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Modelling and Software Platforms for Extensive Power System Studies of Distribution Networks with Low Carbon Technologies and Smart Solutions

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About this report

The Institution of Engineering and Technology was commissioned by the Council of Science and Technology (CST) to research the emerging challenges for modelling electricity systems and how Britain's capabilities would need to be adapted to assess electricity system resilience as GB makes the transition to a low carbon electricity system.

This project commissioned, and received, fifteen individual papers from GB-based specialists of international standing in power system modelling. The authors of the papers worked with a wide stakeholder base of network companies, academics and others, who provided review and challenge. Professor Graham Ault CEng FIET was contracted to provide technical co-ordination and drafting. The emerging conclusions were further validated by means of an industry and academic workshop sponsored by Government Office for Science. The entire project was conducted under the direction of an independent steering committee composed of senior IET Fellows, two of whom were also CST nominees.

The report is composed of three parts:

■ Part 1: Main report

■ Part 2: Summary of Commissioned Papers

■ Part 3: IET Special Interest Publication – Academic & Industry Papers

All three parts of this report are available from the IET website at:

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EXECUTIVE SUMMARY

The paper presents software, input data and modelling aspects of the recently initiated project 'Study into the 2030 Distribution System'. The main objectives are evaluation of input data and modelling requirements and capabilities for studying future distribution networks, identification of gaps in existing modelling capabilities and currently available input data, critical assessment of the role of distribution network owners and impact on the GB power system performance and security. Modelling of future distribution networks requires integration of low carbon technologies, such as solar and wind generation, electric vehicle and heat pump demands, energy storage, etc., as well as 'smart' network solutions including demand side management and response, new voltage control concepts, power electronics controllers, dynamic network reconfigurations, network meshing, etc. A number of power system studies, namely load flow, optimum power flow, fault/short-circuit, frequency response and system balancing, reliability, dynamics, power quality and protection analyses will need to be applied by future distribution companies in order to assess technical feasibility of the envisaged network solutions.

Several input data and modelling gaps are identified in this paper. Sequential load flow studies with annual load and demand profiles will need to be applied. It is highly desirable to have (single-stage) optimum power flow model with appropriate objective functions and/or security constraints, multi-stage load flow and/or optimum power flow models, network reconfiguration and restoration functions, much improved reliability engine, all with the models of new low carbon technologies and some of 'smart' solutions. Existing graphical information systems should be amended with basic power system analysis tools in order to study low voltage networks within planning stages. Fault analysis should be done in accordance with the UK engineering recommendations, taking into account fault contributions and models of low carbon technologies.

Frequency response, angle and voltage stability studies will require dynamic models of existing and new controllers, as well as of new low carbon technologies and some of 'smart' solutions. Study of very fast electromagnetic transients should be performed on networks with power converters. Assessment of network reliability should be done using the sequential Monte Carlo approach instead of currently available enumeration and explicit methods. To find total harmonic distortions, measurements of background harmonic injections and harmonic injections of new devices are required. New protection schemes, which can cope with bi-directional flows, distribution network meshing, new protection grading, etc., need to be developed.

The first recommendation suggests that distribution network companies could take part in restoration of system-wide emergency operating regimes. Hierarchical control principles between the National Grid and distribution control centres will need to be established and relevant data exchange specified and initiated. Distribution companies could also participate in other auxiliary service markets, which would require exchange of additional data. They should have modern distribution management systems in control centres that will support their role in providing the GB system stability and security. The distribution management systems should have databases of all static and dynamic data required for control, operational and development planning of future networks. In that respect, distribution companies should establish and initiate internal processes for collection of the required data. It is also recommended to have a single software platform to model all network voltage levels other than low-voltage, which would capture demand and generation profiles from the real-time measurement database. The low-voltage networks can be entered into the distribution management system for control purposes, whilst existing graphical information systems can be amended with power systems analysis engines to do the network planning.

Next, distribution companies should be encouraged to provide adequate measuring and communication of real-time data into control centres, in particular, from distribution substations, in order to increase observability of the networks and avoid sometimes spurious allocation of the feeder demands to these substations. Finally, distribution companies should go for the unification of diverse software platforms, network data cleansing and training of staff to be able to cope with forthcoming challenges.

1. BACKGROUND

The Smart Grid Forum Work Stream 3 (SGF WS3) had tasked Electricity Association Technology (EATL) to develop a comprehensive distribution network *economic* model that would offer various types of 'smart' solutions to emerging low carbon technologies (LCTs), instead of applying conventional installation solutions (e.g. reinforcement, replacement and construction). The economic model would be used by all UK distribution network owners (DNOs) in their first 'Revenue, Incentive, Innovation & Outputs – Electricity Distribution' (RIIO-ED1) price control submission. EATL has completed the project and come up with the 'Transform' model [1, 2], which gives various combinations of 'smart' solutions and their costs related to different uptake levels of new LCTs. The network solutions and costs are classified by voltage levels.

