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HubNet

The Supergen Energy Networks Hub

Issues for Distribution System Operation at 2030

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About HubNet

Hubnet is a consortium of researchers from eight universities (Imperial College and the universities of Bristol, Cardiff, Manchester, Nottingham, Southampton, Strathclyde and Warwick) tasked with coordinating research in energy networks in the UK. HubNet is funded by the Energy Programme of Research Councils UK under grant number EP/I013636/1.

This hub will provide research leadership in the field through the publication of in-depth position papers written by leaders in the field and the organisation of workshops and other mechanisms for the exchange of ideas between researchers and between researchers, industry and the public sector.

Hubnet also aims to spur the development of innovative solutions by sponsoring speculative research. The activities of the members of the hub will focus on seven areas that have been identified as key to the development of future energy networks:

- Design of smart grids, in particular the application of communication technologies to the operation of electricity networks and the harnessing of the demand-side for the control and optimisation of the power system.
- Development of a mega-grid that would link the UK's energy network to renewable energy sources off shore, across Europe and beyond.
- Research on how new materials (such as nano-composites, ceramic composites and graphene-based materials) can be used to design power equipment that are more efficient and more compact.
- Progress the use of power electronics in electricity systems though fundamental work on semiconductor materials and power converter design.
- Development of new techniques to study the interaction between multiple energy vectors and optimally coordinate the planning and operation of energy networks under uncertainty.
- Management of transition assets: while a significant amount of new network equipment will need to be installed in the coming decades, this new construction is dwarfed by the existing asset base.
- Energy storage: determining how and where storage brings value to operation of an electricity grid and determining technology-neutral specification targets for the development of grid scale energy storage.

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Issues for Distribution Grid Operation at 2030

This position paper is a response to the Terms of Reference produced by the Smart Grid Forum[1] entitled "Distribution Grid 2030: Validating the technical viability of smart distribution network scenarios for GB in 2030, in a whole system context". Those terms of reference call for a schedule of challenges for 2030 to be established as a first stage of a 5-stage programme of work which culminates in an engineering study of those challenges. Those further stages are the subject of work being commissioned by the electricity Networks Association on behalf of the Smart Grid Forum[2].

A meeting was held on 2nd April 2013 for members of the HubNet universities to discuss the questions raised in the terms of reference. This paper describes the outcome of discussions on the day and subsequent refinements offered.

The first draft was presented to the Smart Grid Forum WS7 and appears as an annex to the first report of WS7. As part of the WS7 process, further consideration was given to the grid modelling required to answer the questions raised in operating distribution systems at 2030. In a meeting on 18th September 2013, a small group drafted the approach of modelling that has been appended to this paper. The paper has then been reviewed and refined in the light of the comments received.

Although the focus here is on distribution grid operation, the context is the distribution grid as a part of a whole system run in a smart fashion where resources in any part of the system (transmission, distribution, generation and load) can be expected to contribute to solving problems anywhere else. With that in mind, all of the operational challenges faced by the whole system are in scope because the distribution grid can have a role in facing those challenges or being a conduit for others when facing those challenges.

Our grouping of the challenges is:

1. Active power balancing and frequency control; in this context focused on relatively short term issues (seconds to minutes) in which frequency response and reserve are sought, as well as contribution to system inertia.

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[1] https://www.ofgem.gov.uk/electricity/distribution-networks/forums-seminars-and-working-

[2] http://www.energynetworks.org/modx/assets/files/news/consultation-responses/Consultation%20responses%202013/SGF_WS7_RFI_%20251113_DSv1.pdf

2. Voltage control; in this context voltage control within the distribution network and at the meter, but also distribution grid participation in voltage control at transmission level.
3. Constraint management; in this context a more heavily stressed distribution grid is expected at 2030 where thermal, voltage and fault current constraints arise in operational time frames and need management. Where these are voltage constraints there is a coupling to issues in 2. Where these are active power flow constraints there may be a coupling to 1.
4. Transient, dynamic and fault events; in this context focused on the presence of distributed and micro generation and power electronic equipment, and the greater use of meshing.

5. Resilience and risk profile; in this context a question of understanding how the risk profile of a grid changes when smart technologies have been used to increase asset utilisation in place of traditional reinforcement and how resilient the grid is to a wide range of contingencies.
6. Quality of Supply; both in terms of power quality and supply interruption.

The first three of these challenges could be described as normal operation (and largely steady-state) and the next two are abnormal operation (and dynamic effects) and the final one addresses the quality of the supply provided to customers.

