CONNECTION AND MANAGEMENT OF DISTRIBUTED GENERATION USING SYNCHROPHASOR MEASUREMENTS AND ADVANCED DISTRIBUTION MANAGEMENT SYSTEMS

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ABSTRACT

In order to reach the targets for connection of renewable energy resources to distribution networks, new control and management approaches are needed. In this paper, solutions are presented for significantly increasing the connection of Distributed Energy Resources (DER), without over-investment in network infrastructure. A Distribution Management System (DMS) provides co-ordinated centralised oversight and management of the system. Synchrophasor measurement provides useful input to the DMS, and can also be used in autonomous area controllers. The paper concludes that the use of flexible control solutions, co-ordinated in an advanced DMS substantially increases the capability to accommodate distributed generation while maintaining security and quality of supply.

INTRODUCTION

Meeting the legislated European and national targets for renewable energy will require a significant proportion of the new energy sources to connect to distribution systems. In the UK, for example, it is forecast that distribution network operators will be expected to connect more than 10GW of Distributed Generation (DG) in order to meet the 2020 target [1].

Historically, DG has usually been connected without active management, and the capacity of generation that could be connected was limited such that it could operate without a constraint in all network operating scenarios, commonly termed ‘fit and forget’. The limiting scenarios defining the capacity that can be connected usually involve the coincidence of high wind and low load, which may be quite uncommon. Thus, ‘fit and forget’ is not an efficient use of the network, and the costs and delays involved in network reinforcements would make many projects infeasible, and the targets would not be met.

An alternative approach is termed ‘connect and manage’, where generation is curtailed only at times when it is necessary to avoid violation of network constraints. Under this philosophy, the distribution network can accommodate much greater levels of DG capacity, with modest curtailment. The UK government formally decided in 2010 to adopt a ‘connect and manage’ model for generation connection [2]. Similar changes to DG connection are being adopted elsewhere in Europe.

To be widely adopted, the ‘connect and manage’ approach requires new practices for monitoring and control. Both centralised and decentralised control can be useful. A Distribution Management System is a key element of centralised supervision and control. Decentralised control involves autonomous measurement and control that operates independently from the DMS, but it is useful for such schemes to inform the operators of actions and status through the DMS.

This paper examines the role of synchrophasor measurement technology in centralised and decentralised monitoring and control.

SYNCHROPHASOR MEASUREMENT

Synchrophasor measurement technology essentially uses accurately GPS time-synchronised measurements of voltage and current to extract the amplitude and phase of AC waveforms, and report the phasor representation of the signals. Because of the time synchronisation, phasors acquired at different locations in the grid can be compared. Phasors are a concise representation of the AC waveform – a cycle is represented by one complex number and a timestamp – and data can be streamed out continuously at a much faster rate than conventional SCADA data.

Synchrophasor data has been deployed extensively in transmission systems. The concept was originally developed in the 1980s, but widespread commercial deployment followed the release of the revised IEEE standard in 2005 [3]. Psymetrix PhasorPoint is a leading example of synchrophasor-based wide area monitoring software, used in control centres worldwide. PhasorPoint applications address network stability, islanding and resynchronisation, and constraint relief.

In a synchrophasor monitoring system, data is acquired at a number of substations, then streamed at an appropriate data rate to a data centre where the data will be analysed and stored. The phasor data and other derived information can then be visualised, used for control, or forwarded to other systems, including the Distribution Management System (DMS).

The following applications are of particular interest for the topic of this paper:

- Phasor measurement input to the DMS
- Detailed information on performance of the distribution system and connected load/generation
- The use of angle difference information for control of renewable energy

DMS CONTROL AND MANAGEMENT FACILITIES FOR GENERATION CONNECTIONS

A structured approach is proposed for DG integration, classified as follows:

1. **Passive integration** Information only
2. **Active integration** Distribution Management Solution (DMS) responding to the current conditions
3. **Proactive integration** Evaluation of potential problems induced by the DG outputs

