Opportunities to exploit Phasor Measurement Units (PMUs) and synchrophasor measurements on the GB Transmission Network

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***Abstract*- As a result of CO_2 reduction legislation at both EU and government level, the GB electricity grid operator National Grid is tasked with connecting up to 30GW of wind generation to the existing transmission system by 2020. The inherent variability in this method of generation will require the System Operator to maximise the use of existing transmission corridors, running lines closer to their thermal limits. In addition, transmission technologies currently unfamiliar to National Grid such as series compensation, intra-network HVDC and an increase in the number of HVDC interconnections will also be implemented to help integrate the additional generation. It is understood that the networks will need to become more flexible in order to maintain security of supply; to achieve this, improvements of overall system monitoring will also be required. Phasor Measurement Units (PMUs) and synchronised phasor measurements have become the 'measurement technique of choice for electric power systems' [1] and to this extent are viewed as a key tool in monitoring oscillations within the GB power system. PMUs are being deployed, initially as an extension to Dynamic System Monitoring (DSM) and with this paper the authors discuss the challenges involved with implementing a Wide Area Monitoring System (WAMS) solution. In addition a number of additional roles and applications that the PMU system could exploit in order to improve control of the network is also proposed.**

***Index Terms*—PMU, SCADA, Synchrophasor, Transmission System Monitoring and Control, WAMS, WAMPAC.**

I. Introduction

In addition to its role as the Transmission Owner in England and Wales, National Grid Electricity Transmission (NGET) became the Great Britain System Operator (GBSO) on 1st April 2005, following implementation of British Electricity Transmission and Trading Arrangements (BETTA). On 24th June 2009, following the 'Go Active' of offshore transmission, National Grid became the National Electricity Transmission System Operator (NETSO), which extended its GBSO operation to include the Offshore Transmission System. [2]

As a result of CO_2 reduction legislation National Grid is tasked with connecting up to 30GW of wind generation, predominantly offshore in the North of England and Scotland, to the existing transmission system by 2020. It is understood that this level of wind will drastically change the dynamics of the grid and result in some radical changes to the transmission system. The 'Connect and Manage' regime implemented on 11th August 2010, whilst facilitating grid access arrangements for this low carbon generation, also imposes a number of new challenges for the designers and operators of the electricity network. To this effect the way the transmission system is monitored and controlled will need to become increasingly flexible in order to maintain security of supply.

The traditional system monitoring approach is conducted too far in advance of operations and will become increasingly unreliable as the rest of the electricity network evolves to accommodate new generation.

Wide Area Monitoring Systems (WAMS) are becoming increasingly popular amongst power systems globally and Phasor Measurement Units (PMUs) with their ability to observe changing power system conditions in real-time, recording time synchronized system data at rates of around 50Hz, are rapidly being installed by transmission network operators to improve system observability and security. However, implementation of this type of system is not without its challenges, not least of all in the large volumes of data being supplied.

The remainder of this paper presents an overview of system monitoring requirements, current progress and future plans regarding opportunities to exploit the PMU deployment across National Grid.

II. Existing Monitoring Systems

Supervisory control and data acquisition, (SCADA) systems observe grid conditions approximately every 5 seconds, which is deemed too slow to track dynamic events on the grid. Usually only rms values without any phase angle information are provided. In addition the systems currently employed at substations and grid connection points are obsolete, working on old technology that is not suitable for the evolving network. They are essentially all performing similar tasks but not all feed into the central system, meaning data analysis and comparisons can be quite convoluted, figure 1. This large number of systems points to an unnecessary level of complexity as well as commissioning and maintenance issues.

In essence the operations of the existing monitoring systems work through analogue voltage and current data that is provided from the secondary side of instrument transformers. This is then sampled/digitized for processing, all be it at varying resolutions. From this point various applications are carried out to provide information on the current status of the electricity network, however direct comparisons are not possible without high accuracy time-synchronization at the point of measurement.

The current arrangement of the substation systems results in a convoluted and excessive amount of data processing, with some of the legacy monitoring data having to be manually retrieved through dial up systems such as the public switch telephone network (PSTN), this arrangement also makes data comparisons between sites unnecessarily complicated. Going forward all of this information will be required in a more efficient fashion.