We also recognise that one needs both technical measures and commercial arrangements for meeting these challenges. The approach to be taken here is to consider how one would meet the challenges if a single vertically integrated utility was in place (and sometimes described as a system run by a benign dictator) in order to find the solution that is most effective and then one can turn ones attention to finding the commercial and regulatory framework that approaches that solution sufficiently closely.

In what follows, we sometimes refer to a Distribution System Operator (DSO) as an organisation with an expanded role beyond that of a Distribution Network Operator (DNO) without at this stage seeking to define the extent and form of that extended role.

1 Description of Challenges

1.1 Power/Frequency Control Challenge

It is anticipated that the 2030 system will have a generation fleet with a proportion of inflexible generation plant that cannot (at least not economically) provide reserve and response services to control frequency and cover for contingencies. This is expected to be particular challenging on windy summer nights when total demand could be met entirely by “must run” inflexible generation but where some of that would need to be constrained-off in order to run part-load thermal synchronous plant to provide reserve and response. This gives the economic case for seeking reserve and response services from non-traditional resources located in distribution grids.

The frequency control problem can be treated in two stages. The first is to assess control efficacy assuming there are no network flow constraints (sometimes referred to as a single-bus system since line flows are not a concern and network connections need not be modelled). The second stage is then to assess control efficacy when network constraints apply (meaning some resources might not be accessible or may be committed to solving constraint problems and unavailable for frequency service).

Issues of concern are:

- The need for (and extent of) visibility to the system operator of both the reserve and response resources and the characteristic of the loads of the system in terms of inherent response to frequency.
    - Resources smaller than the current Balancing Mechanism (BM) threshold need to be visible (through a changed threshold and/or the use of aggregation) and the number of individual units could be very high.
    - Unconventional resources need to be modelled (response rates, contribution to inertia, energy payback), particularly active demand-side devices but also the low carbon generation technologies.
    - Changes in technology of non-active loads need to be modelled (variable speed motors in place of direct-on-line motors; growth of constant power electronic loads immune to voltage variation, new heat pump and electric vehicle loads), all assessed in terms of impact on system inertia.
    - Micro-grid operation of some network areas (AC or DC) in which the generation and load responses are managed by some local agent.
- The need for (and extent of) visibility of renewable generation characteristics notably fast ramp-rate events.
- The data communication and processing requirement to enable sufficient visibility.
- The assessment of how much inertia, response and reserve service is needed. This will include consideration of how natural system inertia has reduced by displacement of synchronous plant.
- The assessment of how much inertia (synthetic and real) is needed.

Some of these concerns will rest predominantly with the Transmission System Operator (TSO) with its lead responsibility for frequency control but many of the new resources and changed generation and load technologies are distribution-connected and have a connection relationship with the DSO.

It is noted that in the no-network-constraints (single-bus) case, demand and renewable generation modelling and prediction (at least over the timescales envisaged here) is eased by the aggregation of large numbers of actors and the geographical diversity removing the effects of localised wind gusting and cloud shadowing.

When turning to a network with constraints (voltage constraints in semi-rural distribution grids, thermal in urban grids and transmission constraints of various forms) further challenges arise:

- The need for (and extent of) visibility of constraints
    - Real-time modelling or measurement of constraints (including cyclic ratings and dynamic ratings and ratings of old assets)
    - Understanding of which services, not just which flows, are subject to a particular constraint.
    - Fine-grained (feeder level) modelling/measurement of demand and distributed/micro generation. This might include real-time load modelling to account for changing characteristic of a small service area over the course of a day.

It is recognised that demand of small numbers of customers or of generation subject to, for instance, localised cloud shadow movement, is necessarily subject to higher volatility than aggregate national-scale demand and generation and the prediction task more challenging and reliant on a richer set of data.

1.2 Voltage Control Challenge

The expectation is that demand growth (through electrification of building heating and private transport) and clustering of PV installation will lead to voltage constraints on distribution networks. It is also recognised that resources in distribution networks may be called on to assist voltage control in transmission networks.

Challenges are:

- Ensuring sufficient coordination between localised control actions to ensure a good (and stable) overall voltage condition. There is an unfinished debate on the merits of centralised versus decentralised control. However, it is clear that the control of various actors must be coherent and approach the optimal solution.
- The re-dispatch of active power flow to combat voltage problems in low *X:R* feeders interacting with power/frequency and thermal constraint problems.
- Ensuring voltage control coordination (and proper protection operation) if/when a greater degree of meshing (in previously radial networks) is used for voltage control.
- Ensuring coordination of transmission (T) and distribution (D) actions (for instance, use of transformer switching to change reactive power consumption in D network to aid T network).
- Ensuring coordination between varying voltage to influence demand (as a means of achieving demand response) and varying demand to influence voltage (as a demand service in voltage control).
- Ensuring unbalanced phase load does not prematurely cause voltage excursion on a particular phase.

