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Clean Energy Research Cluster

P1: Power and Energy Systems Modelling and Security

Milestone Report 1a - CSIRO Future Grid Flagship Cluster

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Milestone 1a Report

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Preface

The goals of project P1 are to:

1 Explore the capability of the grid to adapt to the changing energy supply mix over future decades and possible scenarios which improve the resilience to expected changes.

2 Develop detailed static and dynamic models of clusters of diverse generation, loads, and transmission systems with DC and AC options, FACTS devices, global control schemes and storage in a selected software platform.

3 Perform typical static and dynamic stability studies in "future electric power grids" with the packages developed in Step 2 above for the integration of renewable energy, storage and loads through case studies based on the Australian grid and motivated by scenarios from a wide range of sources

4 Expand our current work with TransGrid to the NEM on assessing the maximum penetration of different generation sources at locations (allowing for limited transmission augmentations and stabilising control) to meet the stability limits.

5 Model the impact on grid performance of various scenarios and options including demand management, energy efficiency measures, distributed generation and the technical requirements for successful application of demand response while considering climate conditions, electric vehicles and smart grid technologies.

6 Build on the experience of the existing team in storage technologies and trends, to investigate different technologies, alternative architectures for connection to the grid, i.e. LV versus HV or both, and coordinated control schemes for their relative capabilities in enhancing the stability and security of the transmission network.

7 Study other dynamic interactions such as between the electricity and natural gas, transport networks and the ancillary services in the electricity markets in conjunction with P2.

List of Abbreviations

ACE	Area Control Error
AGC	Automatic Generation Control
BAU	Business as Usual
CSP	Concentrating Solar Power
DG	Distributed Generation
DNSP	Distribution Network Service Provider
DSP	Demand-Side Participation
EV	Electric Vehicle
FACTS	Flexible AC TRansmission System
NEM	National Electricity Market
NER	National Electricity Rules
PV	Photo Voltaic
RE	Renewable Energy
SWIS	South West Interconnected System
VCPI	Voltage Collapse Proximity Indicators
VG	Variable Generation
WECC	Western Electricity Coordination Council of USA
WF	Wind Farms

1 Literature Review

In conventional power systems, large thermal power plants have been the main objects underpinning the whole operation. They have mostly been the source of electrical energy and centralised system control. They were placed close to the basic energy supplies (coal, gas) and water and later (after concerns about air pollution) not too close to people's backyards. Then transmission networks (referred to as 'the handmaiden of generation' [1] were built to ensure demands were met efficiently (physically) and later according to the market (economically). The load demand was variable, but the generation was able to follow by a combination of dispatch and regulation processes. Among other system needs, a priority after basic balancing of energy and power is to ensure that power flows and dynamics are within bounds and stable (for angle, frequency and voltage) in normal operation and after events (faults, failures). The further requirements here are ramping ability and stability. We can compare with driving a car where we need energy (enough fuel), power, acceleration and stability on the road as the car drives harder and copes with different events. Scale this picture up to a system with hundreds of oscillating type machines all connected by a network of energy flows and we get a very complex system, arguably the most complex human-made system ever built. It is an engineering achievement that is often underestimated, particularly for how few collapses occur! Contingency analysis was used mostly off-line to check stability in all the anticipated situations of loading and events. For some voltage related control, more distributed network control has been used in recent decades after voltage collapse problems arose as geographical distances between generation and load increased. Security was guaranteed by a combination of planning for worst-case scenarios (N-x criteria) and security control, which anticipates and responds to the events. Recently in Australia, the rapid increase in electricity prices has been attributed in the media to excessive investment in 'poles and wires', bringing the existing planning model under question.

The above planning and control models, which are well-known and standardised, will be further challenged by all the new features of future grids: renewable energy (RE) sources[1] (which are less predictable) and distributed generation (DG), cost constraints on 'poles and wires' and new loads such as EVs which add new peaks. Given the diversity of generation (type, size, location) and the need to optimise networks, planning of both generation and the grid will need to be seen as a single coordinated problem, most likely with statisti-

[1]is understood that all energy is conserved, but it is usefulin terminologyaround electrical energy to speak of generation, supply, consumption and the like. Further, unless otherwise stated, terms like energyand demand refer to actual kWhrs and powermeansjust that, i.e. kW, MW etc.

cal security constraints (and so inevitably more emergency situations will not be covered by robustness in the basic network). Hence we are led to analysing scenarios and contingencies on an unprecedented scale. And this gives more work to the control systems to cover for the effects of events (given by less robust planning or 'over-engineering' as the journalists call it). On the other hand, new control facilities can be provided by demand-side utilisation, greater use of power electronic converters (four quadrant especially), more communications (smarter grids) and the availability of stored energy at all levels in the system. This sounds fine in principle, but bringing a systematic design to this level of scale (millions of devices) is again unprecedented and certainly not being addressed in typical industry-led implementations of so-called 'smart grids' (a term we prefer not to use unless it is properly defined).

In all the changes mentioned above, the role of modelling and analysis related to security for large numbers of scenarios remains of central importance. Stability limits are part of and constrain dispatch and electricity markets. These in turn influence the system and its stability. Planning clearly wants to achieve as robustly stable a system as economically possible. In fact we could use the word resilient in the sense of being able to work well with minimal intervention for changing energy mix trajectory and loads over decades, with the usual events. A 'plug and play' capability with future technologies, e.g. storage [2], should also be accommodated as best as possible.

