The Institution of Engineering and Technology

Emerging Modelling Capabilities for System Operations

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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 current modelling tools used by transmission system operators have been designed for an era characterised by conventional generation technologies, high predictability of generation and demand patterns and a limited number of control actions to be determined and executed close to real-time. The traditional security provision philosophy has been to adopt a preventive stance and rely on preventive measures with security of supplies being delivered through redundancy in assets rather than through real-time control actions. In a similar vein, operation of distribution networks has been based around one-way flows and a limited scope for resource optimization and control, except post-fault network restoration. Furthermore, the integration between transmission and distribution network operation has been very limited thus far.

However, the transition to a low-carbon economy is rapidly changing the reality of electricity system operation in GB. In the light of increasing penetration of renewable energy sources at the transmission and distribution level, together with expected de-carbonisation of transport and heat sector demands, the traditional operational doctrines are becoming out-dated; security through asset redundancy will have to give way to smart operational approaches and achieve a higher degree of service quality at lower costs. At the local level this will be further challenged by the growing interest in developing smart community energy systems and smart cities, which will require a new approaches to control and in this context, high integration between local energy systems, distribution system operators and transmission system operators will need to be developed if these benefits to be realised. On the other hand, increasing the cross-border interconnection capacity will require full coordination of the EU transmission system to be developed.

The UK energy system is facing challenges of unprecedented proportions and will require radical transformation of all energy sectors, i.e. electricity, heat, gas in terms of technology and associated infrastructures, as well as in the way the energy is supplied, managed and consumed across all energy intensive activities, in order to facilitate a cost effective evolution to a low carbon future.

Along with the challenges that arise in contemporary electricity system operation, new opportunities are enabled by novel technologies. Devices such as Phase-Shifting Transformers (PSTs), Flexible AC Transmission Systems (FACTS), System Protection Schemes (SPS) and HVDC grids promise to increase operational flexibility through corrective security provision. Similarly, application of emerging power electronics technologies at the distribution level in the form of Soft Normally Open Points and various voltage control devices will enhance the utilisation of distribution networks through corrective control. Penetration of various forms of distributed energy resources (DER), including both generation and demand led response embedded in distribution networks, will significantly enhance the controllability of both distribution and transmission networks, provided that full coordination across TSO/DSO boundary is established. Furthermore, the large-scale deployment of Phase Measurement Units (PMUs) along with the introduction of a pan-European common information exchange standard [1] will enable System Operators to have improved visibility over their network. The introduction of novel concepts such as Virtual Power Plants (VPPs) promises to further integrate electricity operation of community energy systems, distribution and energy transmission systems and increase the value of flexibility and controllability enabled by embedded generation and demand led distributed energy sources.

The above create a significant opportunity for a paradigm shift in system operation to make full use of real-time measurements, advanced pre and post fault control in order to maximise cost effectiveness and security performance of the system while making of use of emerging flexible technologies and demand and generation resources of flexibility embedded in distribution networks.

The use of appropriate modelling tools is at the core of this transition and will be an essential pre-requisite for effectively navigating the new landscape of system operation. However, while adequate for the present, the existing modelling capability is seriously lacking in a number of key aspects for the future. Intense effort has to be directed towards developing tools to increase network visibility by making use of new data streams that are starting to become available. Furthermore, it is imperative to extend the modelling philosophy to move beyond deterministic models towards tools that optimise operational decisions such as system balancing and allocation of ancillary services on the basis of the uncertainty present in the system **[2]** The scope of these tools should be extended to consider all control actions that are being added to the operators' arsenal, such as the possibility to provide corrective post-fault control through FACTS, the ability to shift demand or call on storage etc. In addition, such actions would need to be abstracted in such a way to maximize their effective contribution and controllability from a whole-system perspective and be considered on a probabilistic basis to account for non-delivery events, for example arising from capricious human behaviours, weather change, or the movement of electric vehicles. Also, in order to hedge the system against the range of disturbances, it is becoming important for operators to consider multiple timeframes, from micro-seconds to hours and even days. In the longer term, the shift from centralised to distributed operation model will open new opportunities for enhancing cost effectiveness and security performance of future electricity system.

The present paper is structured as follows. In Section 1, we review the existing modelling capabilities and outline in detail the challenges ahead. In Section 2, we identify future requirements for modelling tools and highlight areas for further development to address any areas of concern. In the last section we present the conclusions and recommendations of this analysis.