- Consideration of incorporation of control of DC networks where and when they emerge.

1.3 Constraint Management Challenge

Planning of capacity in distribution networks has sought to ensure that even under worst-case conditions the network is not subject to operational constraints. This is sometimes characterised as "fit and forget" since at the time of fitting (a distributed generator for instance) sufficient capacity is provided to ensure unconstrained operation in normal conditions (but perhaps subject to inter-tripping in contingencies). Making more intensive use of network assets in part relies on releasing capacity at some times by applying constraints at others. This can involve use of resources located in distribution networks to relieve transmission constraints (such as reducing demand in southern GB to relieve constraints in the north-south transmission corridors).

Challenges are:

- Visibility of resource for constraint management
- Verification of constrained demand or generation operation such that network constraint is met with confidence.
- Management of conflicting use of resource such as need to constrain-off PV (or constrain-on some load) to manage voltage on an LV feeder conflicting with need to reduce demand or increase generation in order to respond to a frequency drop.

There is a feeling that moving from fit-and-forget to an active constraint management system may happen in a step-by-step fashion; possibly working down the voltage levels but possibly not if voltage constraints become significant in LV feeders first.

1.4 Challenges in transient, dynamic and fault events

At this stage, the greatest challenge was seen in increasing the sophistication of protection systems in distribution grids to ensure proper clearance of faults and continued operation of demand and generation post-fault in the 2030 context. The greater use of distributed and micro generation, network reconfiguration strategies and the possible use of meshing in distribution challenge the present protection regime. Protection challenges are:

- Avoidance of difficulties of loss-of-mains (LOM) protection (perhaps through obviating LOM protection by changes in working practice or pursuing alternatives to LOM or communication-based solutions).
- Operation of distance and unit protection in distribution grids (for instance on short, low-impedance feeders and with arc voltages relative to feeder voltage).
- Arranging protection and fault location for network with topology changes and mixed cable/line transmission corridors. Further innovations in protection to accommodate emergence of DC networks.

- Visibility of fault current capability given the highly changeable nature of demand and generation on a feeder and the power electronic interfaces of much of that equipment.
- Emergence of new protection technology and integration of protection and control solutions.

Transient and dynamic stability were considered a lower level concern that could follow the challenges discussed so far. However, work to understand how they would be assessed in future distribution networks in needed.

1.5 Resilience and Risk Profile

Recognised as very important but insufficiently discussed by this group so far although it is clear that understanding the risk profile of unconventional demand and generation (and what needs to be measured by a network operator to model this) is important. A further issue is developing an understanding of the failure modes of new control technologies including supporting technologies such as state-estimation.

As an extension of this topic, consideration will need to be given to how validation tests are conducted including the roles of simulation models, hardware-in-the-loop testing, demonstration networks and live testing in progressing validation.

1.6 Quality of Supply and Network Efficiency

Quality of supply includes many issues. Some are grouped under the term power quality and assess how close the supplied voltage is to the specified supply condition when it is present. Aspects such as the voltage and current remaining in tolerance are addressed above but other aspects of power quality concern items such as harmonic distortion and high frequency distortion. Harmonic distortion is a feature of line-frequency switched (diode or thyristor) rectifiers. In large measure, the extent of this problem is controlled by product standards such as EN 61000 restricting the harmonic emission (in the range up to 2 kHz) of individual items of consumer equipment. New network equipment would be expected to comply with similar standards. The use of switch-mode power electronics with modulated switching typically in the 5-20 kHz range has largely been able to avoid low order harmonic distortion. However, there is concern that emission across the 2 – 150 kHz band are not controlled by product standards and the cumulative effect of many items of equipment could lead to sufficient waveform distortion to cause mal-operation of other equipment. This would appear to be a potential problem worthy of revisiting. There may be some risk of increased flicker (rapid variations in voltage magnitude) from some types of intermittent generation or control interactions.

On top of the quality of power when delivered we also have the quality in terms of the availability of the supply measure by interruption rates and time spent off supply (Customer Interruptions, CIs and Customer Minutes Lost, CMLs as presently defined for UK DNOs). This issue adds the effectiveness of redundancy provision, restoration strategy and other post-fault measures in retaining or returning supply. Restoration times have been reduced in recent years by increasing the number of tele-operated switching points in distribution networks and refining the post-fault restoration scripts to deal with a wide range of operating and fault conditions. The move to more meshed networks and more sophisticated network operation can aid in reducing restoration times and occurrence of non-restortion but both can also increase system complexity and the occurrence of unforeseen combinations of conditions.