The SGF Work Stream 7 (SGF WS7) has recently initiated a 'smart' network project, that would be based on the full nodal modelling of distribution networks and application of various power system studies [3]. The main objectives of the SGF WS7 project are assessing the technical feasibility of 'Transform' 'smart' solutions applied to representative real-life networks and identifying software, input data and modelling requirements that the future DNOs are faced with. The project 'Study into the Distribution System 2030' was awarded in June 2014 to the consortium comprising 'Parsons Brinckerhoff', 'The University of Manchester', 'Power Planning Associates', 'Chiltern Power' and 'Grid Scientific'.

The project consists of five work packages [3]. Work package A has responsibility for overall project and risk management and dissemination of results. Work package B considers modelling tools and techniques, more specifically, reviewing and proposing software platform(s) to enable required modelling, network and other input data flows, and development of modelling use cases. Work package C is responsible for in-detail specification of base representative distribution network models including Liverpool and London urban areas, and their further development until 2030. Development of demand and generation profiles for existing types and new LCTs and their integration into the network models is done in work package D. Finally, work package E is responsible for full scale modelling and power system analyses of all previously developed distribution networks, including reporting on results, findings and conclusions.

More details about the project requirements are given in [3] in the form of questions that need to be answered. The questions are classified into 'network challenges', 'whole system challenges', 'active customers' and 'additional questions'. The first two categories consider distribution network and whole system technical aspects using the load flow, fault/short-circuit, frequency response & system balancing, reliability, dynamics, power quality and protection studies. The third category deals with qualitative aspects of the optimum level of customer response, risk on over-reliance on customer response, development of 'intelligent' loads, specification of requirements for customer response and impact of active management combined with customer response on distribution networks. The additional questions consider ICT, design standards, risk & complexity, current practices that can constraint future development and impact of power converters.

The main deliverables are project reports and fully populated distribution network models stored in the proposed software platform database. They will be made available to wider industry, consultants, research institutes and academia.

2. POWER SYSTEM MODELLING REQUIREMENTS AND CAPABILITIES

The recently commissioned project 'Study into the 2030 Distribution System' considers development and analysis of 'smart' distribution networks from 2014 until 2030 with new low carbon technologies (LCTs) and 'smart' solutions applied. The modelled networks will encompass National Grid (NG) reduced transmission network [4] and a representative distribution network consisting of 'typical' distribution voltage levels, e.g. 132kV, 33kV, 11kV, 6.6kV and 0.4kV. A representative distribution network will be connected in turn to several pre-specified 400kV nodes in the reduced NG network and sensitivity analyses will show impact on the whole system. Some of the whole system aspects, which will be studied, are:

- Whole system balancing and frequency response is a crucial element for deciding whether distribution network owners (DNOs) could become distribution system operators (DSOs). The NG reduced transmission network will be used for this purpose and DNO equivalent demands will be replaced with several new objects: equivalent distributed generator (DG) with frequency response characteristics [5], demand side management (DSM) load which can be curtailed [6], demand side response (DSR) load which might contribute to load reduction (stochastic in nature) [7] and an unmanaged load.

- Impact of the large scale penetration of distributed generation (DG), such as solar and wind, connected at different voltage levels, on the thermal capacities, voltage – reactive powers and stability of the transmission network. Of particular interest are winter peak regimes when spare transmission capacities can be created, as well as summer minimum regimes whereby already present excessive transmission voltages can be further increased [8].

- Impact of new demands, such as, electric vehicles (EVs) and heat pumps (HPs) on the transmission network. Different EV charging patterns and profiles will be modelled at the 11(6.6)kV and 0.4kV voltage levels and new annual half-hourly load profiles will be suggested. The impact of air- and ground-source pumps will be assessed in a similar way.

- Impact of energy storage, DSM and DSR will be further investigated at all distribution voltage levels. They will be modelled in a simplified way when assessing the whole system aspects.

A brief description of the representative network models with demand and generation scenarios and developed 2030 study cases, chosen software platform and input data, system studies and modelling requirements, as well as the critical assessment of the identified modelling gaps are presented below.

2.1 Network Models, Scenarios and Study Cases

Evolution of representative distribution networks from present until 2030 will be done using the decision tree concept, which was applied to transmission expansion planning [9]. The decision tree origin will consist of four *initial* 'representative' networks, more specifically [10]:

1. 'Urban' distribution network that models 'typical' suburban areas and comprises 132kV, 33kV, 6.6kV and 0.4kV voltage levels. The considered networks will be either transformer – feeders at 132kV and 33kV, or radial feeders at 6.6kV and 0.4kV.

2. 'Rural' distribution network represents a 'typical' rural area, where both 132kV and 33kV networks are of mesh – ring type, whilst 11kV and 0.4kV networks are radial feeders.

3. 'Urban SP Manweb' network, characterised by highly meshed 132kV, 33kV, 11kV and 0.4kV networks, which are run solid (except for 0.4kV).

4. 'Urban UKPN London' network that comprises 'radial' 132kV and 33kV networks, as well as interconnected 11kV (e.g. half-rings) and 0.4kV networks.