1. BACKGROUND

The transmission and distribution network operators are at the heart of system operation and they are responsible for ensuring that electrical demand is met at all times in an efficient manner. At the transmission level, one of the primary tasks is system scheduling and balancing; determining dispatch levels of generators (in conjunction with market mechanisms) so as to minimize costs while respecting various physical constraints of the power system. Similarly, distribution networks operators are focusing on service delivery and more recently on providing enhanced access to their networks through application of active management techniques. Currently, these problems are formulated as a deterministic optimisation problem and are based on a single forecast for all stochastic variables (i.e. loads, injections from renewables etc.). Explicit post-fault thermal constraints are also included to ensure uninterrupted operation against a list of credible contingencies. In addition, various ancillary services are contracted to safeguard the system against unforeseen plant failures as well as deviations from the anticipated operating conditions. Although the methodologies described above have served the industry well in the past, the looming changes are bound to render them both inefficient and inadequate in the near future. As explained below, there are three main aspects pertaining to current system operation modelling tools that may hinder the low-carbon shift.

1.1 Enhancing the Whole-system Visibility and Predictability

In order to facilitate this development novel modelling tools are required to take full advantage of the increasing amount of information and data that is starting to be become available to system operators [3] [4]. Advanced state estimation in combination with increased amount of real-time measurements obtained via PMUs and smart metering, will increasingly be used to enhance visibility and generate a more realistic a picture of the system condition in real time. Another way of leveraging system monitoring data lies in constructing an ever-expanding database of past system states. By comparing past forecasted and realised system states, the statistical characterisation of the different uncertain variables and the corresponding prediction errors becomes possible. Such information will be instrumental in gaining a deeper understanding of the way different uncertainty sources are correlated between them as well as of the operator's ability to forecast them. Increased application of real-time and historical data will be an instrumental step towards moving beyond current deterministic approaches towards more advanced modelling platforms that can explicitly consider the stochastic nature of system operation variables.

It is important to note that in the DNO centric approach, DSR is also be used for system balancing purposes as long as it does not trigger increase in the peak load.

In the case of more flexible generation system and enhanced interconnection, the need to use DSR for system balancing will be reduced. Therefore, as demonstrated in Figure 1, the additional investment in the local distribution network proposed by the whole system approach, i.e. £70 million is significantly lower than the additional investment proposed in the case of inflexible system (£340 million). Thus, the role of DSR in the flexible system is closer to the role of DSR in the DNO centric approach; this shows the shift of the focus of DSR applications depending on the system needs.

The results of the study demonstrate that the additional investment in the local distribution network to allow DSR to support national level balancing, can be justified since the benefits in the forms of savings in OPEX and generation CAPEX exceed the cost of reinforcement of this particular DNO area. In both cases, the cost obtained by the whole system approach is less by approximately £716 million to £771 million[1]. The savings are not insignificant and should be pursued to reduce the overall electricity cost to consumers. This clearly demonstrates that a coordinated whole-system approach to distribution network design will be important, and will require the consideration of national level objectives when designing local distribution networks, which is in stark contrast with the present approach. These effects are clearly not within the scope of presently established sector centric modelling tools and the present market, commercial and regulatory framework, does not yet support the whole-system paradigm.

1.2 Optimising Short Term Operation of the System under Uncertainty

System resilience against disturbances is currently ensured primarily through preventive measures. This results for example in inefficiently part-loaded generators and a reduced ability to integrate renewable generation, giving rise to economic and environmental costs.

As uncertainty in operational timescales increases and decision-making moves closer to real-time, the possibility for relying on post-fault control actions is a valuable source of flexibility and can result in significant savings by limiting the need for out-of-merit dispatch [5]. Power electronic devices that have already been deployed in GB such as PSTs, FACTS, SPS and HVDC networks have significant potential for enhancing real-time system controllability, thus reducing the need for preventive security measures [6]. Furthermore, the future development of demand response and energy storage solutions present an important opportunity for introducing a range of novel corrective actions to the operator's arsenal [7]. Although the increasing scope for corrective actions to maintain system security has been highlighted in the past [8] and recent surveys indicate their increasing use worldwide [9], this ability is largely ignored by current operational tools. The above highlight the need for novel modelling approaches that consider all available corrective actions in order to facilitate the efficient utilisation of available generation resources and network assets, while ensuring system robustness without pre-constraining the network. With the on-going shift towards post-fault security there is a growing need to consider system dynamic phenomena across a broad range of time constants ranging from micro/milliseconds to hours and the development of appropriate models is becoming critically important.