The literature review below will briefly consider work which relates directly to meeting the new modelling, analysis and security challenges in future grids, particularly in the steps outlined in the project goals - an abbreviated version of the submitted Project 1 goals is given in Appendix A. Accordingly, references will be the most relevant only to represent ideas important to our planned study. This is a subject where the volume of words lately is very high compared to scientific novelty and so we have been selective.

The greater complexity of future grids goes way beyond just dimensional scale. For example, most stability analysis assumes the load demand to be modelled at high voltage buses in terms of aggregated functions of nett powers and voltages, usually static but also dynamic [3]. Such models are invalidated by DG, demand-side response and control and electric vehicles (EV). However, we still want to be able to represent demand in an aggregated manner for stability analysis. Also, stability analysis is usually carried out as a detailed deterministic analysis for each event. Indicators of instability have typically been deterministic measures of some notion of distance to instability in terms of loading or parametric change. There would appear to be a need now for more flexible approaches such as using statistical measures of margins. This will require new tools such as for scanning large numbers of network scenarios. However, the subject of power systems has been served well by understanding very well the performance of standardised sub-networks (SMIB, V-P 'nose curves', the

Concordia-DeMello system) [3]. There is an argument for extending this idea to new systems involving DG, demand response (DR) etc and so achieving understanding of the effect of RESs on power systems performance, stability, security and reliability. This coexists with the equally compelling argument for much greater use of statistical methods to handle the scale of the scenario numbers.

1.1 Future grid modelling

Firstly, we interpret future grid to mean national grid type structures with the above-mentioned transformational changes for the long-term out to 2050. We refer to systems which are developed along the lines of business-as-usual as classical grids, i.e. incremental variations on the situation where large thermal plants dominate in high voltage grids. Further, the security of the grid refers to physical security and so issues related to whole-of-system dynamics (synchronism, stability, viability, collapse, damping, cascading, modes) as has been defined and well-understood in the power systems community. Of course, these dynamic questions will all need to be re-developed for the new systems. The starting point for our studies is the observation that to the best of our knowledge, no international research so far has developed a standardised comprehensive modelling framework for future grids close to what we have been accustomed to for classical systems: a suite of definitions, equations and software for power flow, stability analysis, dispatch, security and reliability. Well-known software in dynamics and market modelling such as PSS/E (Siemens) and Plexos (Energy Exemplar) respectively have included new features to cover renewables, particularly wind-power. Newer analysis software such as DigSILENT has been developed from the outset with future grids in mind, especially in modeling renewable energy. However, deficiencies remain in the capability to represent completely the features of future grids in the long-term where variable and distributed generation, storage and demand-side mechanisms are all participating in balancing and grid services. Further, studies being carried out to suggest and analyse future grids often do not consider anything more than basic simplified power flow. Some ignore the grid altogether. This appears related to a lack of tools and perhaps some lack of appreciation (outside of engineering areas) for the critical role of the actual electrical grid.

For example, a proposal for a future zero-carbon electrical grid of Australia (ZCA) in 2020 [4] is presented assuming RE generation (of electricity), fixed distributed storage and also mobile storage (EVs) are available. In that proposal, 12 large concentrated solar power plants (CSP) and 22 large wind farms (WF) are proposed for the future grid considering limited reinforcement for the grids. The analysis just relied on economic aspects and selection of the wind and solar sites with the highest probability of wind speed and solar radiation. Proximity to the existing grids was considered in an ad hoc way. Lack of performance, stability and security assessment of the proposed network makes the proposal highly speculative for implementation. Such proposals can only have the status of interesting suggestions until system studies are carried out. Even for the existing grid, studies by NEMMCO in 2005 projecting wind power in South Australia showed considerable impact on voltage stability [5]. Further the placement of generation in ZCA has not been carried out with any clear scientific methodology. For future grids it appears that generation placement and transmission expansion must be considered in a coordinated way, an idea that the parallel Future Grid Forum appears to have picked up already.

Another recent study for Australia from the University of Queensland team in our cluster has delivered 'a competitive Australian power system in 2035' based on global energy price dynamics. They have taken a scenario-based approach which allows for business as usual (BAU) and transformational directions. We support this approach for the whole project as the only sensible way to arrive at a robust framework given the uncertainty in long-term scenarios. Their modelling assumptions include use of Plexos for the grid and electricity market. The Plexos optimal power flow (OPF) uses linear power flow with technical constraints which in principle can allow for stability limits. The main assumption to question is use of demand projections as if demand-side (including storage) mechanisms will not be used. This would seem to disadvantage renewable power.

In Reference [6], the UNSW team in our cluster produce simulations of scenarios with 100 per cent RE considering a copper plate model for the NEM. They conclude that relying 100 per cent on RE for the NEM can be technologically feasible within the specified NEM reliability standard. They have also suggested that the best way for peak load generation capacity reduction is through delaying CSPs dispatch and/or demand reduction. However, that study has neglected the transmission network and used a copper plate model. This assumption is very strong, especially for a large network geographically like Australia's. Also, they have studied balancing and hourly time-series simulation without maintaining adequate stability margins. Again, these results need to be checked with more accurate grid representation.

As we were writing, the draft outcomes of AEMO's 100 percent renewables study [7] became available. Again they take a scenario-based approach, but with a set of four scenarios which surprisingly does not include BAU. Nevertheless, they give conclusions which are more promising for high penetration of renewables at electricity price increases over decades which are comparable to what has been seen in recent years for grid upgrades and the carbon price. (These rises have caused alarm for customers, but certainly because of the rate.) They model three storage technologies and allow transmission upgrades to the existing system.