The representative network models are then populated with two DECC scenarios for new LCTs in order to define the amount and type of future (new) load and generation [11, 12, 13]:

- DECC High Scenario [11, 12] with high penetration of EVs and heat pumps HPs, low penetration of solar and wind distributed generation, and NG Gone Green scenario for transmission connected generation [13].

- DECC Medium Scenario [11, 12] with low penetration of EVs and HPs, central penetration of solar and wind DG and NG Gone Green scenario for centrally dispatched generation [13].

The future load and generation predictions on national level need to be further disaggregated to individual network nodes. The methodology developed by Element Energy [14] and incorporated into the 'Transform' model [15] may be used.

After having obtained network models with the predicted uptake of new LCTs, the final distribution system models in intermediate years and 2030 are established by adding 'smart' solutions, such as:

- Centralised and local direct DSM, customers under interruptible contracts, DSR to dual, critical peak and time-of-day prices, as well as generation constraint management.

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- On-network voltage regulators, mechanically/electronically switched compensation devices (e.g. STATCOMs), distribution flexible AC transmission systems (D-FACTS), fault current limiters, energy storage devices, automatic tap-changers on distribution transformers.

- Permanent and temporary meshing of networks, enhanced voltage control concepts, dynamic network reconfiguration, dynamic thermal ratings.

The distribution systems so obtained in 2030 represent the *basic* study cases. Various sensitivity cases will be developed 'around' each basic study case by defining sensitivity parameters (e.g. penetration level of a new LCT, arrangement of network normally open points, level of voltage – reactive power compensation, failure rate data, etc.) and their permissible ranges. A set of power system studies will then be applied to each basic study case and its sensitivity variants.

2.2 Software Platform and Input Data

All initial representative network models will be derived from the real distribution systems and *network data* will be obtained from the relevant DNOs. The UK DNOs' network models are stored in different power system analysis software tools and they are often classified by voltage levels:

- 132kV and 33kV: DIgSILENT [16], IPSA+ [17] and PSS/E [18].

- 11kV and 6.6kV: DINIS [19], DIgSILENT, IPSA+ and GROND [20].

- 0.4kV: GIS – based, DINIS and WinDEBUT [21].

Modelling of all voltage levels of the distribution networks will be done in the DIgSILENT software tool [16] for the following reasons:

- 'Four – wire' network models can be entered and three-phase power flows studied. This feature will be used for the 0.4kV voltage level to find power flows and voltage unbalances.

- Reliability analysis is based either on the explicit model for distribution networks [22], or on the state numeration approach [22], which is a general method that can be applied to both meshed and radial networks.

- Co-ordination of multiple controls by finding 'appropriate' set-point values can be done with the aid of the optimum power flow (OPF) model. The OPF will be used to study some of the proposed 'smart' solutions.

- Analysis of power quality can be done using the harmonic power flow and impedance scan.

- Both electromagnetic (very fast) and electromechanical (slower) transient processes can be simulated. Detailed dynamic models of power electronic converters can be integrated into the network models and very fast and slower transients calculated in a single run.

- There are models of various power system components including new LCTs, for example: different types of DFIGs and solar plants, static generator model for fully converted machines, several load models including specialised low-voltage load models, AC voltage and current sources for modelling of unified power flow converters (UPFCs), booster and three-winding transformers, various shunt and series compensation devices, components for coupling DC networks, diverse switching devices, etc.

The input data flow is briefly outlined below:

- Network data from different software tools need to be entered into the DIgSILENT software:

  ○ PSS/E and IPSA+ models can be input directly into the DIgSILENT.

  ○ DINIS data need to be input into the IPSA+ first and then input (possibly via PSS/E) into the DIgSILENT.

  ○ Some of GIS systems have connectivity tables in the databases, which can be used for 0.4kV network models. However, data extraction software with extensive data cleansing needs to be developed.

- Demand and generation data on new LCTs will be imported from Excel spreadsheets into the DIgSILENT network models. One-to-one mapping between network nodes in DIgSILENT and new LCTs will be specified and appropriate objects (e.g. new types of DG, loads, etc.) entered into the DIgSILENT network models.

- 'Smart' network solutions will be entered directly into the DIgSILENT network models.

2.3 Power System Studies

All power systems studies will be done in the DIgSILENT power system analysis tool; the main features are briefly discussed below.

Load Flow Study

The three-phase load flow will be used to study each distribution system including the NG reduced transmission network model.

The 0.4kV networks will be modelled using the four-wire model with *single-phase* connection of individual houses - loads, whilst 11kV single-phase circuits in rural areas will also be modelled. The rest of network will be considered as balanced, symmetrical system and represented with a single-line diagram, although the three-phase load flow will be executed in the background.