1.3 Modelling Requirements for Decentralised System Operation

The shift from a centralised to a more decentralised operation model will open new opportunities for enhancing cost effectiveness and security performance of future electricity system. This will be supported by the development of advanced active network management models that will enable more cost effective integration of future generation and demand technologies in local distribution networks. In stark contrast to the present approach, control algorithms deployed within a fully decentralised paradigm will be meeting dynamically changing objectives while the network topology, network conditions and control infrastructures are also changing, with the aim to deliver a truly integrated self-controlling, self-optimising, self-healing and self-protecting electricity network.

2. THE WAY FORWARD

In the context of the above discussion, this section will map out the principal functional specifications of future modelling tools that will enable more efficient and robust system operation. The increasing deployment of monitoring equipment presents an unprecedented opportunity for operational practices to be significantly better informed by real-time measurements. System controllability will be increasingly enhanced through application of new network technologies and a more responsive demand side, expanding the control choices available to system operators. Although the complexity of the electricity system is bound to increase as a result of the above, recent advances in the fields of mathematical programming, statistics, machine learning and power system simulation can be leveraged to construct suitable modelling tools to assist with real-time system operation. To this end, we identify advances in relevant research areas that will be useful in filling the gaps of current modelling and will be instrumental in propelling system operation into the new era of smart grids.

2.1 Enhancing the Whole-system Visibility and Predictability

Supporting Coordinated Control of Distribution and Transmission Networks through Enhanced Measurements and Advanced State Estimation.

New concepts aimed at enhancing visibility and controllability of distributed energy resources (DER) from the transmission level are gaining traction. In this context the Virtual Power Plant (VPP) is a flexible representation of a portfolio of energy and/or demand-side resources, abstracted in such a way to be fully controllable by a TSO (or DSO) and capable of providing a range of balancing and ancillary services [10].

Of course, maximising all synergistic effects through deriving appropriate control parameters and robust operating limits is a challenging task, especially when intermittent sources are involved [11]. However, the use of such concepts in future system operational tools is essential for a closer integration between transmission and distribution systems, enabling the optimal use of available resources and system assets across all voltage levels, and this is an area that will require significant further modelling work.

One of the important questions would be to examine the extent to which the flexibility embedded within the distribution networks can be used to provide network services such as active and reactive power, voltage control and various forms of reserves at the point of connection with the transmission network. One of the key challenges is to develop models of the aggregated dynamic responses of the DERs and deal with the uncertainty associated with their availability and level of response. This will be critical for providing the necessary assurance to the system operators that the DER will be able to support the operation of the system at the national level whilst respecting the local distribution network operating constraints and limits. This will enhance the interface between distribution and transmission network and enable the development of a whole-system approach to cost-effectively integrate and actively control DER in support of operation of both distribution and transmission networks. In addition, it is envisaged that new entities such as aggregators, smart energy communities and smart cities will further support the behavioural change challenges associated with large-scale uptake of DER at the household level.

In order to facilitate this development, novel modelling tools are required to take full advantage of the increasing amount of information and data that is starting to be become available to system operators. State estimation in combination of real-time measurements obtained via PMUs has been used to enhance visibility and generate a realistic a picture of the system condition in real time [12]. In recent years, a number of topics in the area of distribution network state estimation have been considered. Several state estimation algorithms are being developed to address erroneous data and make up for cases of limited measurement coverage, ranging from the use of traditional techniques such as maximum-likelihood estimation or Bayesian inference frameworks [13] [14]. Furthermore, alternative approaches to state estimation are being considered, as the weighted least squares estimator, that is commonly employed, is not particularly robust, i.e., it may fail to resolve the network conditions in the presence of inaccurate measurements; similarly, models for state estimation of unbalanced networks are being now considered; in addition, significant effort has been focused on optimal placement of PMUs at appropriate locations [15]-[39].