The various aspects of supply quality can be measured by suitable smart meters and one might expect a much more comprehensive reporting of occurrences of poor power quality and of interruptions through which a better understanding of the problems can be gained.

At present distribution networks have power losses in the range 3-9% depending on their local characteristics (feeder lengths and loadings etc) and this accounts for 80% of the power lost in the combined transmission and distribution network. A more heavily utilised set of primary assets as anticipated for the distribution network of 2030 would be expected to have higher losses (dominated as they are by I^2R terms). This needs to be recognised and quantified. There may be some scope for mitigation of a portion of the increased losses by optimisation of asset use and capacity sharing through greater meshing and reduction of peak loads by demand side action and reduction of imbalance through compensation devices (since serving unbalanced loads causes greater ohmic power losses than the equivalent balanced load).

2 Approach to Modelling

The main thrust of the modelling strategy is to use sufficiently representative network models to provide insight into whether the technologies expected to be implemented by a DSO in 2030 will work together to proper effect and without unintended consequences. "Sufficiently representative" is meant to mean enough detail and variations to cover the expected ground but without modelling so much detail that the volume of data obscures the salient features. It is not expected that a single all-studies model will be used. Instead different models and simulation tools will be used to answer different questions because the temporal and spatial reach of the various phenomena under study are different. As far as possible, established commercial software should be used so that results can be readily verified. Possible software packages would include PowerFactory, PSS/E, IPSA, PSCAD, SimPower Systems. Forms of analysis include load flow (balanced and unbalanced), sequential load flow, time-step transient analysis (electro-mechanical and electro-magnetic), fault current calculation, harmonic load flow and reliability anlaysis. In general, there is a need to check that in steady-state there is the expected capacity released by deployment of the solutions indicated by the Transform Model[3] (that was

[3] http://www.energynetworks.org/modx/assets/files/electricity/engineering/SGF%20Seminar%20event%20141013.pdf

developed by EA Technology on behalf of Work Stream 3 of the Smart Grid Forum) and then check that the transients experienced when controlling the new technologies are well-conditioned. A major extension over many traditional power system models will be the inclusion of a communication system over which control actions or feedback are sent.

It is also recognized that the issues raised in Section 1 cover a lot of ground and that each can be pursued to varying depths resulting in a mixture of studies to perform that are variously "essential", "nice-to-have" and "open-research-question". Further, some questions are clearly in the realm of "will the technologies work together?" and some are "what are the implications of these technologies for the wider DSO consideration?".

Because the questions to be addressed concern operation of a distribution system facing new demand and generation (and storage) connections, it is necessary to develop a number of scenarios covering the extremes of possible uptakes of various low carbon technologies within the DSO and covering the mix of generation technologies that are transmission-connected.

For distribution network modelling, it is expected that the principles used by the UKGDS (UK Generic Distribution System) models will be followed, namely, that there are a small number of example networks types covering:

- high-density urban, urban, semi-urban and rural load densities and distances
- overhead line and cable networks
- voltage level
- radial and meshed/interconnected

In particular, coverage of LV feeders needs to be extended and unbalanced examples covered.

Experience from the development of Transform Model in representing future networks should be built upon.

Increasing the degree of meshing is a network enhancement that may be expected by 2030 and so special attention needs to be paid to modelling new forms of meshing in terms of the voltage levels which are meshed, the protection of meshed networks and how the new mesh connections are achieved.

Several new technologies will need to be characterized and represented within the standard software and analysis techniques. This includes the control behaviour of elements also. Examples include models of converter-interfaced generation, constant-power or controlled power loads (EV chargers, heat pumps, modulated water heaters etc.), fault current limiters, and distribution FACTS. Developing models of some of these in commercial software that has not yet explicitly accommodated them may involve a lot of effort. Furthermore, the choice of any one control approach for a given smart grid technology will need to be justified. There may well be several established and further emerging control approaches for a given smart grid technology and each one is likely to result in different results in the modelling work, especially in the transient studies.

The discussion of modelling in the SGF WS7 was structured around the set of questions defined by WS7 which are ordered differently to the issued raised here in Section 1. In the table that follows, the discussion has been restructured to follow Section 1 with an additional category of waveform quality.