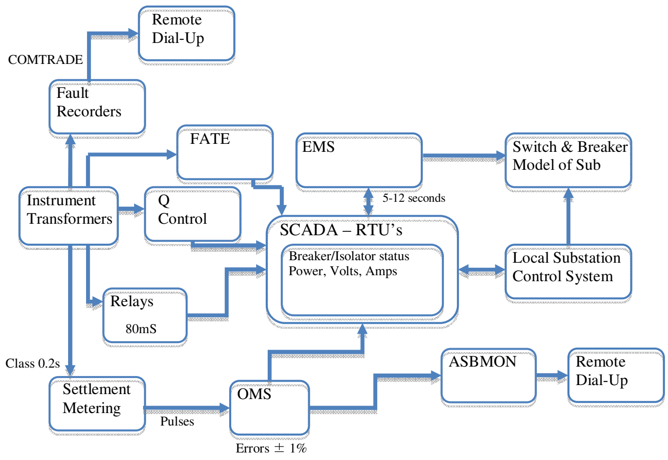

Fig. 1. Substation SCADA Systems

A. Frequency And Time Error system, FATE

The operational frequency at present is monitored through the FATE system; around 10 sites monitor the local frequency and this information is sent back to the control room, where one of these readings represents the system frequency. This is normally taken from the electrical centre of the network, which should be an area of stability and less susceptible to the deviations that occur on the outskirts of the network. This data is refreshed on a second by second basis, not fast enough to track dynamic changes in the system. As the frequency information is not time synchronised direct comparisons cannot be made between different areas of the network. The geographically distributed impact of system disturbances through online comparisons could add significant capacity to the system to identify emerging power system conditions and play an important role in situational awareness. [3]

B. Operational Metering

This metering is intended to provide both National Grid and the generators with real-time information on power flowing both to and from connection points all around the network. This is used for system control and offline modelling. At present this data is provided via a pulsed output from the Settlement meters; this in itself is prone to errors, around ± 1%. If this information was also time synchronized at source true comparisons could be made across the network, vital to accurately modelling the system.

C. Ancillary Service Business Monitoring, ASBMON

ASBMON is a single system installed at generating sites designed to evaluate the contracted frequency response as provided by the generators. Again, data are provided via a pulsed output from the settlement metering equipment and in this case the information is manually retrieved, disjointed from the central system.

D. Protection Relays

Relays can already be considered as a first level of wide area measurement protection and control, (WAMPAC) if equipped with a GPS receiver. Full integration with the rest of the systems could allow a number of unique protection applications that would employ an angle-based logic.

E. Reactive Power Control

Monitoring systems used to detect voltage problems are becoming increasingly important as the networks complexity increases. The ability to supply reactive power exactly when it is needed to help systems achieve new stable operating points is vital.

It is suggested that PMUs would be more suitable for adopting the roles mentioned above and would provide the ideal platform to pull all of the different application data together. This would also facilitate the installation of PMUs onto the network. However, there are various security issues involved with combining these systems, most obviously with the protection systems and redundancy, that of course have to be taken into consideration.

To accommodate the functionality of all the above devices a method is proposed whereby, data from instrument transformers is made available to a dedicated high accuracy analogue to digital converter; from here the data is time stamped locally through GPS to allow synchronized comparisons. The data can then be stored in this raw form before finally being distributed over an Ethernet service bus at desired resolutions for individual applications. This method would greatly simplify the monitoring systems within the substation and provide a more adequate platform for data comparisons. The benefits of this integration would be realised through reduced capital and support costs and consistency in the accuracy and availability of data that will be critical to the operation of the transmission system of the future. In order for this to be progressed as a serious solution confidence has to be gained in both the security and reliability of Ethernet communications.

III. DSM & SYSTEM STABILITY

National Grid is required by Grid Code CC6.1 to ensure the Transmission System is operated within certain technical, design, and operational criteria, which define allowable frequency & voltage variations, waveform quality and voltage fluctuations. In order to meet this obligation National Grid must be able to monitor and record these measurements at appropriate locations. [4] Typically DSM solutions have been achieved through a mixture of Fault Recorders and data loggers that sit outside standard substation SCADA systems and are manually contacted to retrieve the necessary system information.

DSM is required for use at selected 400kV, 275kV, 132kV and other lower voltage substations to provide data on a substation and system-wide basis of "System Dynamic behaviour". It enables post-event analysis of system events, aids in identifying the cause of specific system incidents providing a greater understanding of the power systems overall behaviour. This information is also used as part of system stability assessments, which allows the identification of network weaknesses that in-turn feed into the transmission reinforcements.