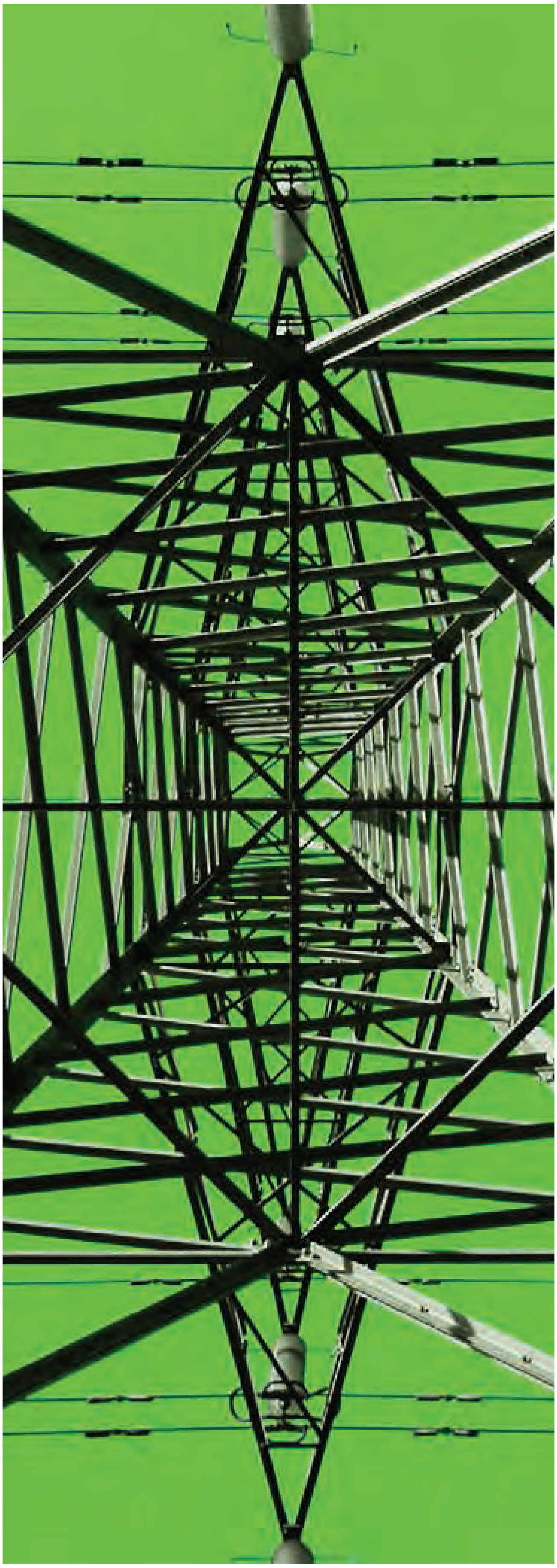
At the same time, the large-scale deployment of smart meters can enable a bottom-up approach towards increasing visibility at distribution level demand and generation patterns. The smart-grid paradigm with its telecommunications, monitoring and control functions is further changing the distribution operational doctrine from passive to active. A wealth of new measurements (e.g. voltage, line flows, topology states) will become available to system operators, enabling the smarter real-time control of their networks [40].

Further areas of modelling work should include application of state estimation techniques to provide not only robust and global system observability in real-time, but also include assessments of uncertainty associated with system stability margins, which will be an important criteria not only for deployment of PMUs but also for determining the set of preventive and corrective controls needed to enhance system resilience.

Informing Relevant System Operation Scenarios from Historical Data

Another way of leveraging system monitoring data lies in constructing an ever-expanding database of past system states. By comparing past forecasted and realised system states, the statistical characterisation of the different uncertain variables and the corresponding prediction errors becomes possible. Such information will be instrumental in gaining a deeper understanding of the way different uncertainty sources are correlated between them as well as of the operator’s ability to forecast them. The latter can be fundamental in quantifying the level of risk that different operational decisions entail and ultimately inform the dynamic allocation of ancillary services. This utilization of real-time and historical data will be an instrumental step towards moving beyond current deterministic approaches towards more advanced modelling platforms that can explicitly consider the stochastic nature of system operation variables. Further investigation of advanced statistical techniques such as vine copulas along with clustering and dimension reduction methods [41]-[50] will be a fundamental step towards the accurate modelling of the high-dimensional uncertainties that characterize electricity system operation.

Naturally, decision-making models will have to evolve in a similar manner and take advantage of this wealth of new information. The main step towards this direction is the explicit consideration of uncertainty within operational models. The deterministic models currently used ensure system security and efficiency along a single best-guess worst-case trajectory; decisions are in the form of sequential actions and do not consider the need for recourse to deal with alternative realizations.



In practice, operational planning spans several timeframes from day-ahead to real-time with the operator's objective being the identification of the optimal preventive and corrective actions to best cope with a multitude of possible operating points and potential faults. As a result, actions must be identified ahead of time so as to ensure that the system will be tenable under all different eventualities [51]. It follows that this task entails detailed consideration of the statistical and temporal properties of the different uncertainty sources. By accurately capturing the inter-temporal resolution of uncertainty in the system [52] it is possible to identify which scenarios must be addressed pre-emptively 'here-and-now' by finding and engaging suitable openings for strategic action and which scenarios can be dealt with in the future, thus deferring decisions on a 'wait-and-see' basis. Thus, an important consequence of non-deterministic approaches is that ancillary service requirements are not defined a priori, but are optimised against the operator's risk-averseness according to the current operating point and the uncertainty it entails towards its short-term evolution.

