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Modelling Requirements to Assess the Resilience of The Electricity System as it is Adapted to Deliver Low Carbon Transition: "Dynamic Analysis of Systems with New Equipment, Devices, Control Approaches and Operating Modes"

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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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1. INTRODUCTION – WHERE ARE WE NOW?

From humble beginnings in the 1880's the electric power industry has grown into one of the largest industries. It has done an excellent job of meeting the energy needs of the 20th century and electricity has become a basic necessity in modern society. It has also been recognised that the electric power industry has an adverse impact on natural environment and that there is a need to refocus business in order to meet energy needs of society in a way that is "sustainable" in the long run. The Industry has been undergoing major restructuring over last twenty, twenty five years including shift from monopolistic to competitive structure, following new economic/social/environmental requirements and accommodating new sources/types of electricity generators.

In spite of all these changes the major characteristics of the power systems remain to be: Large, conventional power plants dominate; Monopolistic vertically integrated structure (mostly); Limited (<10%) cross-border power transfers; Limited application of FACTS devices and power electronics (PE) in general; Limited use and integration of ICT (Information and Communication Technology); Preventive control design/actions; Deterministic system studies; Unidirectional power flow; Passive distribution networks; Small or no involvement of customers in network operation and control; Limited exchange of data between neighbouring utilities.

There has been a substantial amount of work over the last few years in the general area of modelling and dynamics studies of future power networks. The overview below focuses on work published over the last five years and predominantly in the UK and Europe.

- Transient stability assessment and control islanding scheme
  - Based on IEEE test network [1]-[4]
  - Method that can be used for preventive islanding purposes [5]
  - Controlled islanding [6], [7]
  - Online Dynamic Security Assessment using Decision Trees [8, 9]
- Data driven method for electromechanical oscillations and voltage stability
  - Iceland power system (Oscillation source location using logic regression, wavelets) [10-13]
  - Nordic System (Finland/Sweden/Norway/Eastern Denmark) [14, 15]
  - Mexican System [16]
  - Ecuadorian Power system (real data) and Northeast Power Co-ordinating Council (NPCC) network (Oscillating modes identification using classification trees) [17]
  - Wind farm oscillations detection using wavelet-based support vector data description [18]
  - Modal Identication of Transient and Ambient Data Oscillations by IEEE Task force [19]
  - Adaptive voltage stability protection [20]
- Estimation using real-time dynamic data
  - State Estimation (IEEE test network) [21] [22]
  - Synchronous machine parameter estimation [23]
  - Inertia estimation using WAMS [24]-[26]
  - Inertia estimation using WAMS in GB network [27]
  - Wind plant Inertia estimation [28]
  - Frequency and power [29]

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- GB power systems/Analytical tools
  - GB Electricity Transmission Network [30, 31]
  - GB Wide Area Measurement System [27, 31-34]
  - UK network Modelling [35, 36] PSSE [37] DigSilent [38-40] PSCAD [41, 42]
  - UK network modelling Wind [43] [44] Generation capacity [45] Corrective control method (DigSilent) [46]
  - GB frequency response from EV [47]
  - Operating strategies for gas and electricity considering wind in GB system model [48]
  - Framework for modelling uncertainty in the input data for risk calculations and application in GB system [49]
  - Impact of wind and HVDC on GB system [50]
  - Control thermostatic loads to provide inertia in GB Gone Green 2020 scenario [51]
  - Transient Assistive Measures using HVDC on GB system (DIgSILENT) [52]
  - Offshore wind turbine contribution to frequency stability in real frequency excursions of GB network [53]
  - Transients measurements in GB network (co-author and funding by National Grid) [54]
  - General overview of offshore wind power integration in UK and Europe [55]
  - Frequency stability using dynamic model for aggregated refrigerators in GB [56]
- Modelling of distributed generation for stability study
  - Wind Generation [57]-[62] Danish System (DIgSILENT) [62]
  - Wind generator models for stability studies [63], [63]-[66]
  - Extended Equal Area criterion to assess the impact of offshore Wind Power through HVDC on transient stability [67]
  - HVDC model based on PMU measurements for voltage stability on IEEE 39 bus system [68]
  - Limit Induced Bifurcation using Dynamic wind farm model [69]
  - Reduced order dynamic models of Active Distribution Networks [70]-[73]

