, the healthy 0.415 figure of the fit-and-forget approach goes down to 0.408, i.e., a 2% decrease.

Loss of Mains

In most distribution networks around the world, intentional islanding is not permitted, mainly due to safety reasons and protection issues. This means that every effort has to be made to detect loss of mains, i.e., the disconnection of part of the distribution network (where generation is connected to) from the rest of the transmission/distribution network. For example, in Fig 4, the disconnection of any section of the feeder would result in loss of mains. Immediately after loss of mains is detected, all DG plants are required to trip in order to avoid islanding. Rate of change of frequency (ROCOF) devices are commonly used for this purpose. A typical window of operation (i.e., tripping of DG plants) would be 0.40 to 0.60Hz/s over a period of 0.5s [6], depending on the characteristics of the power system being considered.

Crucially, if a power system has a relatively volatile frequency or is prone to significant frequency deviations due to N-1 or N-2 contingencies, ROCOF devices end up tripping DG plants that had not separated from the supply. This not only results in loss of profit for the DG owners/operators, but it also has implications on the manufacturer's guarantee of the DG plants which may be void after a certain number of on-load trip events. In addition, the aggregated effect of the tripping of many MWs of DG capacity can result in a cascading effect leading to a further dip in frequency [6]. This very case was seen on the Great Britain power system in May 2008, as shown in Fig 3, after the loss of two major bulk power plants.

By using synchrophasor technology it is possible to improve the loss of mains detection in a way that unintended, spurious tripping is avoided or at least

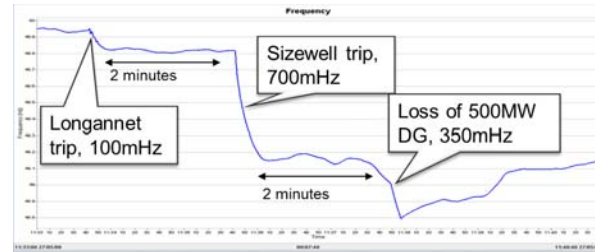


Fig 3. Frequency of the Great Britain power system – May 2008.

significantly reduced. Phasor measurements provide a very direct measure of system separation, and can clearly distinguish between local generator loss-of-mains and a wider system separation. Using the example shown in Fig 4, the angle difference between two points in a given feeder will reflect in real-time that both locations are electrically connected. An angle change greater than 90° will mean there is an open point between these two PMUs, requiring the immediate tripping of the affected DG plants.

For security reasons, a fail safe mechanism in case of loss of communications is that the scheme will work together with a conventional ROCOF scheme. If the angle-based loss of mains detection is operational, then the ROCOF scheme is inhibited. Otherwise, the ROCOF scheme will be enabled.

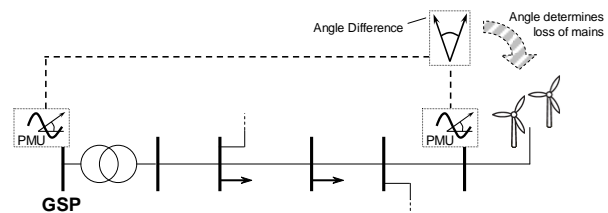


Fig 4. Angle-based loss-of-mains detection scheme on a radial feeder.

Model Validation

An accurate representation of the distribution grid is important for assessing the true limits of secure operation. A particular challenge in the distribution system is that loads and smaller generators are not observed in detail, and available data may be averaged over as much as 30 minutes. The averaging may hide particular conditions that could be of interest, and does not provide sufficient insight into the time-varying characteristics of load and generation.

Phasor measurements provide very good time resolution. Data is provided at up to 50 or 60 samples per second, replicating both the steady-state and dynamic behaviour. Furthermore, phasor measurement is an efficient form of measurement, and gives information on the activity in the network, even if it is not directly measured.

In the example shown below (Fig 5), the MV system has two connections to the HV system. Both of these are monitored with phasor measurements so that the boundary conditions can be defined. Deploying phasor measurements

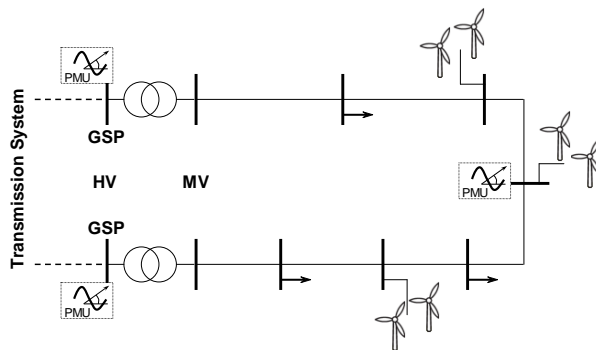


Fig 5. Transmission or sub-transmission connected distribution networks with distributed generation.

at the interface between the systems means that the subsystem to be identified can be assessed independently of the external system. This can be very useful, for example, in assessing whether modelling errors arise in the equivalent model of the transmission network or in the local network. It may be noted that the example shows three PMUs for identifying the meshed system. For a radial system, only two PMUs would be needed at the transformer and the remote end.

The PMUs can be used to determine the net generation and load between two measured points. This can be obtained at any data rate up to 50 or 60 samples per second. Furthermore, if there is a change in one generator or load within the section, the change of angle relative to the change of current can be used to identify where in the network the change occurred. Changes closer to the HV end will have a smaller effect on the angle difference, while changes near the remote end of the LV side will affect the angle difference more strongly. Using short time resolutions, the occurrence of separate events of load and generation changes are relatively common.

Frequency Stability of Island Networks

In current practices, a small isolated island operates in terms of frequency stability in a similar way to a larger grid. Reduction or loss of generation leads to a drop in frequency, and this is balanced by frequency-responsive conventional generation that increases output. Similarly, loss of load causes a rise in frequency and frequency-responsive generation output reduces in proportion. The requirement for frequency reserve response has so far placed a constraint on the penetration of renewable generation that can be accommodated in an island network.

It is envisaged, however, that the penetration of renewable generation could be substantially increased if the frequency response service could be provided not by conventional generation, but by a combination of demand-side control, renewable generation control, and energy storage. If these control resources were available, the network could be operated without a requirement for a base level of conventional generation.

While distributed frequency response is feasible, there is the potential for distributed continuous controls to interact across the grid, leading to frequency instability. Conditions of frequency instability may occur in unusual network scenarios, and can be difficult to predict. It is therefore important to be able to measure the stability of the grid and identify and take action on conditions of near-instability, to steer the system away from a potentially damaging occurrence of instability.

Synchrophasor measurement technology has been widely deployed in transmission systems over the last decade for measurement, analysis and ultimately control of stability. This technology has been used for frequency stability and electromechanical stability analysis and design improvements. Applications have also been developed based on synchrophasors to identify system separation quickly, and present key information to the system operator for sustaining the islands and reconnecting the grid. This technology could form a very important part of the monitoring and control capability to improve the capability of the distribution network to accommodate renewable generation and maintain stability and security of supply.

CONCLUSIONS

This work has presented a practical introduction to synchrophasor measurement technology and its applications in smart distribution networks, including control of distributed resources, loss of mains, model validation, and frequency stability. It is expected that synchrophasor measurements will play a crucial role in enabling high quality monitoring and real-time control required for the envisaged low-carbon, smart distribution networks.

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