2.2 Optimising Short term Operation of the System Under Uncertainty

Most of the current operational system modelling tools rely solely on deterministic analysis. High levels of renewable generation combined with the growing decarbonisation of heat and transport sectors, alongside with emergence of flexible technologies dispersed storage and demand side response means that traditional energy usage profiles will be changing rapidly and the tasks of demand forecasting and real-time system balancing are set to become even more complex [3].

Stochastic Generation Scheduling

In a probabilistic context, the objective of stochastic methods is the minimisation of expected system cost while respecting the system's physical and security constraints. Stochastic optimisation techniques have been successfully applied to system scheduling problems in the past, , focusing on uncertainty due to demand [53], renewable generation [54] and demand-side response [55].

In addition, novel modelling methods such as robust optimisation can move beyond risk-neutral stochastic problem formulations and identify the operational strategy that performs optimally under all possible realisations. This is achieved by employing uncertainty sets to define the range of possible realisations [56] [57] [58].

Naturally, such approaches are more conservative and are typically driven by the worst possible realisation. Incorporation of spectral risk measures such as the Conditional Value at Risk [59] and chance-constrained programming [60] are more flexible methods for modelling risk-averse behaviour, enabling operators to minimise costs while abiding to a pre-defined risk profile.

Enhancing the existing modelling is required to deal with multiple sources of uncertainties; in addition to supply side uncertainties, particularly relevant are demand side response (DSR) uncertainties, as the preferences and requirements of demand response cannot be accurately predicted on a day-ahead or even hour-ahead timescale. Representative examples include the temperature set-points of heating systems and the availability and willingness of consumers to respond to a control signal. In a preliminary effort to model the effect of demand uncertainty, the demand side is considered elastic, with the parameters of the price-demand curve modelled as uncertain variables [61]. However, price elasticity cannot accurately capture fully the complex operational properties of DSR technologies.

It is also important to stress that one of the most challenging aspects of stochastic and robust optimisation techniques is computational intractability due to the dramatic increase of the size of the problem. It is also worth noting that increasing cross-border interconnection capacity will further couple GB system operation with the rest of the continent, further increasing problem size. Multi-stage stochastic methods employ scenario trees to capture possible evolution paths of the uncertain variables of interest, informed by historical data of prediction errors [62]. Given the temporal coupling of operational decisions due to ramping constraints, minimum up/down times etc., these scenario trees usually span several hours and can grow very large in size. This issue is especially evident in the presence of high-dimensional uncertainty, where the combinatorial explosion of possible future scenarios is usually managed by limiting the resolution of the undertaken analysis by variable aggregation. As a result, scenario reduction techniques [63] are gathering growing interest, with various algorithms focusing on different aspects of uncertainty, such as extreme cases via heuristic selection [64] and user-defined distribution quantiles [62]. Another type of approach is Stochastic Dual Dynamic Programming (SDDP), which utilizes the full description of uncertainty; Monte Carlo simulations are sequentially run to obtain linear approximations of the expected cost of each stage [65].

Although, such decomposition techniques currently rely on problem convexity and have limited uses in real-time operational modelling, recent efforts have indicated ways to extend to mixed-integer non-linear problems [66].

Security-Constrained Dispatch Models

Even with a severely reduced description of uncertainty, security-constrained operational problems are notoriously hard to solve for systems of realistic size [67]. The backbone of electricity system modelling is AC Optimal Power Flow (ACOPF); although linearization efforts are growing in number [68] it remains a fundamentally non-linear problem. Modelling complexity is further aggravated by the growing number of controllable variables related to energy storage, demand-side measures and VPPs; inter-temporal constraints are necessary to coordinate actions across a multi-hour horizon. Furthermore, abstraction of distribution systems as easy-to-predict passive loads is no longer adequate; advanced models capable of inferring demand variability while considering the technical characteristics of each subsystem (e.g. penetration of electric vehicles, presence of DER schemes, local district heating systems etc.) are increasingly becoming necessary. In a similar vein, another major source of computational complexity is the vast number of security constraints that describe and couple pre and post-fault operating conditions. To this end, a number of developments will enable solving operational problems more efficiently. Significant efforts have been made to alleviate the computational burden imposed by security constraints, through solving reduced but equivalent problems [69]. In addition, suitable decomposition techniques such as bi-level programming, Benders decomposition and Lagrangean Relaxation that can split the multi-horizon operational problem into more manageable contingency-specific subproblems are being investigated [51],[70]-[75]. However, the challenges of increasing spatial and temporal uncertainty resolution, ensuring system robustness against an exhaustive list of credible events and identifying optimal decisions on a rolling planning basis from day-ahead to real-time, remains a very challenging task. Given that the full problem is very complex to be tackled directly, heuristic-based techniques that focus on a few worst possible cases are rising in popularity [76]. As the range of possible system states expands dramatically, future security dispatch modelling tools will need to comprise of successive contingency-filtering stages of increasing complexity, combining uncertainty description modules with suitable optimization techniques [77]-[79].