Passive integration

The first challenge to address is providing 100% observability of DG resources in real-time. New DG resources usually provide real-time telemetry, typically over DNP 3.0, using the SCADA function of the DMS system. For existing DG resources, the telemetry may not be available. Having an accurate estimation of DG injection into the grid is thus key to provide accurate understanding of the current grid state. ALSTOM Grid's **e-terra***disgen* module was developed to address this need. This application is in operation in France and in Denmark, where DG is mainly wind turbines and small CHP. In France, for example, 95% of wind generation is connected to the distribution grid (20 kV). Only 75% of this production is telemetered, and the remaining 25% is estimated based on rules and surrounding DG equipped with telemetry. Using **e-terra***disgen*, the utility has full observability of wind injections in real-time. Aggregation is also useful to provide efficient monitoring and alarming at different level of granularity – wind turbine, wind farm, transformer, wind cluster or distribution control area. Phasor data can also be transmitted from PhasorPoint system to the SCADA system to improve observability.

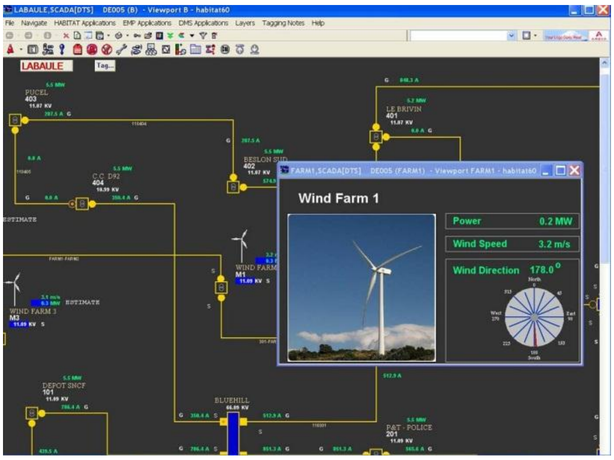

Figure 1 User interface for turbine real-time monitoring

The renewable energy production forecast is important for intermittent generation. Forecasts are integrated within the grid operation applications to provide visibility of developing conditions (look-ahead) to the operators in an intuitive graphical way. Configuration of dedicated alarms such as high rate of change of wind conditions between two time points, large deviation between actual and forecasted wind production data provide warning and alert signals to prevent turbine stall conditions and complement situation awareness of the operator.

Synchrophasor measurements are useful for improving the observability of the distribution system in the following ways:

- Faster measurements provide more detail on network operation, for example where rapid changes cause transient or periodic power quality issues that are not observed in conventional SCADA / RTU measurements
- Improved Distribution State Estimation and observation of network loading. The capability of the network to accommodate DG depends on network loads as well as generation. Real-time data on loads can be sparse in the distribution system, and synchrophasor measurements provide concise information to observe the monitored buses, and also neighbouring buses.
- Detailed analysis information, for example for assessing short-circuit capacity of the network [4].

As well as observability of DG resources, it is also valuable to have detailed information on the loading of the distribution system. Real-time information on loads can be sparse, and some distribution utilities have observed quite significant differences between actual active and reactive power flows and estimated values. This is important for identifying dimensioning events and planning network additions. The detailed time-resolution of synchrophasor data, integrated with other data sources, can significantly improve the accuracy of the information available.

Active integration

Active integration of DG resources can be achieved at several levels. At field level, "intelligent" devices such as automatic reclosure equipment or remotely controllable switching devices help to maintain grid supply. Such equipment are is modelled and integrated within ALSTOM Grid's **e-terra***distribution* applications and user interface. The DMS operator is to have a complete view of the current status of new devices, and can reconfigure the network topology and follow-up outage restoration.

Generator controllers located at DG premises can be interfaced to leverage ancillary service capabilities of DG resources such as voltage support. For example, **e-terra***distribution* Distribution Network Applications Functions (DNAF) include a Voltage Var Control (VVC) capability to provide recommendations on reactive power controls available on the distribution network to optimize distribution feeders (e.g. loss minimization or voltage profile follow-up). The VVC function can take into account all active and passive VAR support equipment including DG resources. Such control logic would be available at both individual control and grouped control levels. Active voltage control mitigates the voltage rise issue that can limit the extent of DG that can be connected.

