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Choosing appropriate power system simulation models for different events

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Abstract

This report forms a discussion relating to what types of power system models there are and what software packages are available to investigate different power system phenomena. The responses which might emerge to perturbations to the power system are tabulated to provide examples of *Automatic* and *Manual* interventions – that is, responses which can emerge endogenously from the system or those which can be controlled by human operators over different timescales. Similarly, the types of simulation models which could be used to investigate these different aspects are described and how they may interact or be leveraged in a wider-ranging resilience assessment. These are categorised based on being either *Initial Condition Simulators* that allow a range of different system conditions to be postulated, defined in such a way as to allow subsequent assessment of the impact of disturbances, or *Power System Perturbation Simulators* such as dynamic simulators which model the impacts of disturbances on these original conditions, such as short circuits or loss of generation infeed.

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Introduction

An accompanying report, *Defining the Simulation Scope for Extreme Events* [1], produced as part of the Scenarios for Extreme Events project [2], explored the potential scope of modelling extreme events, in particular how to model the energy system when subjected to extreme weather events, though there was also discussion of non-weather events. It discussed, for example, how to link a wind speed to a failure probability on a given asset [3, 4], and models also exist to determine non-weather extreme events and their impacts, such as how to relate a magnitude of earthquake to the level of damage to a distribution substation [5]. However, the energy system itself and how it responds to these outages is a separate matter.

If we are to define an extreme weather "event" on the power system, there are various levels at which we could define what that "event" is. There is the causal "event" driving the weather system (e.g. a region of low pressure moving across an area carrying high winds), the "event" induced by the weather system (e.g. a pattern of high wind speeds), an outage or perturbation to the network on the power transmission system (e.g. transient outages due to flashovers caused by swinging of overhead line conductors, or permanent outages from mechanical failure of lines), or the power system's electrical and electro-mechanical response to that perturbation (e.g. frequency and voltage variations, potentially leading to disconnections of equipment).

Different levels of abstraction of the power system will facilitate different types of power system modelling, subject to temporal and computational constraints. That is, power system modellers must at all times make a choice balancing accuracy, precision, time (in both the building and use of a model), and computational cost. It is for this reason that power system simulation tools tend to be specialised for specific phenomena: a platform designed for the simulation of real-time frequency response and protection actions on a microgrid will not be appropriate to schedule generation on a national scale on the transmission system, for example.

Pairing the correct tool to the correct power system phenomena therefore is a non-trivial task, which is further complicated in the context of extreme weather due to the significant spatio-temporal ranges on which a weather system can act on the grid. In many cases, integrated simulation tools do not exist which combine features which may be desirable to co-simulate to capture the impacts of a large-scale power system disturbance. In these situations, it may be necessary to combine models or even generate bespoke simulation models using scripting languages such as *MATLAB* or *python*.

In [6], there is significant discussion about what models actually require to be useful and informative, and a key aspect is that there should be "an appropriate level of detail (spatial, temporal, physical) which allows the results to be meaningfully representative of the real-world system being analysed, and be open about the modelling choices made". Relatedly, in [7], more generally it is argued that the results of models and evidence presented to stakeholders should be appropriate to both the complexity of the challenge being investigated and the knowledge of those who are being presented to. That is, models should not be oversimplified to make the results easier to understand, nor should they be overcomplicated or "modelling for modelling's sake". This therefore means that choosing the appropriate level of abstraction for modelling power system resilience will be a key factor in determining the usefulness and success of any project investigating power system resilience.

The material presented here provides examples of different types of simulations for different types of "event" or perturbations which can affect the power system and tools which will be necessary to simulate them, either in terms of specific power simulation packages which could be used to model them based on some of the phenomena identified in the accompanying report or the more fundamental generalised categories into which different software packages may fall. They are categorised in terms of *Automatic* and *Manual* responses to power system disturbances, and *Initial Conditions Simulators* and *Power System Perturbation Response Simulators*. The former allow a range of different system conditions to be postulated, defined in such a way as to allow subsequent assessment of the impact of disturbances. The latter, such as dynamic simulators, model the impacts of disturbances on these original conditions, such as short circuits or loss of generation infeed. Further discussion of these issues can also be found in [8] and [9].