Some studies overseas are also worth mentioning. In Reference [8], the future grid for the PJM network in Eastern USA has been proposed considering a copper plate model for the transmission network. The impressive 28 billion scenarios were evaluated for 4 years of load and weather data. The authors have assessed the ability of RE to meet real hourly demand, and have calculated the least cost mix of technology. They have shown that the least cost solutions yield seemingly excessive generation capacity, almost three times the electricity needed to meet electrical load. Also, they demonstrated that the electric system can be powered 90%-99.9% of hours entirely on RE, at a cost comparable to today's but with a mix of generation (renewable and fossil backup) and storage technologies. However, that study has evaluated a huge number of scenarios to find the cost effective mixture of RE which can serve loads most of the time. This raises the issue of the scale in the number of scenarios for a large power system with RE as being potentially gigantic, and assessing all scenarios takes a substantial computing resources. Also, that study has ignored the transmission network and used a copper plate model to reduce the complexity of the network. Again, this assumption is not valid, especially for a large network geographically like Australia's, because it ignores line congestions which could affect the active power set point of generators. Also, they have studied balancing and hourly time-domain simulation without considering the market effects and constraints.

There is an apparent and notable absence of future grid type modelling studies at national or international level for Europe, Asia or the Americas. This is perhaps not surprising given the difficulty to coordinate across borders for the long-term, various coordination bodies notwithstanding. For example, the European ENTSO-E's roadmap 2013-2022 [9] is comparable to Australia's AEMO National Transmission Network Development Plan [10] in providing strategic directions on the next decade (and beyond less clearly). One study by the CSIRO and the Cluster Newcastle team [11] has suggested a major transmission infrastructure, often called a *supergrid*, spanning Australia and Asia. They use an economic dispatch model with intermittency, connectivity and storage all considered in a market dispatch model for 2025. Stability is not considered. The authors have heard IEEE conference discussion on proposals to interconnect the three separate USA grids into a supergrid, but have no report available at this stage. Such proposals would be more likely to have stability uppermost in the minds of researchers given the newsworthy collapses with major electricity blackouts that have occurred since the 1960's in the relevant networks.

In the USA PSERC Future Grid Initiative [12], funded by the Department of Energy, researchers are studying how to enable higher penetrations of renewable generation and other future technologies into the grid while enhancing grid stability, reliability, and efficiency. This program does not appear focused on a national grid structure as such although connections between the three main grids are being considered.

Reference [13] has also determined the least cost mix of wind, solar, geothermal, gas and hydro generations for California in 2050. The proposed low-carbon portfolio, can achieve an 80 per cent reduction in electric power sector carbon emissions from 2005 levels while supplying over 99 per cent of the annual delivered electrical load. Because their mix includes dispatchable hydro, pumped hydro, natural gas, geothermal, and centralized solar thermal with storage, their variable generation (wind and photovoltaic solar) never goes above 60% of generation. Similarly to the previously mentioned study, this one has made their conclusion based on balancing and hourly-time domain simulations. They use Monte Carlo simulation of the dispatch optimisation without a grid model, so stability again is not considered.

All of the above studies wherever a grid model is actually used, have used conventional load models and neglected DR. In the long-term it can be expected that DR will play a major role alongside storage and so affect the result of power system studies significantly. It is important to consider DR for the future grid studies. Storage, as mentioned above, is included in various ways but not according to a systematic framework allowing for overall capacity between households to grid.

In Reference [14], an analytical framework has been developed to estimate future balancing requirements in the USA Western Electricity Coordination Council (WECC) for 2020. The cost-effective scenario for different storage types to maintain real-time balancing of that network has determined. That study assumed that additional wind power generation will be built to attain a 20 percent renewable generation portfolio target for WECC. They demonstrated that the total intra-hour balancing requirement to address both load and renewable volatility are expected to be between 3 to 5 percent of the peak load in future. Also their analysis indicated that different storage technologies are required to meet the future balancing needs. The study considered that more diverse RE in their network (i.e. a combination of CSPs and wind) might decrease the required amount of storage for the future. Moreover, since storage technologies might not operate with their whole capacity, considering percentage depth of discharge (DOD) and ramp rating should be included in the cost analysis to attain more precise results.

In Reference [15], the amount of regulation under 20 and 33 percent RE penetration, has been calculated for the California electricity system. The researchers have run secondby-second simulations of the power system for five typical days and four renewable scenarios and assessed the effect of different system controls and storage on system performance. They use an area-based model across the WECC with California (and Mexico or CAMX) as one area.

They develop a simplified power-angle power flow model with ACE as a metric for balancing. They have illustrated that current system controls are not able to accommodate future RE levels, while acceptable performance could be achieved using storage and modifications in current AGC algorithms. Also, they concluded that a 30 to 50 MW fast storage is more effective than a 100 MW combustion turbine for regulation purposes. Due to time-consuming simulations of their network, they only focused on the technical potential of storage. However, a cost optimization analysis seems necessary to achieve optimal required storage capacity and ramp rate among different storage technologies. To draw a general conclusion, it would seem better to study more sample days to reflect extremes in renewable volatility and ramping. Furthermore, second-by-second simulation will be very demanding of computing resources.