- Battery Energy Storage System dynamic model and control [74], [75]
- DG clustering [76],
- DG Modelling Overview [77],
- Wind Generation clustering [78]
- Impact of PV on stability [79]-[81]
- Isolated system with increased wind and hydro (modelling in PSS/E) [82]
- Representation of external grid for DG stability studies [83]
- Integration of EVs [84] (Portuguese network), [85]-[86] (Danish Power system)
- WAMS and PMU monitoring data
  - GB [27, 31-34]
  - Mexican System and Finland System [87]
  - Transient faults simulated by DigSilent [88]
  - Voltage Stability
- Modelling and simulation for system dynamics [89]-[92]
  - Oscillation damping [93] (VSC-HVDC Model Predictive Control), [94], [95] (Wind Power plants)
- National Grid Reports
  - 2013 electricity ten year statement [96]
  - UK Future Energy Scenarios [97]
  - Wind Energy in the UK [98]
- Projects and involved organisations in the UK
  - Aims at increasing Sub-synchronous oscillation visibility in the UK network. [99] https://www.ofgem.gov.uk/ofgem-publications/84811/nicsubmissionforsptransmission-visor.pdf
  - Focus on the Distribution system operation. In WS3 the Transform Model was developed to assess the costs and benefits of smart developments of the GB distribution system. [100] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/285417/Smart_Grid_Vision_and_RoutemapFINAL.pdf
  - "Request for Information", Energy Networks Association. Part of SGF WS7 in association with ENA. Working on technical details on the report "2030 Distribution System" which is also included in the following draft.

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Development of models and scenarios based on the transform model. http://www.smarternetworks.org/Files/Announcement_of_Opportunity_-_Exploring_the_Operation_of_the_GB_Distribution_Network_in_2030_131125122541.pdf

○ Equivalent models for the GB system for future studies. [101] http://www.theccc.org.uk/wp-content/uploads/2013/12/CCC-Infrastructure_TD-Report_22-04-2014.pdf

○ Working in collaboration with Smart Grid Forum. [102] http://www.theiet.org/factfiles/energy/pnjv-page.cfm.

○ "GSR016 Application of scaling factors and inclusion of embedded wind in SQSS Chapter 4 studies" and "GSR010 Review of Onshore Entry Criteria", National Grid. Workgroups working on modifications for DG unit representation requirements.

In spite of noticeable activity in modelling future network scenarios the software tools used are to a large extent conventional (PSCC, DIgSILENT/PowerFactory, EMTDC, IPASA, etc.) and the models used largely limited by software environment. The studies carried out are almost exclusively deterministic with very little attention paid to modelling uncertainties and the test systems used are generic test networks or simplified real network models.

2. WHERE ARE WE GOING TO BE?

It is widely anticipated though that there will be enough public support and sustained political will to build enough renewable generation capacity to produce 50%, or more, of the demand for electrical energy. Many of renewable energy sources (RES) have a low energy density and are therefore distributed. The majority of RES will be connected to the network through power electronics interface. Some of them are intermittent (driven by astronomical factors) and other stochastic (dependent on meteorological conditions). The exploitation of low intensity renewable resources requires large investments that are economically viable only if the utilization of the primary energy is maximized. Intermittent RES thus provides little control and causes much uncertainty in the operation. Because of the intermittency the renewable generation capacity will have to represent a significantly larger fraction of the total installed capacity.

Currently major type (by volume and installed capacity) of renewable generation, large off-shore wind farms, will be most likely, connected to an off-shore sub-marine transmission grid first and then to the shore.