Power system utilities, most notably the network owners and system, use models of the system in different business processes in different timescales:

- “system development” that determines investment in new network facilities and system controls up to about a year ahead of ‘real-time’.
- “operational planning” that prepares for operation of the system up to a day ahead of ‘real-time’.
- “system operation” that concerns everything that happens ‘on the day’ including responding to events.

These processes and timescales are illustrated in Figure 1.

In the following pages, Table 1 summarises different types of disturbance or perturbation and how they affect a power system and its constituent parts including, specifically, automatic responses by protection and control equipment. It also summaries existing approaches to modelling the different disturbances and their impacts, many of those approaches being long-established in the sector and particular to different physical phenomena and sets of assumptions or approximations that simplify modelling. Table 2 summarises something similar but focussing on manual responses, i.e. actions taken by operators in a system control room, staff out ‘in the field’ at substations or making repairs on the network, or owners of generators, energy stores, interconnectors or loads connected to the network. Table 3 summarises different approaches to determining a set of initial power system conditions given a set of exogenous conditions such as demand for electricity, market prices, the initial availability of different power system assets, and weather conditions. It also notes the different timescales in which the various types of model tend to be used today. Finally, Table 4 presents a summary of existing forms of simulation that allow the power system impacts of different disturbances to be simulated given a set of initial conditions. It also includes non-exhaustive lists of examples of existing software designed to carry out the respective simulations and the timescales in which the different forms of modelling are commonly used at present.