In Reference [16] the effect of generation mix and storage on curtailment levels of variable generation (VG), or non-dispatchable RE, in the USA ERCOT grid (Texas) is evaluated. It is shown that 80 percent VG penetration with less than 20 percent VG curtailment can be achieved with suitable generation mix and storage with a capacity of four hour system average demand. Moreover, it is demonstrated that attaining curtailment levels less than 10 percent requires very large amounts of storage capacity which might not be economic. They suggested that increasing ERCOT connection to its neighbours along with taking advantage of diverse RE and demand response could be more economic to increase RE penetration with low energy waste. However, in that study a copper plate model for their network was considered and transmission constraints were neglected. It is noted that in some cases, VG curtailment occurs due to transmission constraints and thus in a more general assessment line congestions should engaged in the analysis. Finally, because of the studied network limitations (like inability to exchange power with neighboring grids), they couldn't utilize the advantage of diverse resources. The results might be affected by the presence of different resources of wind and solar with different geographical locations.

1.2 Future grid stability and security

The basic requirement after balancing (energy, power and ramping) is maintaining adequate stability margins (angle, voltage, frequency) for power systems. Power system stability deals with the power system response to disturbances. In the subject of stability theory, this usually relates to dynamics of the system around the equilibrium point. In power systems analysis, the suitability of that equilibrium in some sense is also rolled into the stability concept in more practical discussions, e.g. voltage stability is commonly seen as just about the level of the voltage after a disturbance. Analytical purists would rather the two questions be kept separate: 1) what is the equilibrium voltage level and 2) whether any dynamics are at play and do the trajectories reach the post-event equilibrium point. Putting these debates aside, we consider that power system stability for classical grids can be divided into three types [17]:

1 Transient (angle) stability: the ability of the system to keep synchronism after a large disturbance (e.g. short circuit or outage events);

2 Small disturbance stability: the ability of system to keep stable after small disturbances, usually in terms of positive damping of any oscillations that persist including some time after a large disturbance;

3 Voltage Stability: the ability of the power system to keep voltages near their nominal values after a disturbance, usually including the levels being within specified ranges.

Frequency stability as the ability of the system to keep frequency near its nominal value after a severe disturbance is also discussed but not normally within a formal stability framework. Voltage stability definitions [17] caused a lot of debate in the 1990's, but eventually accepted that there were steady-state and dynamic aspects. Several books give a modern summary of stability for classical grids [18, 19, 20]. See also notes by the author which integrate all stability types [2].

There are well-known suites of software for analyzing stability that have been used for decades including: DSATools (Powertech Labs), PSS/E (now from Siemens), EUROSTAG (Tractebel). Time-domain simulation-based methods are accepted in practice as the most accurate method for assessing power system transient stability. Critical Clearing Time (CCT) is the most important indicator used in order to measure the transient stability of power systems. CCT is maximum time duration that a fault may persist (before protection clearing) such that the system remains able to recover to a steady-state operation. The simulation method can be applied to any level of detail of power system models and gives visual information about state variables. However, this method requires intensive and timeconsuming computational effort. For situations such as contingency testing, fast simulation and direct methods have been developed as alternative approaches. Besides detailed simulation based approaches, researchers and boutique software vendors have produced an array of more specialized tools. Direct methods [21] can determine transient stability without the time-consuming numerical integration of a power system and can provide a quantitative measure of the degree of system stability in terms of the system states. Modern approaches often used network-based modelling which follows our early work in this subject [22]. One approach, called the Extended Equal Area Criterion [23] (after the well-known textbook stability test for a one-machine system) has been included in widely-used commercial software. However, direct methods must overcome several challenges (modeling, function and reliability) and limitations (scenario, condition and accuracy) before they can become a widely accepted practical tool. They have been under development for decades in the hope of providing a stability scanning tool that can deal with large numbers of contingencies. This line of work has stalled in the last decade, but might see a resurgence as we will explain below.

A point to make is that, whether using simulation-based or direct methods, the lower voltage networks were aggregated into load models which relate real and reactive power demand to voltage (and sometimes frequency) [3]. Some of our work extended these models to allow the dynamic recovery of demand after voltage jumps [24]. Later work focussed on how to derive such models [3, 25, 26].

The normal method of analysis for small disturbance stability combines simulation and use of linearized dynamic models and eigenvalue derived measures for damping [3]. These methods have been stable for decades. The influence of dynamic loads on damping was studied in [27]. Following a theme of network-preserving modelling, our work related damping to wider network features [28].

Voltage stability can be assessed by simulation or monitoring so called Voltage Collapse Proximity Indicators (VCPI). The point here is that just voltage level is typically not a good indicator of how close the system is to voltage collapse in modern networks (due largely to the amount of capacitive compensation typically used). Many different indices in terms of power flow solutions have been developed. We refer to those based on the power flow Jacobian and measures of singularity including eigenvalues, singular values, sensitivity and indices based on worst-case reactive margin [29, 30, 31, 2, 19]. Among these, the singular value method is now regarded as reflecting Jacobian singularity of the power system better [32, 2], and we suggest can be used for future grid studies. Again socalled direct methods for finding voltage collapse points in the power system have been developed by expressing the collapse point in terms of solving the power flow equations and the singularity of the Jacobian matrix [30]. This method can be used as an alternative for the singular value method. It gives a more accurate estimate of the stability limit but at more computational cost. Methods to reduce computation by exploiting structural features are also useful [33]. Simulation-based approaches, which were developed for voltage security assessments [19] are another useful approach these days. However, it is not clear that this approach will be useful for voltage security assessment of large numbers of future grid scenarios.

