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Technical impacts of high penetration levels of wind power on power system stability

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Abstract

With increasing penetrations of wind generation, based on power-electronic converters, power systems are transitioning away from well-understood synchronous generator based systems, with growing implications for their stability. Issues of concern will vary with system size, wind penetration level, geographical distribution and turbine type, network topology, electricity market structure, unit commitment procedures, and other factors. However, variable-speed wind turbines, both onshore and connected offshore through DC grids, offer many control opportunities to either replace or enhance existing capabilities. Achieving a complete understanding of future stability issues, and ensuring the effectiveness of new measures and policies, is an iterative procedure involving portfolio development and flexibility assessment, generation cost simulations, load flow and security analysis, in addition to the stability analysis itself, while being supported by field demonstrations and real-world model validation.

Wind energy is being rapidly integrated into many power systems across the globe, with a total installed capacity of 370 GW, and with 51 GW added in 2014 alone[1]. As the penetration of wind generation increases, the impact on power system dynamics is becoming increasingly apparent, and will become a more integral part of system planning and renewables integration studies[2]. Historically, power systems have been based around large synchronous generators connected to a strongly meshed transmission network, with the dynamic characteristics of such systems being well understood. However, renewable generation, particularly in the form of wind and solar generation, is increasingly universally connected via power electronics interfaces, may well be connected to the distribution network, or weaker parts of the network, may offer new control capabilities, and, of course, is subject to the variability and uncertainty associated with local and regional weather patterns[3,4]. The time variability and non-dispatchable nature of wind generation may pose substantial challenges, particularly at higher levels of penetration, including an increase in regulation costs and incremental operating reserves, but can also lead to increased opportunities for energy storage, demand-side response, cross-border interconnections and other flexibility measures. In addition to onshore wind power installations, which are already saturating in some countries, such as Denmark, a large number of offshore wind power plants have been developed recently, and this trend is likely to continue into the future[5]. Increasingly, such plants will be sited further offshore, in the form of larger wind farms, and will be connected onshore either individually through a HVDC connection, or as part of an interconnected DC grid[6]. Wind generation, by its mere presence, does not necessarily worsen the stability of a system, but it does change its characteristics, and through intelligent co-ordination of power electronic based controls, system capabilities could even be enhanced in some situations[2,7].

System stability issues range from the ability to maintain generator synchronism when subject to a large disturbance (transient stability); the ability to restore steady-state conditions (voltage, current, power) after being subject to a small disturbance (small-signal stability); the ability to recover and maintain system frequency following a major generation-load imbalance (frequency stability); and the ability to maintain an acceptable voltage profile after being subjected to a disturbance (voltage stability)[8-10]. Those issues of concern for a particular system will depend on system size, wind distribution relative to the load and other generation, along with the unit commitment / economic dispatch (UC/ED) decisions and network configuration. However, they are likely to be first observed during the night or seasonal low-demand periods when instantaneous wind penetration may be high[11], say greater than 20%, or alternatively when wind exports across a region are high, even in cases when the annual (wind) energy contribution to the system is comparatively low. So, for example, during periods of high instantaneous wind penetration, with reduced numbers of conventional (synchronous) generators online, frequency stability may be affected due to the reduction in governor response[12,13], and, particularly for smaller systems, by the reduction in synchronous inertia[14-17]. For example, the All-Island system of Ireland would be insecure, without additional measures being taken, for approaching 30% of the year 2020 due to a lack of adequate synchronous inertia[18], as shown in Fig. 1. Similarly, a study of the Electricity Reliability Council of Texas (ERCOT) system observed a decline in its frequency response, based on frequency event records taken over a span of four years with increased wind penetration[17]. The transient stability of a system may also be reduced when synchronous units are de-committed and replaced with wind generation connected at lower voltage levels, and hidden behind a relatively large impedance[19,20]. However, transient stability impacts are largely affected by the turbine technology. For example, a study performed by Transpower (New Zealand) reported that ‘old’ technology, fixed speed induction generators (FSIG), worsen the transient stability of the system, as they absorb reactive power during and after a fault, and are generally not voltage ride through (VRT) compliant[21]. On the other hand, variable speed wind turbines (doubly fed induction generators and direct drive full converters) have VRT capability, and can improve the transient stability of the system. Alternatively, angle stability, both from a small-signal and transient stability point of view, may be threatened due to large voltage angle differences, when a large wind power export occurs from one region to another[22]. In addition, the reverse power flow from former load feeders may have implications for associated protection systems[23].