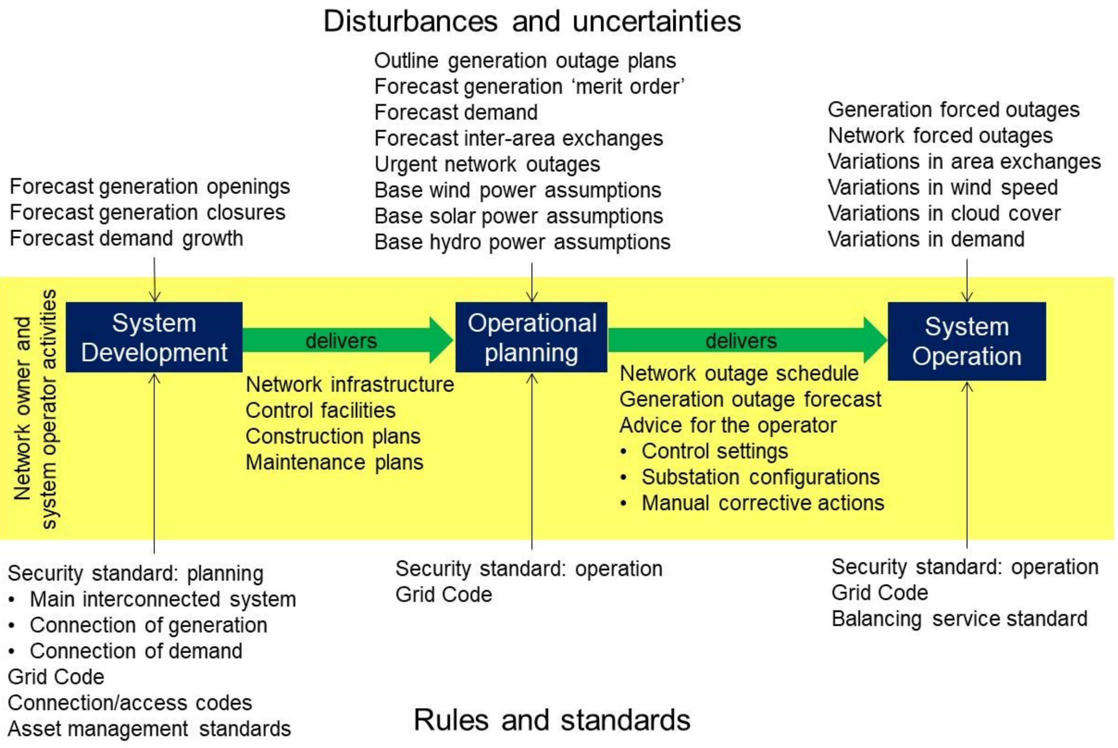

Figure 1: Network and system operator processes and their inputs and outputs

Table 1: Automated system responses to perturbations

TYPE OF PERTURBATION	***TEMPORAL RANGE OF PERTURBATION***	***RESPONSE(S)***	***RESPONDER(S)***	***MODELLING APPROACH(ES)***	***EXACERBATING FACTOR(S)***
SHORT CIRCUIT/FLASHOVERS - TRANSIENT	Microseconds - minutes	injection of current from voltage or current sources; switching of wind turbines and power electronic converters into and out of fault ride-through mode; isolation/tripping of circuits; generator excitation system responses; automatic restoration of circuits with DAR	protection equipment; Delayed Auto Reclosers (DARs); power electronic converters (PECs) including HVDC, wind farms, batteries and static Var compensators (SVCs); generator and synchronous compensator automatic voltage regulator (AVR)/excitation systems	Electromagnetic transient (EMT) simulation software to assess, in detail, the responses of protection and power electronic converters; Root-Mean-Squared (RMS) simulation software for assessment of electro-mechanical dynamics on large systems	Short circuits on bus sections lead to loss of multiple circuits; failure of primary protection and dependency on backup protection can lead to loss of multiple circuits; sympathetic tripping can contribute to cascading outages
SHORT CIRCUIT/FLASHOVERS - PERMANENT	Microseconds – hours	injection of current; switching into and out of fault ride-through mode; isolation/tripping of circuits; excitation system responses; automatic restoration of circuits with DAR; frequency response, demand response, voltage regulation	protection equipment; Delayed Auto Reclosers (DARs); power electronic converters including HVDC, wind farms, batteries and SVCs; generator and synchronous compensator AVR/excitation systems; automatic tap changers; frequency response, e.g. through governor action	EMT software, RMS simulation software, load flow software	Short circuits on bus sections lead to loss of multiple circuits; failure of primary protection and dependency on backup protection can lead to loss of multiple circuits; sympathetic tripping can contribute to cascading outages

PASSIVE OUTAGES WITHOUT FAULT CURRENT, E.G. LOSS OF GENERATORS OR INTERCONNECTORS DUE TO CONNECTED SIDE FAULTS, OR MANUAL SWITCHING DUE TO ALARMS	Microseconds – hours	Frequency response, demand response, voltage regulation	Generator governors, power electric devices, demand response, SVCs, AVRs, automatic tap changers, storage, PECs; system operator	RMS software, load flows, EMT software	Concurrent outages could lead to breaches of system limits and to cascading outages
GENERATION OR DEMAND RAMPING	Seconds - minutes	Frequency response, demand response, voltage regulation	Demand response, storage, frequency response, demand response aggregators, AVRs, SVCs, PECs, generation	RMS software, load flows, weather modelling	Can lead to high generation costs, tight margins, risk of cascading outages from frequency or voltage excursions or line overloads
CASCADING TRIPPING (NON-THERMAL)	Microseconds - hours	Failure of power electronic interfaced resources to ride through; failure of frequency response; hitting of controller limits leading to breaches of system limits; inadvertent or maloperation of protection; action of Low Frequency Demand Disconnection (LFDD); action of generator protection to trip generator	Power electronic converters; protection equipment; demand response; generation protection; Low Frequency Demand Disconnection (LFDD) relays; AVRs; governors	RMS software, weather modelling, load flows, EMT software	Can lead to breaches of system limits and action of protection to trip equipment

CASCADING TRIPPING (EXCEEDING THERMAL CAPACITY OF ASSETS)	Minutes - hours	flashovers triggering action of protection to isolate circuits;	protection equipment; system operator; automatic controls responding to short circuits and changes in voltages	load flows; RMS simulation; EMT simulation of protection and power electronic converter actions	Can lead to breaches of system limits and action of protection to trip equipment
CONTROLLER FAILURES	Microseconds - hours	Failure to inject correct current; failure to switch; failure to trip; failure to change tap position	Power electronic converters; demand response; Low Frequency Demand Disconnection (LFDD) relays; AVRs; governors; automatic voltage control on tap-changing transformers	RMS software, load flows, EMT simulations	Can lead to breaches of system limits and action of protection to trip equipment
GAS SUPPLY INTERRUPTIONS	Seconds - weeks	Tripping of generation	Generation	UCs, load flows, weather modelling, market simulations	could lead to power shortages and extreme market conditions; gas supply interruption may be due to high demand for gas due to cold, which also causes high electricity demand.