The primary role of DSM is to monitor the oscillatory stability in real-time across the network. As transmission lines are run closer to their thermal limits the power system becomes increasingly vulnerable to instabilities that could lead to equipment damage and cascading blackouts.

The UK grid is a dense network with relatively short lines. However, the NGET Transmission System is connected to the SPTL Transmission System to the north and it is these 2 double circuit 400kV AC connections that are currently a large cause for concern. An inter-area mode at around 0.5Hz is present between generators in Scotland and England and on occasion this has become unstable [5]. The increasing generation in the North of the system is going to apply further pressure to these circuits, so it is important to gain an increased knowledge of the system dynamics in this area.

Power system oscillations once noticed on the network are typically well damped through the use of control systems; however it is through faults or excessive variations in demand that cause this damping to break down. This needs to be monitored closely and is becoming an increasing concern as the system becomes more complex and National Grid take on technologies that are currently unfamiliar such as series compensation and intra-network HVDC. Extensive installations of wind generation twinned with a decrease of connected synchronous generators will have significant impact on system inertia and therefore frequency as well as damping of the inter-area oscillations.

IV. Phasor Measurement Units, PMUs

PMUs receive analogue voltages and currents from the secondary sides of instrument transformers. From these inputs, using digital signal processing techniques, the devices calculate estimates of positive sequence voltage and currents (magnitude and phase angle); line frequency and rate of change of frequency. Active and reactive power is also calculated. These values are typically calculated once for each cycle of the fundamental frequency and then time stamped at source using the 1pps signal provided by the global positioning system (GPS). The data is then sent to a phasor data concentrator (PDC) where it is time aligned with information retrieved from other devices installed in the power system. The accurate time synchronisation of this system is a unique feature among existing monitoring systems, allowing assessment of phase angle information with a global common reference and providing relation between phase angle measurements of remote locations.

The PMU was originally developed through logical progression of the symmetrical components distance relay (SCDR). [6] This used a relaying algorithm based on the measurement of positive-sequence, negative-sequence and zero-sequence voltages and currents at the transmission line terminal. It was soon recognised that the positive-sequence measurements were of great value. They constitute the state vector of a power system and it is of fundamental importance in all of power systems analysis. [7]. The earliest modern applications involving direct measurements of phase angle differences was reported in 3 papers in the early 1980's [8, 9, 10].

The ability to make direct real-time comparisons between different points on the network would prove to be a vital tool and it soon became clear that GPS offered the most realistic and effective method of synchronizing power systems measurements over a great distance. At present it is possible to achieve synchronization accuracies of 1μs (0.018°) or better at the nominal system frequency 50Hz. Today they are becoming the tool of choice for monitoring power system dynamics and in the future it is suggested that the PMU may take over the role of many existing pieces of equipment. In the meantime a large amount of investigation is required into the correct implementation of PMUs and WAMS within the existing control systems at National Grid.

A. Systems standards.

IEEE C37.118-2005 is the current globally recognised standard for reporting PMU or synchrophasor data. It should be noted that this protocol leaves transient performance unspecified and as such, the performance of devices under system transient conditions could vary wildly. [11] This standard is due to be updated and will be published in two parts, 118.1 – Measurement and 118.2 – Data Transfer, with the intention of creating a harmonised standard between 118.2 and the substation standard IEC 61850. IEC 61850-90-5 should provide some important enhancements to the communication of phasor data whilst addressing the data transfer requirements identified in IEEE C37.118. [12]

B. Data volumes and reporting rates.

The quantities of data being reported by the PMUs is substantially higher than that of traditional metering or monitoring systems, to this extent there will be a significant impact on the network bandwidth at the substation level. The resolution of data required for individual applications requires consideration and the necessity to archive 100% of the data resolution into long term storage needs to be questioned.

C. Network dependency

For synchrophasor based applications to become part of critical network operations confidence will have to be gained in PMUs. The accuracy and reliability of their measurements, both as individual units and in comparison with other devices will have to be proven. In addition, the impacts of losing the GPS signal through anticipated solar activity [13] must be analysed carefully if a large amount of operation and control applications in the network are dependant on this signal.