Following the concern about voltage stability in the 1970-80's, the subject of stability analysis was not greatly affected by the process of industry deregulation except in ways related to whose responsibility it is to do the studies or to give and collect the data needed. Some work [34] suggested that the dynamics of markets could interfere with stability but this never really caught on.

However, the arrival of substantial penetration of renewables does appear to demand a reassessment of stability analysis techniques. Some analytical issues that arise are:

- With high levels of volatile generation, the concept of an equilibrium point used in most stability theory becomes unusable;
- The load models for aggregated demand need to now allow for demand response and low level storage effects;
- The dynamics of large thermal plants may no longer be dominant.

These questions certainly affect applicability of direct methods where the use of load models for instance is more sensitive for the viability of the techniques.

So, not surprisingly, new studies of the effect of renewables tend to use simulation methods and so avoid the above-mentioned analytical issues as best as possible. There have been several studies of probabilistic power flow, including our own work [35]. A recent paper has considered the case where the uncertainty is due to wind power [36]. Recent work has reported simulation-based approaches for stability assessment of power systems with RE [37, 38, 39, 40, 41, 42, 43]. These are mostly focussed on wind power, but some recent work has also looked at the specific influence of large-scale solar PV [44, 45] and CSP plants [46]. The effect of renewable power sources on voltage stability has been the subject of several recent publications [47, 48, 49]. Simulation and direct stability assessment methods in a stochastic framework following our earlier work is reported in [50, 51]. Consideration of how storage can play a role has also been studied [52, 53]. One study has considered the interaction of renewable power and the strength of the grid [54].

There are some special characteristics and difficulties for the future grid of Australia which deserve attention. For example, the NEM is one of the longest power systems in the world (about 4000 kilometres) with restricted interstate power flow. Long lines and the specific topology of the NEM might result in some unique challenges for which the limited overseas experience will be useful but not adequate. Also, the best place for CSPs and WFs might be far away from the existing national grid. So, long transmission lines that will add future RE can cause performance and stability problems. Furthermore, due to the specific topology of the national grid, high penetration of WFs and CSPs might cause serious performance and stability problems. Particularly, due to large penetrations of WFs in South Australia, the system stability margin will reduce [5]. Moreover, connecting the NEM, SWIS and NWIS grids for utilizing more RE might bring more stability and performance restrictions for the whole grid.

Up to now in Australia, most dynamical issues have related to system damping (for small disturbance stability), including every time two state networks were connected. This is natural for such a spread out 'stringy' system.

Of course transient stability is always a basic consideration and voltage issues have occurred across the NEM system. However, we have managed to avoid any of the major collapse type incidents that have occurred in Europe and the USA. The arrival of mandatory targets for renewable power around the world, including RET in Australia (20 percent by 2020), combined with various incentive schemes and carbon pricing initiatives have accelerated the connection of renewable power to grids faster and with less scrutiny of grid impacts than would normally be allowed in classical grids. There are examples internationally where the transmission infrastructure is inappropriate for basic balancing let alone stability considerations. Recently, larger WFs and CSPs are now being connected within transmission networks and it will be necessary to determine what effect they may have on system wide stability mechanisms. This of course motivates researchers to report studies of the impacts of some kind of renewable power on some kind of stability.

This brings us to make a major general point. All of these studies that we know of are focused on one network and usually one type of stability. While interesting for some audiences, they are of little use widely and have generally not led to any universal conclusions about the effect of renewables. In fact, the scientific level has been way below what we recall at previous crucial times in the development of electrical power systems analysis. There was always a useful debate between the analysts and practitioners, but for the new era of high RE the grid has not so far received enough attention around new challenges. We contend that there should be more work looking for sensitivities of stability to a range of changes including technologies, placement in terms of network structure and strength. Nevertheless, some studies are significant for our project and will be described briefly.

The effect of high penetration of WFs in South Australia on the NEM stability has been studied in Reference [5] by DIgSILENT. Transfer capability between South Australia and Victoria was used for stability margin assessment. Increasing the transfer capability was interpreted as an improved stability margin, while decreasing the transfer capability indicates a stability margin reduction. That study assumed that all WFs are non-scheduled and dispatched at full capacity, committed network augmentations are modeled and at least around 500 MW scheduled generation remains on line in all scenarios. Finally they came to the conclusion that:

- In terms of transient stability, high penetration of WFs tends to increase export capability from SA and impact on export from Vic was small;

- In terms of damping stability, small reductions in damping have observed in some cases, and improvement in some other cases have detected;
- In terms of voltage stability, system voltage stability margin reduced and voltage collapse occurred in Adelaide due to high penetration of WF and under high demand.

An important aspect of this study was the consideration of all types of stability.

An interesting study in terms of voltage impacts has been carried out in Germany where renewable penetration is amongst the highest in the world [55]. They set up a time series for electricity consumption across the whole country. Weather data enables time series of electricity generation from renewable sites. They then use ENSTO-E grid models, determine which generation and consumption is attached on which grid bus. Based on power flows, energy storage is operated. Stability implications in terms of frequency and voltage are studied.