Table 2: Manual responses to system perturbations

TYPE OF PERTURBATION	***TEMPORAL RANGE OF PERTURBATION***	***RESPONSE(S)***	***RESPONDER(S)***	***MODELLING APPROACH(ES)***	***EXACERBATING FACTOR(S)***
SHORT CIRCUIT/FLASHOVERS - PERMANENT	Microseconds – hours	Switching, asset repairs, deployment of spares, backup generation, manual balancing mechanism action, manual action to re-dispatch voltage targets	System Operator; network field staff; actions by owners of flexible assets/balancing mechanism units/aggregators	load flow software; RMS dynamic simulation software	Short circuits on bus sections lead to loss of multiple circuits; failure of primary protection and dependency on backup protection can lead to loss of multiple circuits; sympathetic tripping can contribute to cascading outages; weather can hinder restoration
PASSIVE OUTAGES WITHOUT FAULT CURRENT, E.G. LOSS OF GENERATORS OR INTERCONNECTORS DUE TO CONNECTED SIDE FAULTS, OR MANUAL SWITCHING DUE TO ALARMS	Microseconds – hours	Switching, asset repairs, deployment of spares, backup generation, manual balancing mechanism action, manual action to re-dispatch voltage targets	System Operator; network field staff; actions by owners of flexible assets/balancing mechanism units/aggregators	load flow software; RMS dynamic simulation software	Weather can hinder restoration; concurrent outages could lead to breaches of system limits and to cascading outages
GENERATION OR DEMAND RAMPING	Milliseconds - minutes	Manual balancing mechanism action, manual action to re-dispatch voltage targets	System Operator; actions by owners of flexible assets/balancing mechanism units/aggregators	load flow software; RMS dynamic simulation software; weather modelling; decision support optimisation for the system operator	Low demand, high renewables scenarios can exacerbate severity of frequency deviations; can lead to high generation costs, tight margins, risk of cascading outages from frequency or voltage excursions or line overloads

TEMPERATURE EXTREMES	Hours - weeks	Manual balancing mechanism action, manual action to re-dispatch voltage targets; asset re-rating	System Operator; actions by owners of flexible assets/balancing mechanism units/aggregators; network owners	load flow software; RMS dynamic simulation software; weather modelling; decision support optimisation for the system operator	Can lead to shutoff of generation at high temperatures, or large concurrent outages on transmission networks associated with line icing; ice loading can lead to physical damage to assets.
RESOURCE SHORTAGE	Hours - weeks	Manual balancing mechanism action, manual action to re-dispatch voltage targets; rota disconnections	System Operator; actions by owners of flexible assets/balancing mechanism units/aggregators; network owners	load flow software; RMS dynamic simulation software; weather modelling; decision support optimisation for the system operator; demand forecasting; modelling of forward energy markets	There are both long-term and short-term supply interruptions - i.e. Ukraine an example of a shock to prices that continues for a long time, whereas e.g. a pipe explosion could cause a sudden interruption of supply to a region rota disconnections are a possible action but they raise political questions
CASCADING TRIPPING (NON-THERMAL)	Microseconds - hours	Manual balancing mechanism action, manual action to re-dispatch voltage targets; rota disconnections	System Operator; actions by owners of flexible assets/balancing mechanism units/aggregators; network owners	load flow software; RMS dynamic simulation software; weather modelling; decision support optimisation for the system operator	Can lead to breaches of system limits and action of protection to trip equipment
CONTROLLER FAILURES	Microseconds - hours	Manual balancing mechanism action, manual action to re-dispatch voltage targets	System Operator; actions by owners of flexible assets/balancing mechanism units/aggregators; asset owners to	load flow software; RMS dynamic simulation software; EMT simulation to investigate protection or	In a cybersecurity context it's possible multiple sites using the same firmware could be subject to the same attack at the same times, meaning a severe common cause fault; can lead to breaches of