The DIgSILENT scripting tool will be used to develop *sequential* three-phase load flow that would account for half-hourly profiles of different types of demand, generation, storage and DSM/DSR. The load flow studies will be used to assess power equipment thermal limits, voltage regulation, losses, active power – frequency balancing in quasi steady-states, and possibly optimised steady-states with co-ordinated controls. Feeder load balancing will be applied on 11(6.6)kV circuits, and coincidence of low-voltage loads on the 0.4kV level. A unique approach needs to be specified for thermal ratings because DNOs tend to use different ratings in their (intact network and contingency) studies. For example, cyclic and/or distribution ratings can be used for 11(6.6)kV cables [23], long-term emergency ratings for transformers [24], continuous ratings for newly connected generators, etc. Voltage regulation will consider automatic tap adjustment on double-transformer substations including line drop compensation, automatic shunt compensation adjustment (SVC, STATCOM), voltage control on new types of DG, DSM/DSR and generation constraint management, new power electronic devices, etc. Whole system balancing will be done for quasi steady-states immediately after a disturbance (based on generator inertias), and following primary and secondary P-f control. Co-ordination of several (voltage) control devices can be done using the OPF with an 'appropriate' objective function. An alternative is application of full AC sensitivity analysis [25] which would require substantial scripting effort.

Several models of solar and wind DG are available in DIgSILENT [16]. 'Static generator' model can be used for this purpose in load flow studies. EVs and HPs will be modelled as static loads and induction motors, respectively. However, models of different types of energy storage (e.g. pumped hydro storage, flywheel, compressed air, battery, magnetic energy, super capacitor, etc.) are not available. Simple generator (storage production) and demand (storage consumption) will be used instead. Similarly, different types of DSM and DSR will be modelled as 'appropriately' constrained static generators.

Fault/Short Circuit Study

The DIgSILENT tool supports several fault calculation methods, such as 'VDE0102', 'IEC 60909', 'IEC 61363', 'ANSI' and 'Complete' [16], but there is no British 'G74' standard [26]. It is likely that 'IEC 60909' and 'Complete' methods will be selected in order to find 'make' and 'brake' fault levels and their temporal variations.

Short circuit results will be used to check make/break capabilities of circuit breakers and to derive protection settings. Where circuit breaker break duty is inadequate, either its replacement or a 'smart' solution (e.g. fault current limiter, network rearrangement, generation disconnection, etc.) will be proposed. Short circuits are usually placed at 'nodes of interest' to find fault levels; however, they can also be placed on pre-selected network locations (particularly 11kV and 6.6kV feeders) to validate whether switches are adequately sized.

Power system component modelling for short-circuit studies is adequate in DIgSILENT. Detailed (dynamic) models of synchronous and induction machines, various types of directly connected DFIGs, NEC/NER and common impedance for transformer earthing (unbalanced faults) can be directly used. Where the 'Static Generator' model is applied for power converter connected generation, no fault level contribution is provided, as it is assumed that this is the worst case scenario. The motor fault level contribution from general loads needs to be modelled using the 'DIgSILENT Method', whilst 'G74' approach cannot be applied.

Frequency Control and Whole System Balancing

This study is probably the most important from the whole system perspective. Its objectives are several-fold:

1. It shall clearly show how big is the contribution from each DNO towards the restoration of a major fault on the transmission network (i.e. outage of the largest generator). This is particularly important for high solar and wind generation scenarios.

2. Each DNO's contribution to the restoration of a major fault shall be disaggregated into several categories, more specifically: total available DNO inertia immediately after the disturbance taking into account fault ride-through capabilities of generators, super-fast response of power electronics connected generators and storage units, total aggregated under-frequency load shedding by frequency levels, total equivalent governor droop of units taking part in the primary frequency control, total sensitivity of all loads to frequency changes, total load that can

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be disconnected by DSM, available spinning reserve by generation type and response speed, and possibly relevant time constants.

3. The study shall indicate the level of each DNO's participation in auxiliary service markets, such as inertia – super fast response (new service), frequency response and operational reserve.

4. The study shall specify data which have to be exchanged between DNO control centres and the NG control centre on a regular basis. It shall also indicate features-rules of the hierarchical control between the NG and local DNOs' control centres, as well as roles and duties of DNOs' dispatching centres.

The NG reduced equivalent model will be the basis for this study. In the current model, all distribution networks are represented as equivalent loads connected at 132kV busbars of the major grid supply points. To study the impact of DNOs' contribution to the restoration of a major grid fault, it will be necessary to replace the equivalent DNO loads with several components. For example, an equivalent DG with speed governor, an equivalent super-fast converter connected DG (& storage), an equivalent frequency dependent demand, total demand curtailment by frequency levels, total DSM/DSR load that can be shed, and unmanaged-constant load will be required. The DIgSILENT tool supports some of these objects; the rest will have to be modelled before computer runs.

Two types of studies will be performed. The quasi steady-state immediately after the major disturbance (often called inertial power flow), after the completion of the primary active power – frequency control (often called primary power flow) and possibly after the secondary control (often called secondary power flow) will be studied using the load flow engine. The results will indicate contributions of all DNOs in specific time snapshots to the restoration of a major grid fault.

Full dynamic frequency response studies up to several minutes after the major grid faults will be done and results compared with the quasi steady-states. The dynamic results will show potential voltage, angle, power flow, etc. oscillations, potential loss of synchronism of some machines (i.e. cascade outages), protection actions and frequency stability (or instability) of the studied cases. As the studies are done on the NG reduced transmission networks, there will be no full set of dynamic results for the entire transmission network and conclusions about inter-area power oscillations, sub-synchronous resonances, etc. will not be drawn.