During times of system stress, wind power curtailment can be seen as one solution to maintain system stability, and other security-related concerns which have been foreseen[24]. Such a measure though should be seen as a last resort option, and is more likely to be observed in small isolated systems, such as Hawaii, Ireland, New Zealand, etc.[15,25-26]. A simple metric, known as the instantaneous system non-synchronous penetration (SNSP), which is essentially representing the proportion of non-synchronous generation (wind and HVDC import) w.r.t. total load (including HVDC export), within a synchronous region, is being used by the All Island TSOs (EirGrid and SONI). It has been identified that higher SNSP levels (50+%) may require wind curtailment, unless some alternative measures to maintain system security are considered[25,27]. However, even for much larger systems, such as the European Continental synchronous area, critical instantaneous penetration rates can be associated with an anticipated growth in wind and solar generation, although such limits will vary with operational conditions[28,29]. The primary objective of dynamic analysis of a future system is to identify areas of concern, before proposing measures which reduce the risk of wind curtailment due to the introduction of dynamic constraints[30]. Soft measures may include appropriate modification of controller settings, co-ordinated protection schemes, and market-based flexibility incentives, while hard measures may include network reinforcement, and phasing in / retro-fitting flexible generation plant.

SYSTEM MODELLING

As a precursor to assessing the stability of a system for given future snapshot scenarios, production (generation) cost simulations will ensure that a given wind integration scenario is feasible. In addition, steady-state load flow[31,32], N-1 contingency[33,34] and short circuit analyses[8,31] will have been performed in order to assess the steady-state adequacy and utilisation of the transmission system, and to assess if the plant portfolio and grid network are sufficiently strong to cope with a number of pre-defined disturbances, linking to significant system failure. Such analysis, represented in Fig. 2, may already have implicitly addressed some dynamic issues for the system, e.g. ramping capabilities of conventional units, plant flexibility associated with wind forecast uncertainty, spinning reserve requirements, minimum number of, or locational, must-run generation units[33]. It is also noted that the steady-state and dynamic capabilities of wind power plants (WPPs), and their control capability, can be observed within the load flow and stability analysis blocks.

Consideration of a future power system for production cost simulations will clearly include portfolio development, i.e. the retirement of existing plants and the introduction of new units, in specified locations and with particular dynamic characteristics, in order to support increased demand growth. The capacity value of wind generation[35] and overall system reliability may inform the required installed conventional generation portfolio, as part of a capacity expansion model[36]. An evaluation of the reserve requirements on various timescales, recognising the variability and time-varying nature associated with large-scale wind penetrations[37-39], and associated wind and demand forecasting capabilities must also be considered[40,41]. The resulting flexibility of the portfolio, including any plant retrofits, particularly at sub-hourly intervals, will need to be addressed, to recognise unit ramping limits and startup / shutdown costs, as well as hydrological constraints in the case of hydropower[42-44]. It may also be appropriate to consider the cycling costs for existing thermal generation[45-48], or operational practices, along with transmission constraints and market structures that may impact the realisable flexibility of the system[49,50]. System-wide voltage control and reactive power management may also need to be more closely integrated with unit commitment procedures at higher wind penetration levels, before any dynamic studies can begin[51,52]. For example, Denmark is moving towards undergrounding its transmission system, to be compensated by switchable shunt reactors, by 2050[53], while at the same time aiming for a 100% electricity share from wind generation by 2035, with very few (or without) conventional central power plants in operation, thereby reducing overall short circuit capacity and the number of continuously acting automatic voltage regulators (AVRs) in the system. Under such circumstances, wind power variability may necessitate frequent switching of discrete controllers, particularly shunt reactors to regulate voltage, which will in turn so significantly impact their lifetime as to make this an economically infeasible practice[54]. Therefore, the Danish TSO, Energinet.dk, is considering a co-ordinated automatic voltage control (AVC) system to overcome future operational challenges[55].

Large-scale wind integration will most probably also necessitate upgrades or expansions of the transmission (and distribution) network, particularly if offshore DC grids are incorporated. Measures such as dynamic line rating or high temperature low sag conductors[56-58], special protection schemes and local storage[59] may also enable increased network utilisation, and/or ease (planning) delays in network expansion. Reactors, static var compensators (SVCs), flexible ac transmission system (FACTS) devices, etc. at particular locations may also be required to maintain steady-state (and later dynamic) network performance, and to provide an acceptable voltage profile. Iterations may be required between production cost simulations and load flow studies, before obtaining a plant portfolio and network configuration which is deemed cost effective, relieves / reduces network congestion and maintains security of supply. Dynamic simulations may introduce a further iteration to this process, by further requiring revisions in operational practice, network reinforcement, and plant portfolio characteristics. So, for example, line (congestion) limits may be set by transient stability concerns rather than steady-state thermal limits[60-62]: maximum power throughput over a transmission line is normally limited by thermal limits for short transmission lines, voltage stability limits for medium length lines and rotor angle stability limits for long transmission lines.