			investigate and correct failure	control performance in detail	system limits and action of protection to trip equipment
GAS SUPPLY INTERRUPTIONS	Hours - weeks	Manual balancing mechanism action, manual action to re-dispatch voltage targets; rota disconnections	System Operator; actions by owners of flexible assets/balancing mechanism units/aggregators; network owners	load flow software; RMS dynamic simulation software; weather modelling; decision support optimisation for the system operator; demand forecasting; modelling of forward energy markets	There are both long-term and short term supply interruptions - i.e. Ukraine an example of a shock to prices that continues for a long time, whereas e.g. a pipe explosion could cause a sudden interruption of supply to a region rota disconnections are a possible action but they raise political questions
CASCADE FAILURE (EXCEEDING THERMAL CAPACITY OF EQUIPMENT)	Minutes - hours	Manual action to switch out overloaded circuits; manual balancing mechanism action to change power flows and replenish power reserve; manual action to change voltage targets	System Operator; actions by owners of flexible assets/balancing mechanism units/aggregators	load flow software; RMS dynamic simulation software	Can lead to breaches of system limits and action of protection to trip equipment

Table 3: Models for generating initial conditions

TYPE OF MODEL	*EXAMPLE SIMULATOR PACKAGE(S)*	*EXAMPLE USER(S)*	*NOTES*	*INVESTMENT PLANNING TIMESCALES*	*OPERATIONAL PLANNING TIMESCALES*	*OPERATIONAL TIMESCALES*
OPTIMAL POWER FLOW	OATS [10], Powerfactory [11], Pandapower [12], MATPOWER [13], PyPSA [14]	Academics, consultants, market operators	Not commonly used in practise in industry; generally load flows used. Not all OPFs have the ability to optimise against security constraints or voltage and reactive power constraints. Highly sensitive to poor data.	✓	✓	
MARKET AND RESOURCE ADEQUACY MODELLING AND OPTIMISATION	Plexos (also known as Energy Exemplar) [15], BID3 [16], ANTARES [17], RETScreen [18], Homer Energy/Legacy [19], NEPLAN [20], PyPSA	Academics, consultants, system planners, policy makers	Vary significantly in scale, in practise in industry often outsourced. Not commonly used in operational planning or system operation timescales.	✓		
STATE ESTIMATION	Energy Management Systems (EMS)	Control room operators	EMS vendors often outsource development and maintenance to specialists			✓
MONTE CARLO SIMULATION	Powerfactory, Plexos, BID3, ANTARES	Academics, consultants, investment planners	Vary widely, often bespoke solutions generated using scripting languages. The Monte Carlo aspect involves sampling of events, perhaps also of initial conditions. Assessment of impact of events might be done using load flows or RMS simulation and might involve sequences of events. Operator	✓		

TYPE OF MODEL	*EXAMPLE SIMULATOR PACKAGE(S)*	*EXAMPLE USER(S)*	*NOTES*	*INVESTMENT PLANNING TIMESCALES*	*OPERATIONAL PLANNING TIMESCALES*	*OPERATIONAL TIMESCALES*
			responses might also be modelled, e.g. via OPF.			
UNIT COMMITMENT	Powerfactory, PyPSA	Academics, consultants, investment planners, generation operational planners; system planners; market operators	Often also outsourced or in-house solutions.	✓	✓	

Table 4: Simulation models for power system perturbation simulations

TYPE OF MODEL	***EXAMPLE SIMULATOR PACKAGE(S)***	***EXAMPLE USER(S)***	***NOTES***	***INVESTMENT PLANNING TIMESCALES***	***OPERATIONAL PLANNING TIMESCALES***	***OPERATIONAL TIMESCALES***
RMS DYNAMIC SIMULATION	Cyme [21], PSSE [22], Powerfactory, Eurostag [23], OpenDSS [24], Simulink [25]	Control room operators, investment planners, academics, consultants, operational planners	Well-established, lots of proprietary software. Detail of controller models often hidden deep within an interface or hard-coded	✓	✓	✓
MONTE CARLO SIMULATION	Powerfactory	Academics, consultants, investment planners	Vary widely, often bespoke solutions generated using scripting languages. The Monte Carlo aspect involves sampling of events, perhaps also of initial conditions. Assessment of impact of events might be done using load flows or RMS simulation and might involve sequences of events. Operator responses might also be modelled, e.g. via OPF. Not commonly used in operational planning or system operation timescales.	✓		