Reliability Analysis

The reliability engine in the DIgSILENT tool makes use of the state enumeration method [22] with the user defined contingency order [16]. This is a reliable method that can be used to study all types of networks. The DIgSILENT offers two reliability study options, namely 'Network Connectivity Analysis' and 'Network Load –Flow Analysis'. The former option will be used because industry-wide reliability indices applied by DNOs are customer-interruptions – CIs (a.k.a. SAIFI [22]) and customer-minutes-lost – CMLs (a.k.a. SAIDI [22]). Several types of outages can be studied, such as independent outages, common mode outages, maintenance (i.e. planned) outages and outages of switching devices.

Input data for individual power system components will be equipment failure rates, switching and repair times, classification into automatic, remotely-controlled or manual (switching) devices, customer numbers by distribution, primary and bulk supply point substations, etc. It is likely that these data are not entered into the DNO models, so they will have to be input manually into all distribution network models. The initially input data will be adjusted to obtain realised circuit performance. Both damaged and undamaged permanent outages will be studied [20], whilst transient outages that last less than 3 minutes will not.

The DIgSILENT tool is capable of modelling and reliability calculation of *power system* components only. However, 'smart' solutions will often involve centralised, hierarchical and local automatic controls, novel protection schemes, which all make use of various communication systems. Reliability analyses of all these additional systems need to be incorporated into the reliability calculations of future distribution systems, and the differential reliability indices should be found. This will be done using the basic probability – reliability principles in conjunction with DIgSILENT reliability results.

Dynamic Simulations

Further dynamic studies will be done using the DIgSILENT transient's analysis engine, which is capable of studying both fast and slow network transients. All dynamic simulations are automatically initialised by load flow calculations, whilst simulation events are user-defined. Short-term transients (i.e. electromagnetic phenomena) are calculated as instantaneous values, longer-term transients (i.e. electromechanical phenomena) as RMS values.

The studies will address protection response to imposed faults, fault ride-through capability of different generation types for varied protection settings, voltage stability analysis and assessment of voltage stability criteria, analysis of voltage sags on 'remote' network parts (with respect to faults), impact of different control schemes on stability, etc. Generation scenarios with high penetration of solar and wind are of particular interest.

DNOs do not have dynamic models of speed governors, automatic voltage regulators, automatic tap changers and shunt/series compensation devices, power electronic converters and other 'smart' solutions. Generic models will be used for this purpose.

Harmonic/Power Quality Analysis

Balanced and unbalanced three-phase harmonic power flows can be calculated using the DIgSILENT engine in order to find total harmonic distortion. Another possibility is to apply 'impedance scan' – 'frequency sweep' to get equivalent harmonic impedances at certain network locations. It is likely that the latter method will be used and the additional calculations based on rules from the Engineering Recommendation G5/4 [27] done in Excel spreadsheets.

To do the above calculations, both 'background harmonic injections' of existing generators and loads as well as harmonic injections of new LCTs (and some 'smart' solutions) are required. They will have to be assumed or some recommended values from international standards used, because there are no real-life data. Sensitivity studies around these values will be done.

Protection Study

Protection study will address global protection strategies and solutions of specific protection problems related to future distribution networks [28]. Protection strategies for future low-voltage (i.e. 0.4kV) networks will be specified first, with particular emphasis on interconnected networks run split and solid.

Several protection schemes and strategies will be proposed for 11kV and 6.6kV networks whose structure is radial, or semi-ring type, or ring type, or completely meshed. Finally, protection of 132kV and 33kV networks will be critically assessed and a way forward proposed.

Some of the considered specific problems are: bi-directional power flows on 0.4kV networks due to solar generation connection and/or network meshing; over-current protection grading and installation of directional

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relays at future 0.4kV networks; bi-directional power flows on 11kV and 6.6kV networks due to changed load profiles, new generation and circuit interconnection; over-current protection grading coupled with directional relays, earth-fault and unit protections; multi-ended unit and distance protections with new loads/generators at 33kV and 132kV circuits, etc. All these problems will be supported by fully worked out examples.

2.4 Critical Assessment of the Power System Modelling Capabilities

Critical assessment of power system modelling capabilities for individual power system studies is briefly presented below. The assessment addresses adequacy of the modelling of future networks, identifies modelling gaps and presents issues related to input data requirements.

Load Flow Study

Potential modelling and input data issues are:

1. *Load flow convergence:* simplified transmission and entire distribution networks from 132kV to 0.4kV are modelled. Modelled demands range from several tens of MW to a few kW. Accuracy of load flow solutions have to be set to very small power mismatches, which can cause convergence problems.

2. *Size of network models:* future distribution networks will become more interconnected and traditional modelling with three separate models (i.e. 132kV and 33kV; 11kV and 6.6kV; 0.4kV) may be inadequate. Developing a single model of 132kV, 33kV, 11kV and 6.6kV networks may imply analysis of several hundreds of thousand nodes and the selected software tool will have to have capability to deal with such networks.