Some works pay particular attention to the affect that the energy storage can have on system security. In Reference [56], a procedure for choosing the optimal storage size to regulate wind power variation and increase wind energy integration and voltage stability is proposed. An eigenvalue technique is used to evaluate voltage stability margin. It is shown that integrated use of storage and wind generation have the potential to increase voltage stability margin of the network. However, they have considered only a single wind generation plant connected to an infinite bus and so did not evaluate the effect of type and place of wind and storage in their cost optimization procedure and stability margin evaluation.

There have been numerous commissioned reports done in research centres around the world on the influence of windpower and DG on stability and damping for particular systems. It is hard to keep up with these, but we will endeavour to have an updated list available throughout the project. What remains clear in the published (in journals referred to here) and reported work along the lines of [5] for Australia is that at this point we just have a lot of observations including:

- All stability types are affected by new dynamics;
- Locations and generation types are important as before;
- Structure of the network and demand-side influences need to be assessed;
- It is hard to make many general statements along the lines of sensitivity.

The need for more fundamental studies that can be applied to new situations is certainly evident.

2 Research Plan

The goals of project P1 are listed in the Preface and the detailed milestones are provided in the Appendix. Clearly from the literature review, some fundamental questions that should be addressed in order to complete the proposed tasks are as follows:

- Accurate versus fast models for power flow and stability analysis of power system with RE, DR and storage, i.e. capability to flexibly study an issue in detail versus scan massive numbers of scenarios and contingencies;
- How should aggregated load be represented in stability studies including DR and storage influences? In conventional power systems, loads were modelled with voltage (and sometimes frequency) dependent nonlinear models; however with DR, the demand is modified by system conditions and previous models are not valid anymore;
- What is the effect of various type, size and placement of RE and storage on power system performance and stability with general conclusions which can be used across different situations?
- How the electricity market with RE dispatch will affect power system performance and stability?
- How to find points of vulnerability directly rather than scan massive numbers of scenarios?
- Where are the tipping points of renewable penetration for being unable to use conventional controls (fault currents, voltage and frequency control from large generators) to stabilise the system?
- What levels of storage and demand response are needed for a given high level of renewable penetration?

In the rest of this Section, we elaborate on how we will respond to these problems. Particular attention will be given to how the plan includes interaction with the other three projects of the Cluster.

2.1 Demand modelling

We saw in the literature review that studies, even those claiming a long-term view, typically do not model the electrical network and/or demand-side control, both of which can be a powerful tool to help balance variable renewable power. The first point to keep in mind is that the basic balance equation at any node, cluster or system is now more complicated: G = D is replaced by G+DR= D+S where G is generation, D is nominal demand (usually represented as power versus time), DR is demand response and S is storage. The energy taken to storage is recoverable. Instead of G following D, we now have a situation where D and G are variable and DR and S act to bridge the two in balancing. DR is assumed to include all kinds of changes from nominal demand initiated by customers, aggregators from market signals or direct control, i.e. demand is responding to the system situation. This equation affects stability and security by shifting the basic operating point of the system.

To carry out stability analysis, we also need a representation of the power-voltage relationship of the aggregate demand to replace aggregate load models. This is also more complicated with the presence of demand response and storage. Load models affected all kinds of stability, so we can only assume that how storage and DR are used will also affect stability.

These questions are an early focus for the project.

2.2 Sensitivity analysis

Previous models for stability analysis were mostly deterministic, i.e. a particular system at a certain point in the demand cycle subjected to a specified disturbance is either stable or not. To translate this paradigm to all the points arising from variable generation and demand becomes prohibitive. The aim is to develop the tools which can predict how a change in the network will affect stability without checking every possible combination. One such tool is sensitivity analysis, previously widely used in the study of system damping [28].

The key word for the early stage of this project is sensitivity. The typical paper we reviewed above looks at one stability type on one system and so is of little use for general application; we want to look at dependence of all stability types on:

- Generation type (node dynamics)
- Structure (graph of connectivity)
- Strength of network (coupling)

To date there has been very little thinking in this direction in the literature, although some studies hint at it [54]. An initial emphasis will be given to finding ways to parameterise these features of the networks as well as the level of penetration of RESs. Then scenarios which test the interplay between them will be devised. The motivation here is the theory used in the subject of complex dynamical networks where a clear interplay is given theoretically for synchronism (close to the concept used in power systems) in terms of node dynamics, network connectivity and coupling strengths [57].

This requires development of the techniques and so is better done initially with simplified models where the ideas are not lost in details. Unlike previous studies which treat one type of stability (on one network), we will consider angle, frequency and voltage issues side-by-side. Naturally, the Eastern Australia NEM grid will be the base test case.

Fortunately, a simplified 14-bus model is available to represent the NEM, initially for damping studies [58]. We have been modifying this so it is suitable for analysing all kinds of stability and can be expanded to include scenarios for renewable power, such as those in the ZCA Report [4]. Other features which will need attention are:

- Population projections
- Scenarios for large nuclear, geothermal and gas units with characteristics similar to present large units
- Scenarios for small renewable generators assembled (virtual generators) at 25kv to 330kv
- Major changes to loads: Al plants gone, new desalination plants, demand management, EVs.

This simplified 14-generator model is also convenient to use in connection with market dispatch scenarios for the NEM.

2.3 Scenario analysis

The subject of planning and reliability measures is moving away from deterministic criteria toward hybrid deterministic-probabilistic planning methods to provide a quantified risk assessment using performance indices which are sensitive to factors that affect reliability [59]. Planning is now a merged problem of generation placement and transmission network expansion planning (TNEP). This leads to massive numbers of scenarios to assess. Further, the pressure to see security constraints as probabilistic is a way of avoiding what is now seen as ‘over engineering’ the system (or ‘gold plating’ as journalists call it). So another early consideration is how to revise existing models to accommodate these statistical influences.