An intermittent generation curtailment function is available. In Ireland, for example, some high wind and low load conditions lead to the need to curtail part of the wind production for network security reasons or congestion management. Curtailment instructions are kept and captured in an audit trail log to support settlement conditions. As noted above, if generation curtailment is applied, it is useful to have accurate real-time information on loads as well as generation.

Integration of DG may involve the ability to run a microgrid either in grid-connected or islanded mode. A microgrid consists of several loads (controllable or not), DG resources and distribution feeders, with the capability to balance the microgrid as an operating unit. Most present DNO policies do not allow islanded operation for such microgrids and require fast disconnection of DG in case of faults for safety and power quality issues. Some DNOs are developing capabilities for island operation, and an example of an islanding scheme at 60kV level implemented in Denmark is presented in [5].

Synchrophasor measurements provide a useful resource for generator curtailment, as illustrated in the example in the next section. The technology is also useful for microgrid management, as it can provide:

- Topology-independent identification of islanding (useful also for reliable loss-of-mains protection)
- Where islanding is permitted, synchrophasors can be used to identify whether the conditions exist for a viable island
- Resynchronisation can be managed using angle, frequency and voltage information from PMUs

In the near future, it is expected that the role of load participation in network management will increase significantly. This will provide new opportunities for co-ordinated generation and load management, both for more efficient use of the network for generation connections, and for stable operation of stand-alone microgrids. The latter will be made possible through a combination of advanced logic available locally (e.g. local agents responsible to fulfill goals of voltage support and frequency stability) and a global coordination at an upper level using the DMS.

Pro-active integration

Pro-active integration involves identifying potential problems introduced by the DG outputs, and providing information to respond to these threats. A suite of integrated applications (**e-terra***distribution* Distribution Network Applications Functions, DNAF) provides the following functions:

- **Security analysis**. This includes 3-phase loadflow calculations and security limit monitoring to ensure that the grid operates within the limits of power quality, voltage/VAR regulation, and operational standards as dictated by the regulatory codes.
- **Short-circuit analysis** to monitor fault current levels and check compatibility with the device calibration, including DG fault contribution
- **Fault Isolation and Restoration** to support outage restoration and feeder reconfiguration strategies taking account of DG as well as management of operational switching plans for personnel security
- **Simulator**. Studies and simulations of the network states in various load/generation conditions, with a seamless interface to DG forecast engines and powerful simulators. This supports operator training and network studies with realistic scenarios based on forecasted data

The new paradigm introduced by DG resources as well as storage and demand response calls for new tools to determine and optimize ancillary services. A new application for Look-Ahead dispatch aims at determining generation schedules and reserve contribution from wind generation assets aggregation with other DER assets (such as CHPs, storage devices, hydro plants) over various horizons (e.g.: from 1 hour / 5 minute resolution, to days ahead/1 hour resolution). New stochastic optimization models for developing short-term strategies to mitigate uncertainties resulting from the intermittent character of wind generation and coupling with storage devices can also be analyzed. These concepts are provided in a new function called Intra-day Plant and Storage Optimization (IPSO). IPSO provides an optimal strategy to balance wind power variations with storage in response to events like high wind, low load conditions.

CO-ORDINATING CENTRALISED AND DECENTRALISED CONTROL

In contrast with transmission system dispatch and control, where there is a relatively small number of large generation units to dispatch, distribution networks can have a very large number of small generation and load units. In view of the complexity, it is useful for autonomous controllers to manage individual schemes without operator intervention, and only the higher level supervision requires operator input.

As described above, the ‘connect and manage’ approach to DG connection is increasingly adopted, rather than the ‘fit and forget’ approach involving no network-dependent control. Thus, it will become the norm for network control schemes to be a part of DG connections. These schemes will tend to be autonomous local area controllers, operating independently from centralised logic. An example of an autonomous local area control based on synchrophasor measurement is given in the following section.