	Issue	Modelling Requirements	Data Requirements
1	*Adequacy of power balancing and frequency.*	• First-cut study to assume no network constraints and examine “single-bus” model. • Electro-mechanical transient programme (commercial software) • Apply generation loss and load rejection contingencies and assess frequency excursions • Second-cut study examines reduction in frequency response from units subject to constraint. • Model of transmission network and scaled representation of distribution networks with loading levels such that constraints apply.	For first-cut • Inertia estimates for each transmission-connected generation for chosen scenarios • Inertia estimates for each distribution connected generation for chosen scenarios and representation of frequency response signal (local measurement means) • Characterization of “synthetic inertia” of non-conventional generation and load. • Scenario data for combinations of generation for example operating points (e.g. high-wind, low-load) • Characterization of reserve holding by transmission operator For second-cut • Reduced dynamic mode of transmission (such as recent National Grid release of 29-bus model) • Representative distribution network fragments (scaled to give sufficient load) attached to transmission nodes. • Load scenarios so that constraints make some resources unavailable
2	*Adequacy of Voltage Control Strategy*	• Load flow analysis (available or modified commercial software) • Need to incorporate non-linear behaviour of new loads and generation.	• Need representative, not exhaustive, distribution network models at LV and at various voltage levels. • Use 5-10 sample days across the year with a resolution of about 10mins for load flow and fault.

			• Use short-duration, high-resolution simulation for sequencing verification. • Load and generation data. • Estimates of fraction of deferrable and avoidable load and generation. • Load and generation response services assumed available based on social good (aka benign dictator), i.e. market mechanism assumed ideal for technical study. • Representation of actions of new technologies. • Representation of loads or generation committed and called-up for other services (e.g. reserve or thermal constraint management). • Representation of voltage actions of all new technologies including specifically the voltage dependence of load power of new forms of consumer equipment (such as constant power electronic loads).
3	*Adequacy of Thermal Constraint Management*	• Load flow analysis as main tool. Commercial software available.	• Requirements broadly similar to consideration of voltage control. • Need representative, not exhaustive, distribution network models at LV and at various voltage levels. • Use 5-10 sample days across the year with a resolution of about 10mins for load flow and fault. • Use short-duration, high-resolution simulation for sequencing verification. • Load and generation data. • Estimates of fraction of deferrable and avoidable load and generation. • Load and generation

			response services assumed available based on social good (aka benign dictator), i.e. market mechanism assumed ideal for technical study. • Representation of actions of new technologies. • Representation of loads or generation committed and called-up for other services (e.g. reserve or voltage). •
4	*Assurance of Fault Current Level, Transient Stability and Protection Effectiveness*	• Fault current calculator nad fault flow studies • Electro-mechanical transients analysis and electro-magnetic transients analysis (EMTDC) required for checking that sequencing of events is well conditioned. • Simulation of established over-current protection. (commercial software) • For cases where over-current is not sufficient, established transmission-style protection, e.g. distance protection. (expected to still be in the scope of commercial software) • For cases where transmission-style protection not sufficient, alternative relays e.g. sequence set and dv/dt detection to be explored (may require extensions to relay representation in commercial software)	• Representation of actions of all new technologies in terms of fault current and dynamic model, paying particular attention to those with power electronic interfaces. Inclusion of case study of feeders rich in both high and low fault current .

5	*Maintenance of Acceptable Resilience and Risk Profile.*	• Reliability analysis of the type described in Reliability evaluation of power systems, Roy Billington and Ronald N. Allan applied to radial and meshed networks (commercial software – perhaps – meshed distribution maybe be a challenge in commercial software) • Sensitivity analysis of the characteristic of Transform technologies • Include failure modes of communication links and control (modelling software needs investigation) • Assessment of reliability with all equipment in normal state and in degraded state after response to first failure.	• Failure modes and probabilities of established network equipment • Failure modes and MTBF of all Transform technologies, including ➢ power electronic devices ➢ communication links • Representation of traditional radial, existing meshed and new meshed networks.
5	*Maintenance of acceptable waveform quality.*	• Harmonic load flow analysis. • EMTDC analysis (commercial software). • Run simulations over 10 seconds or less of steady state • Check low order harmonic amplitudes (1-40) against standards • Check band of typical power electronic switching frequencies for possible interference with consumer equipment. • Run simulations over 10 second of sequence	• Harmonic frequency models of feeder and transformers • Models of harmonic sources such as non-linear loads, generation and Transform technologies • Models of HF emissions from switch-mode equipment. • Possible inclusion of active power filter modes of DSO power electronics (e.g. D-STATCOM)

		actions. • Check for sag/swell and flicker	

3 Conclusions

This position paper has set out our view of the issues that need to be studied when considering whether proposed operating regimes, control systems and asset technologies will combine together to create a distribution system in 2030 that will be effective and reliable in meeting our low carbon and smart grid aspirations. It is intended as a checklist of the types of studies that should be performed in both academic and commercial work and an indication of the modelling approach required.