V. OVERVIEW OF INSTALLED WAMS

WAMS technology is readily in use and has been trialled by power systems globally; the initial challenge comes in integrating a synchrophasor-based system into the existing tight network of systems at National Grid. To this effect PMUs are currently being deployed as an extension to DSM, with a series of upgrades to existing digital fault recorders and the installation of standalone devices where available. 19 sites around the England & Wales Network have been upgraded to provide PMU functionality; the initial focus being on upgrading the oscillation monitoring system to enhance the real-time view of the system by improving situational awareness with regards to changing power system conditions and furthering existing knowledge of the network dynamics. The initial system architecture can be seen from figure 2.

The WAMS is integrated with the existing Energy Management System (EMS) to provide alarm information to operators when the system is believed to be approaching instability.

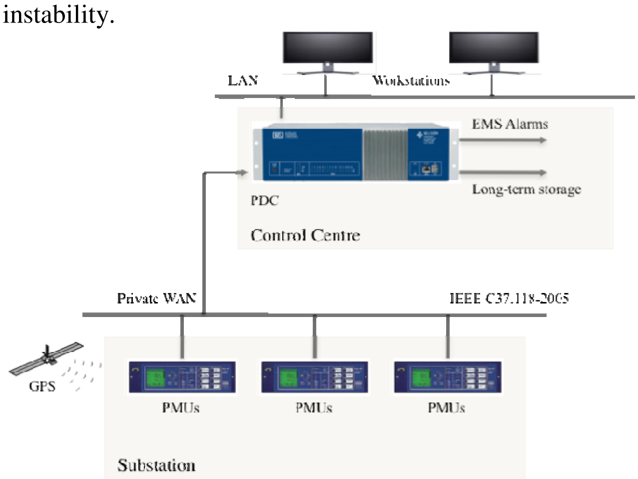

Fig. 2. Structure of the Wide Area Monitoring System.

The WAMS will investigate the following modal characteristics, building on the work in [5], across the 2 double circuits that connect the Scottish Network with the North of England:

- Frequency mode
- Amplitude
- Damping
- Mode shape

It is important to understand these characteristics of the system and study any potential damping problems during unusual loading conditions. The chosen connection points for offshore wind and HVDC interconnection shall be monitored to better understand the anticipated changes to the network dynamics. The data provided by the PMUs combined with SCADA data and network configurations can be used to identify how far the system is from stability margins.

The PMUs are widely spread across the network so early stages of research have looked into ways in which PMUs can assist with existing system monitoring roles such as improving situational awareness for the network operators, tracking emerging power system conditions and oscillation identification; the PMU and WAMPAC implementation will give a much greater view of the network as a whole. The use of the synchrophasor data will allow flows to be viewed in real time over the entire network and this improved observability allows problems (instabilities) to be spotted much earlier and dealt with accordingly. Comparisons have also been made between the offline transmission analysis (OLTA) system and that which is observed in real-time, as a form of model validation. The other main area of focus has been in post-mortem network analysis, to identify the location of faults and demand or generation losses on the system.

National Grid is integrating PMUs onto its network through a series of work streams, initially looking at a widespread of the devices to gain familiarity and once knowledge is gained second level projects are anticipated to look at real-time congestion management tools.

VI. SITUATIONAL AWARENESS

It is important to be able to select the relevant pieces of information from the synchrophasor data and display that effectively to the operators, to enable them to understand the complexities of the system in a timely manner. A recent webinar [14] attempted to answer the question of whether synchrophasor data helps operators and engineers make more timely decisions or is the additional information just ‘information clutter’?

Synchrophasor information can be used to improve situational awareness through real-time system visualisation and offline model validation, but just because data can be shown in a graphical form doesn’t mean it should be. The studies have shown that displaying the information in the form of a contour map can be quite helpful in showing emerging power systems conditions.

A. *System incident captured 19.04.2011.*

Below are the results from an 1170MW loss of generation from the Scottish part of the Network, causing the system frequency to drop by 0.38Hz to beyond operational limits at 49.667Hz, figure 3.