3. *Low-voltage network modelling:* most of DNOs have low-voltage (i.e. 0.4kV) network graphical representation in GIS, with no power system analysis modules. It may be appropriate to integrate load flow, fault level and motor starting engines into the GIS in order to enable basic power system calculations within system planning.

4. *Sequential load flow:* traditional planning and operational analysis of distribution networks is based on studies of winter peak, (summer peak) and summer minimum operating regimes. It will not be possible to apply this approach in future because of significantly changed demand and/or generation profiles; half-hourly analysis on an annual basis will be required. The DNOs will have to be provided with appropriate scripts to do sequential load flow analysis, which will require

input of relevant real-time half-hourly measurements into the power system analysis tool. The biggest challenge is the data transfer from the control centre DMS to the (possibly new) power system analysis software.

5. *Load flow functionality:* currently used software tools do not have 'automated network reconfiguration' function, which is necessary for planning and outage analysis of 11kV and 6.6kV networks. The network reconfiguration function can be based on several objective functions and restoration rules, implying that the UK every-day practice shall be modelled. Next, modelling of multi-stage constraints (i.e. constraints over several half-hourly intervals) will be required for energy storage devices, EV charging, etc.

6. *Optimum power flow:* there is no 'proper' objective function for any type of co-ordinated voltage control on distribution networks in the currently used software tools. A security constrained OPF [29] would be also much appreciated within DNO community. Finally, it would be good to have multi-stage OPF [30] in order to model optimal operation of storage, etc. devices over longer time periods.

7. *Component modelling:* models of different types of storage (e.g. pumped storage, flywheel, compressed air and magnetic energy), EVs and HPs, as well as DSM/DSR with deferred load pickup are missing. The user has to develop and integrate these models.

8. *Component ratings:* UK DNOs often apply different ratings in the load flow – security studies. The power analysis software tool should be customised to enable integration of the UK everyday practice into analyses.

9. *Accuracy of network data:* data on power system components are often different in several DNO databases. A lot of effort needs to be invested into network data cleansing.

Fault/Short Circuit Study

Potential modelling and input data issues are:

1. *Short-circuit calculation method:* DIgSILENT tool does not support the UK standard [26]. On the other hand, IPSA+ tool has this method as an option for calculation of fault levels.

2. *Different platforms for 132-33kV and 11-6.6kV networks:* two software tools are often used to model 132-33kV and 11-6.6kV networks. When studying

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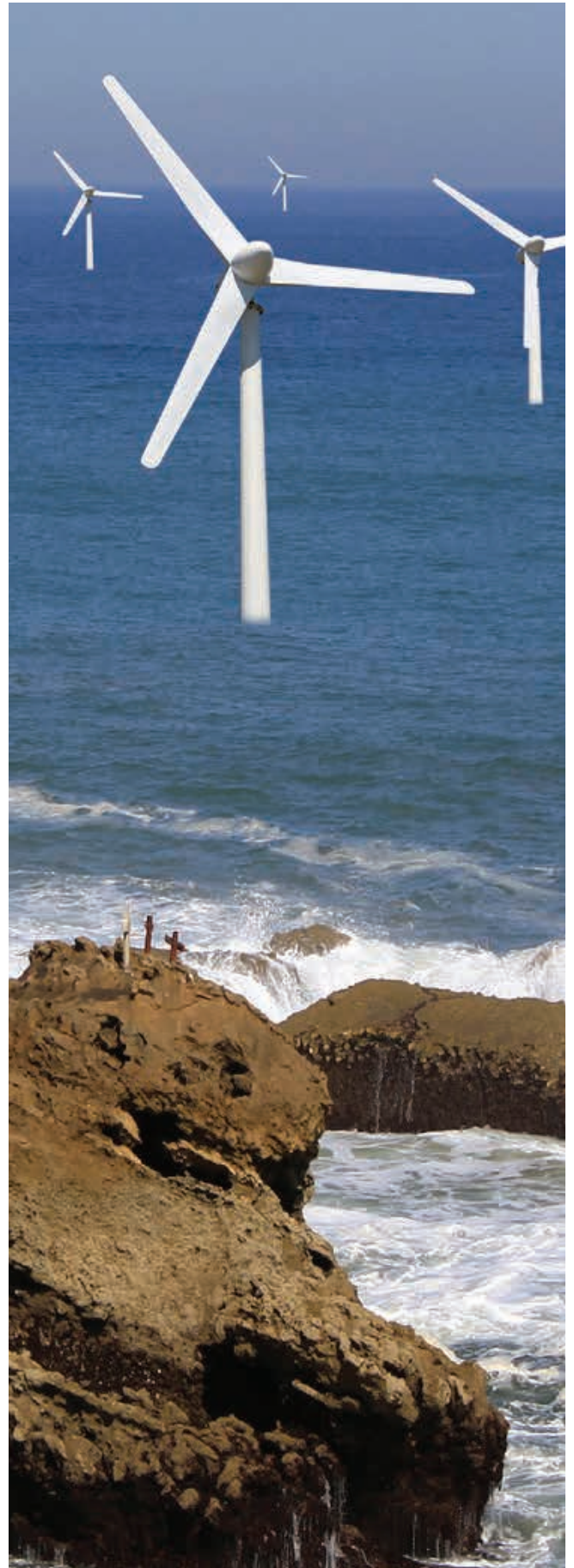
faults on 11(6.6)kV network, reconciliation of fault levels at 11(6.6)kV busbars of primary substations needs to be done. This would not have been an issue, had a single platform been used.