TYPE OF MODEL	*EXAMPLE SIMULATOR PACKAGE(S)*	*EXAMPLE USER(S)*	*NOTES*	*INVESTMENT PLANNING TIMESCALES*	*OPERATIONAL PLANNING TIMESCALES*	*OPERATIONAL TIMESCALES*
LOAD FLOWS	OATS, Powerfactory, PSSE, NEPLAN, Cyme, Pandapower, MATPOWER [26], Powerworld [27], OpenDSS, Eurostag, PyPSA	Academics, consultants, control room engineers, investment planners, design engineers	"DC" approximation often used in investment planning. Different levels of ability to model SVCs, distributed slack bus, voltage control on transformer tap changers.	✓	✓	✓
REAL-TIME/EMT	RSCAD/RTDS [28], Opal-RT [29], PSCAD [30]	Control room operators, academics, protection designers, investment planners	Complicated, expensive, requires advanced computing hardware. Rarely used to support operational decisions. Used mainly to support equipment design and standards.	✓		
SYSTEM RESTORATION	No standard software packages: an excel-based software package is used within the ESO in Britain to support strategy and contracting; some tools in development worldwide to provide advice to the system operator during a restoration process.	Academics, consultants, system operators, investment planners	Tend to be many different approaches within academia but rarely "go anywhere" material	✓		✓

Summary

Various aspects of modelling, and models themselves, have been categorised in this report to illustrate some of the challenges involved in modelling disturbances or perturbations that impact power system operation and against which resilience is required. These disturbances do not form a complete inventory of events which can impact the energy system, with primarily power-system-related phenomena discussed, but should help guide future directions and developments to any modelling intended to assess power system resilience and the impacts of any actions aimed at improving it.

Demarcating what is a human-driven response versus a system-driven automated response is important because this can help determine whether changes to improve power resilience rely more on procedural improvements or improvements to infrastructure and protection and control facilities, or what that balance should be, and what kind of investments or changes to standards should be made for best returns on investments or effort.

It is important to understand what tools are available to be leveraged to avoid “reinventing the wheel” and ensure the adding of value. Similarly, understanding what models can and can’t do is important for understanding what evidence they can be expected to generate – a linearised “DC” load flow can, for instance, inform us if there are sections of the network at risk of being overloaded, and if it is hypothetically feasible for real power to get from source to demand, but cannot in and of itself tell us about what level of risk a section of network is subject to due to voltage or frequency excursions. Such information can be inferred indirectly, however. A large amount of load disconnection in a DC optimal power flow (OPF) – a tool that uses both a linearised model of the network and, if suitably defined, a simplified model of generator frequency response – will imply a significant imbalance of supply and demand at the point of outage, hence a large RoCoF, and thus a significant frequency excursion. The DCOPF might also – again, if suitably configured – identify operator actions, including generator or load curtailment, to respect network branch loading limits. Any of these outcomes would then suggest the need to take the modelling a step further to investigate localised frequency and voltage impacts using other tools.

For heavily constrained networks approaching technical limits of operability it may not take significant perturbations to the system to cause cascades of outages, and especially if those limits are further affected by extreme ambient temperatures affecting the thermal ratings of overhead lines and transformers. Current modelling approaches typically do not incorporate real-time models of thermal ratings, but such a feature could be significant in cascading outages going forward and merit further investigation. So, too, do the protection capabilities and settings of assets on the system and the standards used to design mitigations – what was once a 1 in 100-year flood may become a 1 in 10 year event due to urban development or changes in weather patterns, and hence infrastructure which was once resilient to those events may no longer be so.

Relatedly, outages on the gas system which prioritise consumers ahead of gas generation could cause major problems on the electricity system if it is heavily dependent on gas-fired generation at the time, illustrating a key complexity in the modelling which will need consideration in future whole system models. Determining which modelling adaptations should take priority for further work on resilience and how those modelling changes should be implemented will be a significant body of work in its own right.

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