Modelling of Corrective Security

As mentioned earlier, another highly important feature of operational models is the consideration of corrective security, an aspect which further couples pre and post-fault operation. Given TSOs' current reliance on preventive measures, existing research models take a simplistic view and only a handful of post-fault actions are modelled [80]-[83]. However, along with the new technologies introduced to further enhance operators' capacity for corrective actions (FACTS, HVDC, demand-side response etc.), novel models will need to be designed so as to take advantage of this emerging operational flexibility. Furthermore, the possibility of failure or non-delivery of the corrective actions is currently not considered, which may have dire consequences on an already-stressed system [84]. To this end, it is important to adopt a probabilistic approach towards dependability of post-fault control by developing models that explicitly consider the different failure modes for each control action (including the possibility of failure due to data communication error or untimely signalling due to increased latency and delays etc.) and can balance between the risk of involuntary load shedding and the cost of relevant corrective control actions.

Multi-time Scale Modelling

With the on-going shift towards post-fault security and increasing reliance on power electronics, the high penetration of renewable sources that do not provide inertia response [85][86] and the interconnectedness characterizing modern electricity systems, there is a growing need to consider system dynamic phenomena across a broad range of time constants ranging from micro/milliseconds (e.g. line switching, power electronics) over seconds (e.g. long-term dynamics) to hours (steady-state) [87]-[89].

The development of such modelling tools entails some significant challenges and as a result of the different simulation time steps required, there is currently no single tool capable of performing exhaustive dynamic analysis; the growing interest towards equation-based modelling languages is aimed at tackling this issue [90].

The final challenge is the incorporation of dynamic behaviour in operational optimization problems; the non-linear nature of these phenomena cannot be accommodated in a traditional optimisation framework. Instead, research efforts worldwide (e.g. [91]) are focusing on alternative modelling setups, where a large number of dynamic simulations is run offline and the results are distilled in expressions suitable for optimization purposes.

Once a large number of dynamic simulation results are available, machine learning techniques can be applied to infer more generalized rules, essentially denoting the domain of safe dynamic operation in terms of steady-state pre-fault control variables. Decision trees have been used for this purpose in the past, successfully expressing dynamic stability boundaries for a specific contingency in simple linear expressions [92]. However, building such a Monte Carlo simulation framework is very challenging due to the state-space's high dimensionality and non-Gaussian nature; ensuring that the machine-learning algorithm is being trained on relevant system conditions becomes a critical issue. Given that system behaviour cannot be explored in its entirety, past historical data can be used to infer which areas of the states-space are likely to be encountered in the future and should be analysed further. The use of advanced high-dimensional statistical models [93], dimension reduction and clustering techniques can be instrumental in this context to further enable high sampling densities for enhanced state-space exploration. The applicability of such multivariate statistical workflows employing vine copulas to capture the complex dependence structure of stochastic variables has only recently been demonstrated in the context of a Monte Carlo operational simulation framework [91].

Alternative approaches may involve direct incorporation of simplified dynamic models, described by differential equations, into algebraic optimisation framework. This is likely to be effective in the context of generation scheduling models that need to include dynamic frequency constraints, particularly driven by reduced system inertia in systems with high penetration of renewable energy sources [94][95]. However, further work is needed to incorporate post-fault dynamic frequency requirements (maximum rate of change of frequency - RoCoF), minimum frequency nadir and minimum steady-state frequency, while considering different load dumping effects. This will be critical for understanding the ability of the system to integrate renewable generation and corresponding cost implications.

Defence Plans and System Restoration Models

Many of the above discussion points are also particularly relevant to the development of models oriented towards system defence plans and restoration measures. Defence plans are deployed internationally to outline the critical procedures necessary to form back-stop defences and safeguard the transmission system and minimise the adverse impacts of extreme fault events, that can lead to load shedding and wide-area blackouts [96].