3. *Low-voltage network modelling:* calculation of short-circuit (and motor starting) currents is often done in Excel spreadsheets implying manual transfer of relevant network data into Excel. A fault calculation engine can be integrated in the GIS.

4. *Fault contribution of 'static generators':* there is no fault contribution of converter connected generators modelled using the 'static generator' option in the DIgSILENT tool. This contribution is usually between 120% and 150% of the rated power.

5. *Component modelling:* the models of energy storage, EVs and DSM-DSR motor contribution do not exist in the DIgSILENT. The corresponding fault contributions need to be assessed and modelled by the user.

6. *General load fault contribution:* the 'DIgSILENT' method is the only option in the software tool that can be used for this purpose; it is different from the 'G74 fault contribution method' currently used in the UK.

Frequency Control and Whole System Balancing

Potential modelling and input data issues are:

1. *Whole system balancing:* several components required for inertial, primary and secondary power flows are missing. These are super-fast converter connected generation & storage and flywheels for inertial power flow, frequency sensitivity of general loads and under-frequency load shedding by frequency levels for primary power flow. They will have to be modelled by the end-user.

2. *Frequency response:* dynamic models of converter connected generation and the frequency response need to be developed for dynamics studies. Dynamic models of EVs, HPs, energy storage, DSM/DSR and under-frequency load shedding are also missing.

3. *Control concept:* hierarchical control concept involving NG and DNOs control centres with pre-specified rules cannot be modelled.

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Reliability Analysis

Potential modelling and input data issues are:

1. **Reliability data:** all reliability data need to be entered manually in the DIgSILENT models because they are not contained in the DNO models. The data shall be based on typical historic (or generic) outage data for the considered types of equipment. To avoid problems with data accuracy, reliability data shall be adjusted in such a way that average historic reliability performance of analysed networks is obtained.

2. **Reliability of other systems:** reliability indicators of communication, centralised and local control schemes and (novel) protection schemes need to be assessed and integrated with the power system reliability indicators. This is likely to be done outside the DIgSILENT tool by using fundamental probabilistic principles.

3. **New LCTs and 'smart solutions':** reliability data for new LCTs and some of 'smart solutions' will have to be estimated because there are no historic data. Sensitivity studies around estimated values should be done.

4. **End of life equipment:** there is no reliability modelling for the equipment approaching its end-of-life. This is a very important functionality because of the aging power system components and necessity to determine the best replacement strategy. It can be overcome by running repetitive reliability studies with increased reliability parameters.

5. **Future reliability indicators:** currently used reliability indicators by DNOs are customer-interruptions (i.e. SAIFI) and customer-minutes-lost (i.e. SAIDI) obtained by performing reliability connectivity studies. More accurate reliability indices, such as loss of load probability (LOLP) and expected energy not served (EENS), may be used in future.

Dynamic Simulations

Potential modelling and input data issues are:

1. **Dynamic models of controls:** DNOs currently do not collect data on power system controls (e.g. speed governors, automatic voltage regulators, automatic tap changers and shunt/ series compensation equipment, etc.) from developers. Appropriate data gathering processes, specification of 'dynamic' data and dynamic model building need to be established within DNOs.

2. **Dynamic system studies:** DNOs currently don't perform any dynamic study at all. The studies of interest need to be defined first, the appropriate software platform(s) next, and planning, operation and control engineers need to be trained to run simulations and interpret dynamic results. Understanding the critical transient values is of prime importance.

3. **Management of transient system performance:** performance of current distribution networks is characterised by slow dynamics and long time constants. Future networks will have much faster transients (e.g. wind and solar generation, rapidly changing demands, etc.) and control engineers need to be trained to cope with such situations. It is likely that the dynamic study modules will have to be integrated into the DMS.

4. **Voltage stability criteria:** currently used voltage stability criteria within DNOs are often based on a 'rule of thumb' approach. These criteria shall be determined from dynamic voltage stability studies, particularly for the parts of distribution networks where no significant amount of DG will be connected.

5. **Fast and slow transients:** transients in future distribution networks will be characterised with both very fast modes (e.g. power converter transients) and much slower modes (e.g. electromechanical transients). The dynamics simulation engine will have to be capable of handling the both categories without decoupling the fast and slow phenomena and performing separate studies.

Harmonic/Power Quality Analysis

The potential issues are:

1. **Network model:** harmonic studies are usually done on 'reduced' distribution network models that model an 'area of interest'. Traditional equivalencing of power networks, which is often applied in load flow and fault level studies, cannot be applied here. There is no established approach to defining the 'appropriate' size of networks for harmonics studies, and this is done on a case-by-case basis. It is therefore necessary to develop such criteria.