The first task is to assemble the tools to analyse all kinds of stability across large numbers of scenarios including those generated by a market dispatch process. To start with, we have chosen as a basic set-up to use:

- Plexos for the market model
- DigSILENT for time-series analysis (repeated power flows)
- VSTAB for voltage stability analysis
- Python/PSAT for power flows

We aim to extend the ideas in the German study [55] to study balancing, frequency and voltages across the NEM under the influence of high RE levels. Besides the above tools, our earlier work in Sweden [32, 2] and Canada [33] has produced a suite of tools for analysing voltage stability which we are adapting to the questions at hand.

Scenarios initially are a mix of some taken from the reports, e.g. ZCA, and others derived by assuming a stranded fossil fuel generation asset replaced by a renewable plant following some earlier student work [60]. We plan to be further informed by the scenarios that have appeared in other projects [61] and from the Future Grid Forum which is converging on some clear possibilities.

Tools for analysing large numbers of scenarios for stability has already presented clear problems to overcome. We will rely on repeated power flows, simulation for dynamics and voltage stability metrics. The early task is to package this up so the process can be automated in terms of feeding data and collecting results.

2.4 Advanced techniques

There are directions to take to establish more basic tools. These maybe beyond the scope of the current funding to complete, but will be pursued as possible. Two of current interest are as follows:

a Vulnerable points We aim to explore approaches to directly find weak points motivated by network science ideas on vulnerability [57]. We will formulate indices for the variables, i.e. faultlevel for network, and study influence of varying each in isolation and then look for worst case directions.

b Probabilistic stability margins For metrics of stability, the obvious direction to consider is probabilistic versions of those we used previously. One paper along these lines is already under review by colleagues in Taiwan [21]. This involves using enhanced Monte Carlo techniques to compute statistics of stability margins. Again this can be by indirect or direct methods as described in the Review above. The former involves sweeping scenarios and is expensive computationally. The latter formulates the margins analytically, e.g. bifurcation points for collapse in extended PF equations and uses Monte-Carlo, quasi-MC, experiment design methods.

This work is not started yet and will most likely begin with new PhD projects.

2.5 Influence of Storage and Demand Response

As the level of RE increases, it is expected that the capability of conventional controls will reach a tipping point for the preservation of stability. For instance, the German experience is that conventional controls can deal with a certain amount of generation volatility in the same way it deals with demand volatility, e.g., using conventional frequency control on big plants. But at some point storage and DR will be needed to maintain balancing with stability. Recent research on the sizing and placement of storage is highly relevant and in early stages of development [62].

As described above, storage and DR will form part of our basic modelling methodology. The role of storage and DR control in some aggregated way will be a focus in this project, not only to analyse the impact on stability but also to explore its potential in control. The general idea is that RE penetration (both from planned major plants and widely distributed from households) requires substantial balancing 'levers' and they will be more active the higher the RE level. The two obvious mechanisms are via DR and controllable storage. Clearly, with enough of these and an adequate grid, the system can support 100 percent RE. The limitations will come with the overall cost to ensure security.

We aim to develop methods to quantify the presence of DR and storage at the bulk system level and what levels are needed to achieve a certain carbon limit. Once again, the previously mentioned work tends to be of the ad hoc kind for a particular network. Given the long-term nature of this study, we need to be able to make assessments on the future grid scenarios.

2.6 Interactions with P2-4

The above scenario analysis project suggests one interaction, which will be usefully pursued with the UNSW markets Cluster team. There are actually several interactions, including: energy prices affect electricity market outcomes; market dispatch affects stability; stability limits the market and planning. As we saw in the literature review, system stability and security have not featured

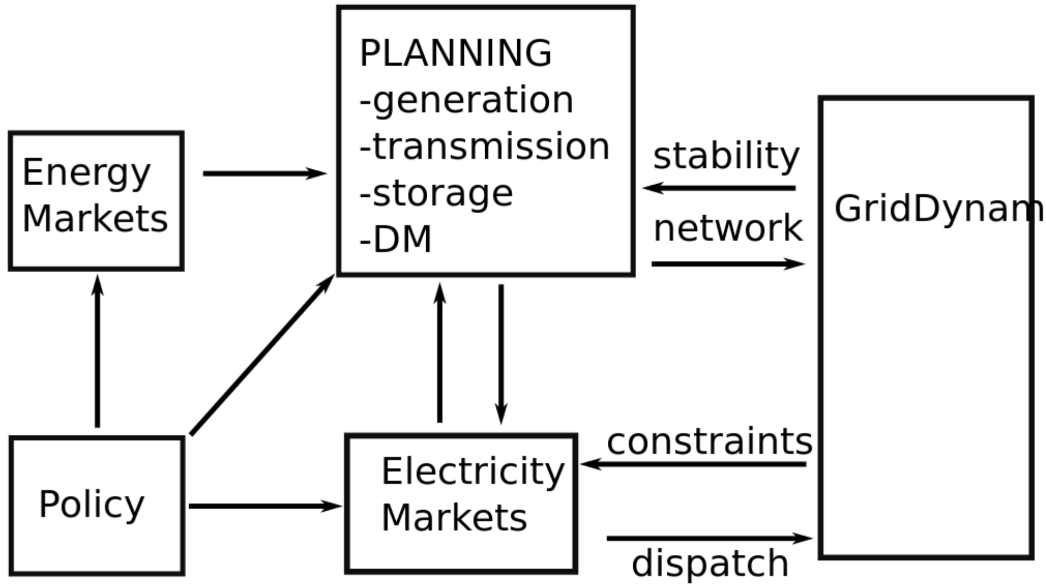

Figure 1. Interaction of grid modelling, analysis, markets, policy and planning

systematically in the study of these interactions. Figure 1 shows our view in general terms of the interactions between various domains of power systems, which correspond to our projects.