Grid connections and off-shore networks could be either AC or HVDC cables. It is envisaged that power electronics will play an increasing role in the grid to facilitate the bulk (cross-border) transfer of power and required network flexibility. This proliferation will be spearheaded principally by HVDC links to assist in stability and power flow control, generator-grid interfaces and increased application of FACTS devices to "soften" existing transmission networks. Because their cost is not likely to decrease significantly FACTS devices will probably remain somewhat auxiliary to the main AC transmission and distribution networks in the immediate future. The HVDC, in particular Variable Source Converter (VSC) controlled HVDC, lines on the other hand, are largely expected to form meshed supergrid on top and in conjunction with, existing AC grid to shift large amount of electrical power over large distances.

Depending on the country and required energy mix to ensure energy security, nuclear plants may represent a significant fraction of the remaining generation capacity. Thermal generating plants burning fossil fuels will continue to provide the balance of the capacity. These plants though may most probably operate under an effective and efficient "cap and trade" mechanism for emissions trading. This will ensure that their operating costs are higher than the cost of producing energy using generation that does not produce green house gases.

In summary the future power systems will be characterised by:

- Much more liberalised market

- Increased cross-border bulk power transfers to facilitate effectiveness of market mechanisms

- Increased use of HVDC lines of both, LCC and, predominantly, VSC technology (in meshed networks and as a super grid)

- Increased presence of static and active shunt and series compensation in AC grids

- Increased deployment of FACTS devices in general

- Large on-shore and off-shore wind farms

- Proliferation of non-conventional renewable generation – largely stochastic and intermittent (wind, PV, marine) at all levels and of various sizes

- Small scale (widely dispersed) technologies in distribution networks

- Active distribution networks with bi-directional energy and information flow

- New types of loads within customer premises (PE, LED)

- Electric vehicles (increasing spatial and temporal uncertainty of the load/generation in the network)

- Integrated "intelligent" PE devices, both at customer and utility premises

- Integrated ICT & storage technologies of different size and at different voltage levels

- Different energy carriers

This new generation and load technology mix may not be able to keep the system in balance if it is operated in the traditional way, i.e. the generation is ramped up and down to follow the load and re-dispatched to resolve transmission constraints. Replacing the current "supply-follows-load" control philosophy by a "load-follows-supply" approach might be considerably cheaper as the heat, cold, energy or material storage that is naturally incorporated in many domestic and industrial appliances and processes can be harnessed to adjust the demand to match the supply. Furthermore, electric and plug-in hybrid vehicles (whose number is growing, although slower than expected) and distributed energy storage, could provide an additional and particularly flexible control resource, though, at the same time may place additional demands on power networks requiring higher network flexibility and operability.

The key characteristics of this future power system will be an unprecedented mix of a wide range of electricity generating technologies, responsive and highly flexible demand/storage with significant temporal and spatial uncertainty, proliferation of power electronics at transmission (HVDC and to certain extent FACTS devices) and distribution (PE interfaced generation and storage technologies, end use customer devices – new types of loads, EV) system level, flexible hierarchical control structure and blurred boundaries between transmission and distribution systems (with distribution system becoming more "transmission like") and significantly higher reliance on the use of global (Wide Area Monitoring) signals for system identification and control and Information and Communication Technology embedded within the power system network and its components, to facilitate two-way-communication.

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At distribution network level, a distribution network (not necessarily electricity, could be energy) cell of variable size (from micro grid to larger part of higher voltage level network) manages, controls and protects itself to ensure adequate security, reliability and quality (possibly differential, different customers receiving different contracted quality and reliability of supply) of electricity/energy supply. Cells may exchange power/energy based on real time energy trading using appropriate interfaces (PE or other). Energy trading is based on local energy flow exchange between cells linked by a global ICT network. The network accepts plug & play cells ("modular self configuring design") some of which may not be internally using AC power. Individual customers will have substantial if not full flexibility to participate, if they wish so, in energy exchange/trading or they might be encouraged to do so through appropriate pricing signals.