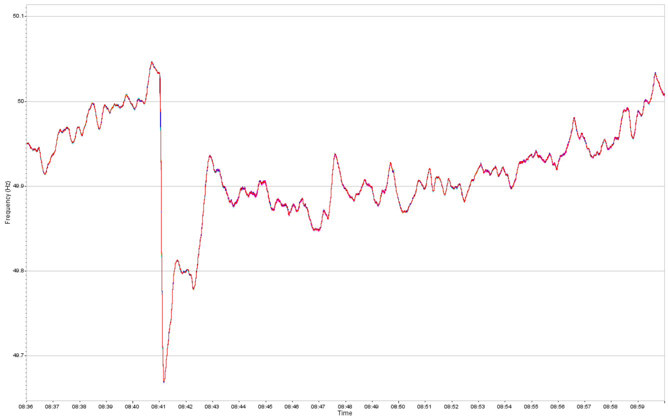

Fig. 3. Frequency trace for all PMUs 19.04.2011

It is possible to trace the source of generation losses or circuit outages on the system in real-time by observing the change in frequency measured at the various PMUs installed on the network, the above generation loss can be pin pointed to a specific region of the grid by analyzing the delay in the immediate frequency drop at different locations. This time delayed effect can be seen to ripple across the system frequency. Figure 4 shows the first 1.5 seconds following the generation loss.

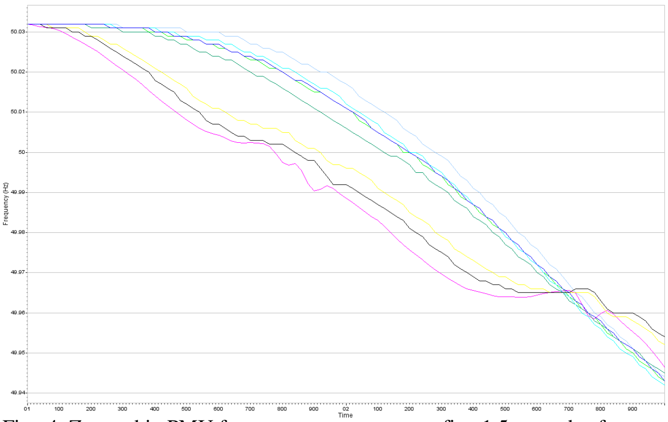

Fig. 4. Zoomed in PMU frequency measurements, first 1.5 seconds of generation loss

This information, if made available to the operators would provide a real-time indication of the evolving power system condition twinned with other system wide information would enable a faster response to system incidents. It is also suggested that this information would be presented well through the form of a contour plot on the map of Great Britain, results in the US in [14] have suggested this is useful.

B. *Offline model of system incident.*

To replicate the system state at the time of the generation loss the OLTA model is fed with day-ahead ½ hourly values for both demand and generator levels. If this data could be provided by the PMUs a more accurate picture of the network could be recreated thus allowing better validation of the network model. For this it is important to ensure that the real time model is the same as the offline model this way the data can be plugged straight from one form to the other.

In Figure 7 the first 1.3 seconds of simulated system frequency in generation loss is shown. There are slight differences between measurement and simulation, the authors assume that especially the dynamic modelling of the load (induction motors) is not adequate. However the general response, reflecting the delay of immediate frequency drop, is the same. Analysing further events by means of PMU measurement results will help to improve the dynamic network model significantly.

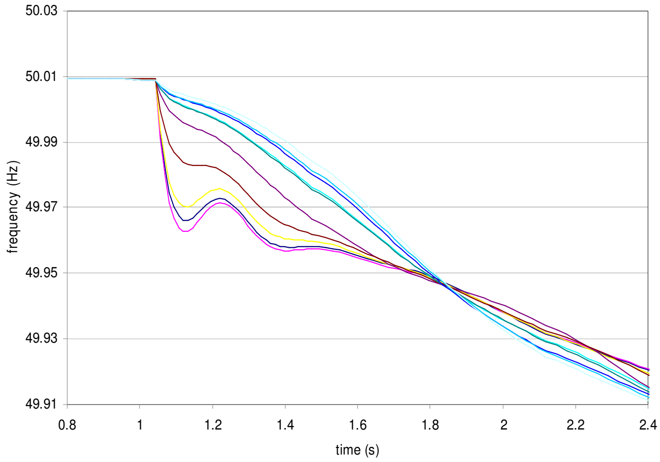

Fig. 5. Modelled view of frequency ripple, first 1.3 seconds.

VII. Conclusion and Further Research

The WAMS described in this paper is in its infancy, the initial goal being to upgrade the DSM solution and through this gain knowledge and understanding of the devices on the network. A system has been proposed to modernize the monitoring and control within substations. The WAMS strategy for the National Grid has been briefly outlined along with some initial results from the system in place. The event captured on April 19th 2011 proves that the acquisition of this wide area information is a vital tool in observing the changing power system conditions to specific system incidents. It is expected that extension of wind power will have an impact on secure operation of the transmission grid. The authors are confident that emerging system changes can be viewed in real time through the use of PMUs

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