The research interactions between the four Cluster projects for Project 1 are as follows:

- Project 3 will provide energy scenarios (as started in their series of reports [61]) to merge with those arising from the Future Grid Forum;
- Stability constraints on the grid limit the market dispatch and these were already problematic in being inflexible and highly approximated [63], but have major economic consequences; this can have input to the studies in Project 4;
- The market determines which generation is dispatched which in turn influences stability; we now have renewable plant to dispatch and the impact of non-dispatched IPPs; this can benefit from new work in Project 4;
- The planning of future grids will consider generation placement and TNEP in cooptimisation; stability and security constraints will play a major role and this requires interaction with Project 2.

Two specific projects are suggested here as follows:

a Market-dynamics interaction

In the literature review, some prior work on market-dynamics interactions was mentioned. Certainly stability limits need to be captured in some way [21], GA3. Usually this is done by placing transfer limits based on stability in the OPF dispatch. Dynamic interactions between the dispatch and the system are not considered in practice. It seems much more likely that this is an issue in the context of renewable power dispatch, but this might be beyond the scope of our work here. We will be mainly concerned with how to ensure the market operates within stability constraints which are appropriate for future grids. A possibility is that: as renewables increase, dispatch along BAU lines will produce situations which are not stable. This will require new ways to assess the stability limits including the impact of any controls implemented.

It is expected that this work will proceed with Project 4. This may involve development of better market models for high penetration of renewables. Use of risk-limiting methods in market dispatch [64] with generic constraints as bands or probabilistic will be considered.

b Generation placement and TNEP

The choosing of optimal scenarios for generation placement and TNEP (GPTNEP) has emerged recently as a planning paradigm. The CSIRO Future Grid Forum has adopted this. However, the large number of possible scenarios that need to be assessed will be much more demanding computationally than the familiar TNEP problem, which is already a large optimization problem. Our prior work will be a useful foundation starting with [65], which first posed the TNEP problem in a markets context, and lately with the Newcastle team to use stochastic optimization and probabilistic security criteria [66]. Further, we need to incorporate the influence of DR, storage (and gas networks according to the CSIRO goals).

It is expected that this work will proceed in close collaboration with Project 2.

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Appendix

Table 1. Summary of Milestones for P1

	Milestone	Due
1a	Completion of the following activities/tasks: - Literature review of related work and projects on future grids, e.g. Europe's SRA 2035, DOE Future Grid project, the relevant modelling, available and likely storage technology - Define, agree and document interactions with Projects 2-4 - Document detailed Research Plan for total project, including interactions with Projects 2-4 ("Detailed Project Plan", signed off by Cluster Management Committee)	1/03/13
1b	Completion of: - Documented challenges and strategy for equipment model and data acquisition and backup for proceeding when there are gaps - Document full list of modelling scenarios developed in conjunction with Project 3 - Document assumptions and requirements for configuration of modelling software suite, in particular covering the demand side participation of distributed generation, demand response and control, storage and electric vehicles	1/06/13
2	Completion of: - Basic core storage model, using mixed-integer linear programming (MILP) to evaluate role of distributed storage on existing grid operation - Progress on formulation of methodology and preliminary grid modelling framework with multiple levels of granularity for specific analyses [based on the existing grid incorporating new or expanded sources of primary energy, storage and loads]	1/09/13

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Table 1 – *Continued from previous page*

	Milestone	**Due**
	- Mid term progress report, including linking between P1 and P2, P3 and P4 -Report for full Financial Year (Year ending 30 June)	
3	Completion of: - Modelling framework based on the legacy grid and the widest possibilities for new sources of energy, storage and loads - Progress on development of security scanning tools and framework - which can check balancing, constraints, dynamics, stability, vulnerability according to indicators of performance for large networks with renewables and new loads - Mid term progress report, including linking between P1 and P2, P3 and P4	1/03/2014
4	Completion of: - Security framework, tools and testing on standard systems (including IEEE) and some NEM scenarios - Storage modelling framework, covering locational, operational and economic factors - Future grid model platform with links to/from P2 to achieve cooptimisation - Report for full Financial Year (Year ending 30 June)	1/09/14
5	Completion of: - Integration of power flow, demand side, storage and future generation options into consistent framework. Linked into P2, P3 models for scenario analysis. - Progress on systematic study of all scenarios for different time horizons	1/03/15
6	Completion of: - Scenario studies across all possibilities and conclusions on trends	31/12/15

Continued on next page

Table 1 – *Continued from previous page*

	Milestone	**Due**
	- Report for full Financial Year (Year ending 30 June) - Final end of cluster report, including multi-dimensional comparisons, scenario analyses and recommendations for continuation. Completion of modelling with validation. - Final Financial Report for the full Cluster Project	