All the above features of transmission like and distribution like network (allowing for greater level of "merger" between the two) will have to be fully integrated to ensure that the system as a whole works, and provides support during emergencies to individual cells or groups of distribution/distributed cells and ultimately to the power system as a whole.

3. MODELLING AND SIMULATION CHALLENGES

Key modelling and simulation challenges in order to efficiently and effectively simulate possible operational scenarios of future power networks include (not given in order of priority):

- Modelling for steady state & dynamic (small disturbance and transient) studies

  ○ Large interconnected networks with mixed generation, FACTS and short/long distance bulk power transfers using HVDC cables and series compensated AC lines operating in parallel.

  ○ Clear identification of advantages and disadvantages of different levels of detail in modelling of HVDC (different technologies including multi terminal HVDC) and FACTS and recommendation of models to be used in different levels of studies.

Comment: While development of these models have already been a subject of many industrial and academic studies, clear recommendation is still missing regarding the level of detail of different models that is absolutely necessary for different types of studies. This is to a certain

extent hampered by the fact that these highly sophisticated technologies are developed by companies who naturally want to protect their IP rights and the sharing of data and information is highly restricted. Classical power system studies (typically performed by electrical power engineers) tend to use simpler models of HVDC and FACTS technology while studies coming from the power electronics area (typically performed by power electronics engineers) focus on very detail modelling of internal circuits of these devices. A "look up table" approach would be a suitable immediate way forward where different types of models could be recommended for different types of power system studies, as well as different size of simulated networks. Analysis to what extent (type of "sensitivity analysis") the use of "one level more detailed" (higher order) model and "one level less detailed" (lower order) model then the recommended, would affect the results of simulations. It is essential that both small (a few buses) and large system (hundreds of buses) studies are carried out in parallel to facilitate physical understanding of interactions between the two systems and justify proposed choice of models and to illustrate practicality of large system implementation and eventual interactions between different subsystems. These recommended models should be in appropriate form so that they could be easily incorporated in commercially available packages.

- Clusters of RES and storage technologies either of the same or different type considering associated uncertainties. The uncertainties considered should include both temporal and spatial uncertainties. The latter are particularly important as hundreds, if not hundreds of thousands of different devices may need to be represented.

Comment: Similar comments as above regarding the recommendations of look up table of suitable models of different technologies for different types of studies as well as applicability to large and small systems. Additionally, the aspects of temporal and spatial uncertainties should be addressed in close collaboration with system operators to restrict the search space when considering uncertainties to feasible regions only. While an attempt should be made to specify best/worst case scenarios when modelling these uncertainties, i.e., to define the bounds of uncertainty, this would not be sufficient to gain a realistic picture about the influence of uncertainties involved as it could lead to either too optimistic or too pessimistic results.

An in-between solution between best/worst scenario studies and full blown uncertainty study with reasonably flexible bounds of uncertainty could be to propose bounds and the most likely/probable scenario(s) and propose relevant models for these few cases. These models would need to be developed and incorporated in commercially available packages.

- Modelling of whole LV and MV distribution network cell (DNC) with thousands of stochastic and intermittent RES which may exhibit temporal and spatial uncertainty.

- Modelling of demand, including new types of energy efficient and PE controlled loads, customer participation and behavioural patterns, EV, etc. Demand modelling as a generic term used here includes forecasting of demand response to network disturbances (not only forecasting of P and Q consumption), i.e., dynamic response of demand to both voltage and frequency disturbances.

Comment: The major modelling challenge above is not modelling of individual devices but rather appropriate *aggregation of a very large number of individual devices considering all associated uncertainties* for large system studies. This aggregation should result in equivalent models with recommended parameter values of specified accuracy, i.e., uncertainties in parameter values should be bounded. The *probabilistic models and parameters* may be one option as it has been shown in some studies in the past that very good results could be achieved [78]. As an intermediate step towards full blown probabilistic studies a few characteristic points/scenarios could be considered, e.g., best/worst case scenarios and the most likely/probable scenario(s) to get the initial assessment of the significance of considering parameter uncertainties. These models would need to be developed and incorporated in commercially available packages.