Given the short timescales of such phenomena, defence plans currently rely exclusively on coordinated automatic and manual measures; special protection schemes such as load or generation curtailment, reactive switching, bus or system splitting etc. that are engaged when a widespread collapse is imminent [97]-[101]. However, given the limited visibility that TSOs currently have, the key concern is that the growing uncertainty may undermine the viability of traditional measures in the absence of full information regarding the current system state. For example, load curtailment by feeder tripping in the presence of uncertain distributed generation output is no longer a straightforward option and should be exercised with caution in order not to push the system further towards instability. Ideally, defence plans and the corresponding restoration procedures need to take into account of the on-going advances in system monitoring and visibility and consider all potential courses of post-fault action available across the grid, from making use of demand-side response, topology switching and FACTS operation to engaging distributed sources through controlling VPPs. A related topic of growing interest, especially in continental Europe, is investigating the scope for coordination with neighbouring systems. To this end, novel operational models capable of orchestrating a multitude of corrective automatic actions across voltage levels will need to be developed to assist operators in handling critical events in real-time with the minimum possible disruption of service.

2.3 Modelling Requirements for Decentralised System Operation

The shift from a centralised to a more decentralised operation paradigm will open new opportunities for enhancing cost effectiveness and security performance of future electricity system. In this section the discussion is focused on the future development of advanced active network management models that will enable more cost effective integration of future generation and demand technologies in local distribute networks. Furthermore, modelling requirements for Autonomic Power Systems are discussed with the objectives to achieve fully distributed decision making process with the objective deliver a truly integrated self-controlling, self-optimising, self-healing and self-protecting electricity network.

Modelling of Operation of Future Distribution Networks

It is widely recognised that the present distribution networks is much less instrumented, automated and actively controlled than the transmission networks. There are two key reasons to increase the degree of real-time control of distribution networks:

a) First is related to the increase in penetration of Distributed Generation (DG) that has initiated development of active network management (ANM) schemes including coordinated control of DG output in conjunction with area-based transformer tap settings and other control equipment on the basis of real-time operating condition. It is now well recognised that significant increase in controllability of distribution networks will enhance its ability to integrate new forms of distributed generation and flexible demand side response while reducing the need for network reinforcement.

b) The second driver for enhancing real-time control of distribution networks is the need to improve quality of service delivered to end consumers. The high level of interconnection and level of redundancy in transmission networks cannot be replicated at distribution level, but instead control and automation could deliver rapid post-fault restoration through real-time assessment of reconfiguration options. There is also a growing body of expertise in condition monitoring of distribution equipment that could lead to pre-emptive reconfiguration around equipment judged to be likely to fail.

These concepts in their basic format are becoming well established and could be further enhanced through recent advanced modelling activities [102]-[125]. However, further modelling is needed for facilitating the application of such schemes at *scale*, while fully coordinating pre and post fault actions of demand side, storage, distributed generation and emerging advanced network technologies, particularly power electronics based, are yet to be developed.

In addition to real-time distribution network state estimation models (using only a limited amount of real-time measurements) that are discussed above, there are that several key modelling tools are yet to be investigated including:

- Models for real-time computation of security and quality indicators including assessment of network steady state and stability margins.
- Models for preventive optimisation of network configuration based on predicted load, generation line ratings including: pre-fault optimisation of settings of

network control devices while considering condition of distribution circuits and switching equipment; this would be a multi-objective optimisation model that balances network security margin, DG export levels, power quality and network power losses.

- Real-time, post fault network re-configuration / restoration including optimisation of settings of network control sources (active reactive power control, voltage control) optimisation of response of distributed generation, demand side response and distributed storage.

This will require development of complex, large scale, non-linear security constrained multi-period optimal power flows, that can optimise not only control actions of distributed resources but also network topology and in future control of electronic substation and soft normally open points. Such models have not yet been developed. Further enhancements of the above models should include risk constrained approaches to directly deal with uncertainties associated with predictions of demand and generation, dynamic rating of overhead circuits (as discussed earlier), including the impact of delays, inaccuracies and losses of real-time measurements. Also, there will be uncertainties associated with post-fault actions that would need to be taken into account.