Although such schemes operate independently from the central DMS, it is important that the actions of the controllers are observable to the operators. The following aspects of control scheme operation should be co-ordinated with the DMS:

- **Controller Status**. The status of individual controllers includes the system health, whether the scheme is armed, and if it is actively curtailing.
- **Forecasting/Simulation**. The resource forecasting and network simulation tools should take account of network-based curtailment schemes.
- **Settlements**. The curtailment has commercial implications and it may be necessary for the activity of the controller to be available for auditing,

settlement and dispute resolution.
- **Manual control**. There may be conditions where the autonomous controller should be disabled, for example for network maintenance.

Since active distribution network management has not yet been widely adopted, many schemes are currently experimental and there is little standardisation. There is a challenge to provide consistent interfaces between autonomous area controllers and a DMS, however, it is seen as an important facet for widespread adoption of active network management schemes. In terms of synchrophasor-based solutions, there is transferrable experience in integrating application data between ALSTOM Grid's transmission EMS/SCADA platform and the Psymetrix wide-area monitoring infrastructure and applications.

EXAMPLES OF DECENTRALISED CONTROL USING SYNCHROPHASORS

Angle-Constrained Active Management

The angle difference between voltages at two locations reflects the changes in loading and generation between the measured points, as illustrated in Figure 2. A limiting high wind / low load scenario will produce a certain angle difference. Increasing load or decreasing generation will reduce the angle difference. An angle difference threshold can be identified which, if the generator output is controlled such that the angle is less than the threshold, will ensure that network limits are not violated. As a result, more DG capacity can be safely connected.

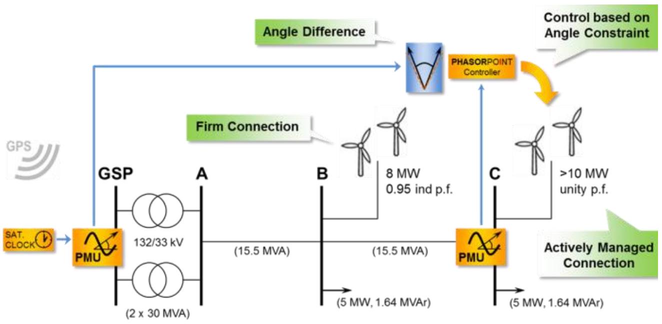

Figure 2 Angle constrained active management concept

This approach has a number of advantages over alternatives that involve measuring a constraint directly. In particular:
- The approach can be implemented with very few remote monitoring points – normally one for a radial network or two for a looped network.
- Various different network constraints can be addressed simultaneously, for example, if thermal limits, voltage rise or transformer reverse power constraints are binding in different conditions or locations, these can all be accommodated in a simple control mechanism.

The approach is considered in more detail in [6]. It may also be noted that the measurements required for the constraint application can also be used for identifying loss-of-mains more reliably than using local measurements (e.g. ROCOF).

This kind of scheme operates independently of the DMS, but should report its activity to the operators. The control mechanism can be integrated into network modelling and forecasting functions, given that angles are identified in the state estimator.

Dynamic Line Thermal Rating

It is well known that the physical thermal capability of an overhead line varies with temperature and wind. This is particularly relevant for wind generator connections because output is highest when the cooling effect of wind is highest. Various approaches are available to estimate the temperature or sag of the line, or use ambient weather data, and derive a less conservative thermal limit. There is a challenge 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 combined approach provides greater confidence.

Furthermore, the angle-based constraint management approach described above can readily be adapted to use a dynamic limit. The range of the thermal limit value can be incorporated into the angle threshold, thus further improving the effectiveness of the dynamic thermal constraint scheme.

CONCLUSION

The aggressive targets for DG connection require innovative technical solutions for managing the network. The developments outlined are intended to provide DNOs with practical facilities to manage the substantial changes in requirements for integrating and operating DG. Synchrophasor measurement and applications in control and monitoring are a valuable resource for a co-ordinated approach, complementing the DMS functionality.

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