As far as large system studies are considered, following the establishment of appropriate equivalent/aggregate models of different devices, the key issue to address is appropriate modelling of uncertainties involved with generation and load. Again, the effort should be directed towards efficient representation of all uncertainties involved and the consequences of network disturbances on system security and stability. *Probabilistic and risk based methodologies* should be developed and incorporated in commercially available packages for large system studies.

Considering that adoption of *Probabilistic and risk based methodologies* would be a significant departure from current practice and that there is lack of understanding and interpretation of results of these studies, both in industry and academia, a series of continuing professional development courses should be offered to highlight some of the key aspects of these types of mathematical approaches and their suitability to practical problems faced by electrical power industry. Preliminary results [103]-[107] have indicated that this could be a way forward for simulating large networks of the future.

- Efficient use and reliance on global monitoring data (WAMS) for state estimation, dynamic equivalents and control (including, but not limited to, real time control).

  ○ Optimal placement of monitoring devices (PMUs or other), though this may not be an issue as over the years number of monitors in the network will increase, should be (re)addressed from the point of view of existing monitoring framework. Considering that there are already a number of monitoring devices in the network of varying types, accuracy and functionality, where should new ones be placed to achieve full observability and subsequently controllability of the network?

  ○ The PMU, or any other monitor placement methodologies should consider accuracy of devices in data capture and accuracy of derived parameters (e.g., voltage phase angle and magnitude are captured at non generator bus in the network but generator speed and angle are needed for on line stability assessment).

  ○ Signal processing/aggregation/transmission (including delay or complete loss) for dynamic observability, i.e., identifying dynamic response of the system close to real time. Different classification and clustering techniques should be used for fast identification of system dynamic signature following disturbance. The dynamic signature of the power system with non-conventional PE connected generation (power system with reduced inertia) and PE connected load would be particularly challenging to estimate.

  ○ A time line defining accuracy of the estimation against the speed of estimation should be established for different parameters and dynamic phenomena to be estimated (e.g., the transient stability of the system can be estimated with 99% accuracy 0.5s after the fault with 15 PMUs and with 97% with 5 PMUs; Dynamic behaviour of groups (coherent) of generators can be described with 98% accuracy 0.8 s after the fault; etc.)

Comment: In addressing the issues above attention should be paid to required *accuracy of information* that WAMS or other monitors should provide [108]-[111]. Starting from the type of study that the data will be used for, the error margin for parameters to be estimated/identified from measurements should be established and the effort directed towards achieving it. Appropriate sensitivity analysis should be carried out to establish required accuracy of estimated parameters (and the time when these parameters would be required in case of corrective control action) before the issue of parameter estimation is addressed [112]-[114]. While on-line estimation of system dynamic signature of conventional power system is very challenging task on its own, the issue becomes even more challenging when the significant portion of generators are non-conventional (synchronous) and when the system response to disturbances, in short time scale in particularly, may be significantly different due to reduced system inertia (generators, hence the inertia of rotating masses are decoupled from the system by PE convertors). In case of reduced inertia systems there is also lack of experience with and understanding of system transient responses. A range of studies would need to be performed on these systems prior to attempting to estimate their dynamic signature in real time. These studies, carried out using realistic networks of different complexities and having different levels of penetration of non-synchronous generators, should result in "data base(s)" of typical responses depending on the type of study (angular stability, frequency stability, voltage stability, fault studies, etc.) and the level of penetration of different "inertia-less generation/storage technologies". A threshold (for each type of study and inertia-less generation/storage technology mix) should be established beyond which further penetration of these new technology types would significantly affect system transient performance so that new system control approaches would need to be applied. In other words, the question "How far can we go with integration of inertia-less generation/storage technology in the network without having to change some aspect of system dynamic control and what is the extent of changes that need to be made depending on the level of penetration?"