Modelling Requirements for fully Autonomic Power Systems

Current development of smart grid concepts is continuing to deliver novel ways to operate and control sections of transmission and distribution networks. However, to cope with the uncertainty and complexity engendered in moving to future decarbonised energy networks, flexible system-wide approaches may be necessary. In this context, Autonomic Power Systems (APS) is a system-wide concept, which provides a flexible and adaptable approach through fully distributed intelligence and control where decentralised, low-level intelligence autonomously makes the decisions necessary to meet the high-level goals of the power system's stakeholders [126]. In other words, in an APS control decisions will be made locally rather than by a single centralised authority and should deliver a truly integrated self-controlling, self-optimising, self-healing and self-protecting electricity network. In stark contrast to the present network control standard, control algorithms deployed within an APS will be meeting dynamically changing objectives while the network topology, network conditions and control infrastructure are also changing.

A significant paradigm for building such distributed systems is Multi-Agent Systems [127], [128]. One approach for coordination being investigated in the APS research is the use of Distributed Constraint Optimisation (DCOP), particularly for arbitration and negotiation within decentralised and distributed multi-agent control systems where conflicting control decisions may arise. Significant work is however required to develop comprehensive APS models and then carry out the analysis and comparison of distributed intelligent methods for applications such as voltage control, frequency control, thermal constraint management, reconfiguration and control decision arbitration. Such models are needed to test the robustness and scalability of the self-organising architecture and carry out a comparison with existing control philosophies in order to evaluate the advantages and disadvantages of APS concept. This would also inform the operation and control of local community and smart cities energy systems and their integration within the national level system operation and control.

3. CONCLUSIONS AND RECOMMENDATIONS

Almost all aspects of transmission and distribution operation will be impacted by the oncoming paradigm of increased stochasticity and controllability. Modelling tools capable of informing real-time decisions are quickly becoming a necessity in network control rooms in order to accommodate developments that reduce carbon intensity while retaining energy affordability and maintaining historic security levels. This trend is set to continue with the increasing dependability on intermittent energy sources and the ever-expanding number of control choices available to transmission and distribution operators.

From the above discussion, the four main trends towards operational modelling could be summarized as: (i) The shift of operational doctrine from empirical practices based on comfortable security margins and drawn a priori for generic states of the system to the development of operational platforms capable of providing bespoke recommendation tailored to the real-time operating point and the envisaged short-term uncertainty. (ii) Further integration between the local community and smart cities energy systems, distribution system operators, transmission system operators and coordination with the EU transmission wide system operators, so as to make optimal use of all energy and flexibility resources and network assets available across all voltage levels and cross border; upstream and downstream systems are not treated as passive elements, but proper interfaces are established in order to reach global optimality. (iii) Operational models that take advantage of all available control choices on the basis of cost efficiency and adequate security. (iv) The shift from centralised to more decentralised operation paradigm will open new opportunities for enhancing cost effectiveness and security performance of future electricity system. In stark contrast to the present network control standard, control algorithms deployed within this concept will be meeting dynamically changing objectives while the network topology, network conditions and control infrastructure are also changing.

A number of modelling developments are needed for this vision to materialize in the coming decade. First of all, system operators must increase visibility to their networks by making appropriate use of new data streams becoming available through the deployment of PMU and smart-metering devices along with state estimation techniques. In the longer term, this need will increasingly extend to gas and heat networks. This data will not only be useful in informing real-time operational decisions but can also serve in characterizing the different uncertainty sources at a high temporal and spatial resolution. Furthermore, models will need to be synthesized to represent distribution-embedded resources and novel demand-side response schemes rendering them controllable from a systems viewpoint. The combination of the above can lead to the development of holistic stochastic optimization models that can operate on a rolling multi-horizon basis along with recommendations for preventive and corrective actions to secure the system against all credible disturbances. Naturally, the increasing number of models necessary to navigate this new reality of complex real-time system operation highlights the need for thorough model validation before deployment as well as the development of back-up system restoration procedures in the event that computer-supported system operation is compromised. Validation process of the robustness will indeed be very challenging for the advanced security modelling platforms since empirical data associated with large-scale disturbances is limited. To this end, recent advances in the fields of mathematical programming, statistics, machine learning, agent based modelling and power system simulation will need to be leveraged to construct novel modelling and validation tools and propel system operation to the smart grid era. Furthermore, the increasing relevance of multi-energy systems will require closer coordination between electricity system operators and the operators of other energy vectors for the exchange of information on a real-time basis. In addition, cross-industry effort is required for identification of all major interfaces between electricity, heat, gas and transport systems; empirical data on how these vectors interact at operational timescales will be essential in rendering multi-energy systems modelling a tractable task.

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