2. **Background harmonic injections:** harmonic current injections of already connected demand, generation and other sources (so-called background injections) are not available in most cases. They can be obtained from field measurements and then entered into the network models. A regular process needs to be established within DNOs to collect these data.

3. *Harmonic injections of new LCTs:* harmonic current injections of new LCTs will have to be estimated because there are no historic data. This should be based on estimates obtained from equipment manufacturers, by comparing with 'similar' devices, by using international standards, etc.

4. *Harmonic study parameters:* specific parameters of harmonic analysis will have to be defined and applied across DNO community. It is likely that the impedance scan method will be used with lumped component parameters (as opposed to distributed parameters).

3. CONCLUSIONS AND RECOMMENDATIONS

A brief summary the most important conclusions and recommendations is presented below.

3.1 Conclusions

1. Future DNOs will need to do the whole suite of power system studies, namely sequential load flow, optimum power flow, fault/short-circuit analysis, frequency response and balancing, reliability analysis, dynamics simulations, harmonic/power quality analysis and protection study. Some of the studies will be done for development and operations planning, some within (extended) real-time control. Both planning and control staff will need to be trained to fulfil new commitments.

2. Identified modelling and data gaps in load flow studies are: sequential load flow will be required to study annual demand and generation profiles obtained from the DMS; new functions, such as network reconfiguration & restoration, optimum power flow with 'adequate' objective function and multi-stage models are required; development of new LCT models, such as EVs, HPs, energy storage and DSM/DSR is required; low-voltage networks should be studied within GIS.

3. Identified modelling and data gaps in fault/short-circuit study are: calculation method shall be compliant with the UK legislation; models of new LCT components, such as energy storage, EVs and DSM-DSR motor contribution shall be developed; fault levels of converter connected generators and motor fault contribution of general loads need to be established; low-voltage networks should be studied within GIS.

4. Identified modelling and data gaps in frequency response and whole system balancing studies are: several component models required for quasi steady-state balancing need to be developed; dynamic models

of EVs, HPs, energy storage, converter connected generators and under-frequency load shedding are required; different control concepts are missing.

5. Identified modelling and data gaps in reliability study are: currently available reliability calculation engines seem inadequate, a Monte Carlo based simulation method shall be developed; reliability of communication, automation and protection systems shall be integrated within reliability analysis; there is no reliability modelling for equipment approaching its end-of-life; currently used reliability indices may be inadequate.

6. Identified modelling and data gaps in dynamics study are: DNOs do not have dynamic models of various controls and do not do transients studies; dynamic models of new LCTs and some of 'smart' solutions are not available; angle, voltage stability and electromagnetic studies shall be addressed in greater detail.

7. Identified modelling and data gaps in harmonic/power quality study are: there are no data on background harmonic injections and harmonic injections of new LCTs and some of 'smart' solutions; approach to determining the network of interest to be studied needs to be developed.

3.2 Recommendations

1. DNOs should establish internal processes to gather various types of modelling data which are required for both steady-state and dynamic studies. New steady-state modelling data are required for LCTs and some of 'smart' network solutions, whilst dynamic modelling data are needed for existing and new control devices because DNOs will need to start doing dynamic analyses. Particular attention should be paid to the data required for frequency response and whole system balancing studies. All required data should be obtained from developers (new connections), equipment manufacturers and other relevant third parties.

2. DNOs should critically assess currently used software platforms for power system analyses. It is recommended to use a single platform for 132kV, 33kV, 11kV and 6.6kV networks. Where the network model is of 'huge' size, 11kV and 6.6kV network model can be stored separately. It is also recommended to use 'smart' GIS for planning studies of low-voltage (i.e. 0.4kV) networks, with the essential power system analysis functions built in. Real-time measurements available in control room DMS should be made accessible to the selected software platform, because future analyses

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cannot be based on representative operating regimes. In that respect, DNOs need to be encouraged to invest into measuring and tele-communicating data from the network, and in particular from distribution substations 11/0.4kV and 6.6/0.4kV.

3. The selected software functionality should be critically assessed in light of future power system components (e.g. LCTs and 'smart' solutions) and operational requirements. It is recommended to consider development of new multi-stage load flow and OPF models, OPF models with voltage-reactive power objective functions and/or security constraints, new network equivalencing models for steady-state and dynamic studies, distribution network reconfiguration and restoration models for 11kV and 6.6kV voltage levels, new reliability analysis model possibly based on sequential Monte Carlo simulation and a new steady-state voltage stability tool.

4. DNOs should participate in the whole system restoration following system emergencies. This applies above all to frequency response, (spinning) reserve and voltage-reactive power services (note that a new 'inertia service' may be introduced shortly). The hierarchical control principles between NG and DNOs control centres need to be established first, which should be followed by detailed specification of technical and commercial data that need to be exchanged on a regular basis. It is envisaged that the data exchange will be required for short-term operations planning and (extended) real-time control.

5. Development of models of new network components, such as EVs, HPs, different types of storage, different types of DSM and DSR, under-frequency & under-voltage load shedding, etc. is required. Reliability models of communication, automation and protection systems need to be developed and integrated into the power system reliability module.

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