- Design of supplementary area controllers based on WAMS to control and stabilise large system (including but not limited to real-time) or parts (which may vary) of it with uncertain power transfers and load models and stochastically varying and intermittent generation and demand.

○ The key issue to consider here is the fact that there are already local controllers in the system (e.g., PSSs, OLTCs) and that they are going to continue to be present and perform allocated tasks. New controllers should be acting only when needed and in addition to existing local controllers and they should accommodate variability in controlled plant parameters. In controller design probabilistic and stochastic control methodologies should be explored and their performance compared (advantages vs. disadvantages) against established conventional techniques. The new area/system supplementary controllers do not need to be necessarily designed using probabilistic/stochastic control methodologies or artificial intelligence methods as long as they can perform allocated tasks.

○ Possibility of having area controllers with variable number of inputs and outputs (the number of I/O may change depending on identified disturbance and area that needs to be controlled) should be explored and feasibility of these types of both off-line and on-line controllers explored.

• Design of hierarchical, adaptive control systems/ structure for power networks with fully integrated sensing and ICT technologies. The consensus control, for example, may be an option considering potentially thousands of individual devices (including different generation, storage and load technologies) in the network and a number of existing or new local/area controllers.

• Modelling/analysis of efficient and effective integration of different energy carriers into self sufficient energy module/cell.

4. SUMMARY

In summary, the future power networks need to be modelled and operated by exploiting possibilities offered by state-of-the-art WAMS, integrated ICT systems and "intelligent" PE devices and using non-deterministic & close to real time approaches for (energy) system control and operation; and stochastic, probabilistic and computer intelligence based models, data handling and methodologies to *minimise* the effect of uncertainties and *maximise* the use of information contained in available data. In order to facilitate a smooth transition to the efficient and secure operation of future power systems the following challenges should be addressed:

• Modelling of new types of PE interfaced generation, demand, storage, transmission and communication technologies (RES interface, HVDC, FACTS devices, PE interfaced loads, storage)

○ large interconnected networks with mixed generation, FACTS and short/long distance bulk power transfers using HVDC lines of different technologies

○ clusters of RES (generation and storage) of the same or different type

○ static and dynamic aggregate models for different types of studies with clear specification of modelling requirements and bounded parameter values

○ LV and MV distribution network cell (DNC) with thousands of RES

○ Demand, including new types of energy efficient and PE controlled loads, customer participation and behavioural patterns, EV, etc.

• Increased reliance on global (WAM) signals but also on global increase in network monitoring at all voltage levels, calling for

○ advanced steady state and dynamic state estimation (observability of the network), dynamic equivalents at different time scales and application for control & stability considering associated spatial and temporal uncertainties

○ efficient data management (signal capture, processing, aggregation, transmission) and analysis (clustering and classification techniques for knowledge extraction)

○ ICT network reliability and interaction with power network

○ Increased penetration of power electronic

• Increased uncertainties in controlled plant (system) both in terms of model uncertainties and operational uncertainties, calling for

○ robust, (self) adaptive control strategies and probabilistic plant modelling

○ probabilistic, risk based assessment of system operation both steady state and dynamic

○ assessment of system control/stability/power quality contribution by new types of generation/load/storage

○ design of supplementary controllers based on WAMS to control and stabilise large system (including but not limited to real-time) or parts of it (which may vary) with uncertain power transfers and load models and stochastically varying and intermittent generation, demand and storage – *stochastic/probabilistic control*

○ design of new control systems/structure *(hierarchical, adaptive, close to real time)* for power networks with fully integrated sensing, ICT technologies and protection systems – *risk limiting control*

The extent and the timeline of the activities addressing modelling requirements specified above will depend on the type of studies that they are aiming at (planning, operation, control, etc.) The key requirement though is that in all cases as realistic as possible scenarios are used and that clear recommendations are given for different types of studies and different phenomena (faults, planning, angular and frequency stability, etc.) considered so that they can be transferred to industrial practice as soon as possible.

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