The load flow analysis and production cost simulations form initialisation inputs to the stability assessment by defining acceptable generation dispatches and network configurations. Traditionally, system stability may have been assessed for particular snapshot cases, such as maximum / minimum system demand conditions amongst a number of cases, in order to reduce the computational burden. To ensure coherency with steady-state (N-1 security) assessments, as highlighted earlier, it can be valuable to perform dynamic analysis under similar conditions. However, since wind power production is typically weakly correlated with system demand, a much wider range of credible analysis cases should be considered, in order to fully appreciate the impact of high wind penetrations on system dynamics. Wind generation may be weakly correlated (diurnally and/or seasonally) with demand, but not uncorrelated with demand, so it is simplistic (and inaccurate) to focus on high wind production coupled with low / high demand scenarios alone[25,45]. Indeed, the statistical likelihood of particular scenarios should be considered in the selection process and when evaluating consequent actions. Furthermore, different wind deployments should be considered for analysis, in terms of turbine technology and geographical spread. Where possible, wind and demand time series should be employed, in order to capture the underlying correlation[63]. Multi-year analysis should perhaps be performed in order to capture less common but threatening scenarios.

Validation of dynamic generator (conventional units and wind power plants) models is of key importance, although an appropriate model complexity will be dependent on the study application. For example, an assumption of constant wind speeds may be appropriate for short-term stability studies of a few seconds duration[9], whereas long-term stability studies over several minutes may need to consider the impact of varying wind speeds. It is generally suitable to employ generic models representing different wind turbine technologies, although the models used should not only consider the underlying physics of wind turbine dynamics but they should also recognise relevant (minimum) grid code requirements for the system under study which have a (significant) impact on the wind power plant controls. Originally, IEEE established a working group on Dynamic Performance of Wind Power Generation, which has now merged with the Western Electricity Coordinating Council (WECC) Renewable Energy Modeling Task Force[64], which again works together with the IEC working group on Electrical Simulation Models for Wind Power Plants[65]. The WECC task force has already published second generation generic models[66], while the IEC working group has recently published the first edition of an IEC standard[67]. Sharing many of the same experts, these models are very similar, but there are some minor differences, with the main one being that the IEC models include options for more details, for example on reactive power capability[68]. The WECC and IEC generic models are intended for short-term power system stability studies of 10-30 seconds duration, assuming that wind speeds are constant during the simulations. So far, there are no standard models available to investigate wind power variability in long-term stability studies, and the need for such models will depend on the particular phenomenon being studied and the size of the synchronous area under study.

The WECC document and the IEC standard specify models for each of the four main types of wind turbines, i.e. type 1 (a directly connected induction generator), type 2 (same as type 1, but with variable rotor resistance), type 3 (doubly fed asynchronous generator) and type 4 (fully-sized power converter). Each model includes a set of parameters which may vary from one wind turbine manufacturer to another. A default parameter set may be used in studies where the specific wind turbines are not known, but the parameters are used to account for variations in the dynamic behaviour of different wind turbines. Also, a specific wind turbine can be operated in different control modes depending on the requirements of a specific TSO. The existing WECC and IEC models cover several different reactive power / voltage control modes during normal operation and during voltage dips. Emulated inertial responses are not directly implemented in the models, because this type of response is at an early stage of development and therefore not considered sufficiently mature for standardisation, but the power reference points can be used to connect the generic models to a specific user defined emulated inertial response control model. So, for example, additional adjustments and extensions to the Type 4 IEC generic model have been considered elsewhere[69], in order to reflect the dynamic features of wind turbines relevant for active power and grid frequency control capability studies. Wind turbine manufacturers covering the majority of the market (Enercon, Gamesa, GE, Senvion, Siemens and Vestas) have contributed to the model specifications, with internal model validation ensuring that the WECC[70] and IEC[71,72] models are applicable to their specific wind turbines. The relation between individual turbine controllers and the centralised plant controller must also be addressed[73-75]. In particular, communication time delays can compromise the ability to perform fast responding services, such as emulated inertia controls. Furthermore, the response time of wind turbine inverters limits their ability to support the grid during the first 10s to 100s of ms after a disturbance has occurred. A study variant may be to assess the advantages of enhanced wind turbine capabilities, coupled with co-ordinated setpoint controls across a network area.

For offshore wind plants connected via HVDC-transmission, the modelling requirements depend heavily on the study scope. In many cases, it is sufficient to limit the modelling to the onshore HVDC inverter, and use a simplified aggregated wind plant model. Such an approach is particularly valid when onshore voltage and reactive power issues are in focus, since the DC stage decouples reactive power flows in the offshore AC system from the onshore grid. However, when discussing active power control and system frequency support, the relation between the HVDC controller, the centralised plant controller and the individual turbine controllers must be addressed[76]. Again, communication delays and response times are important when quantifying the response during the first few seconds after a disturbance has occurred. For fast transients in the millisecond range, the dynamics of the DC system are important, which will require detailed models to be simulated on shorter time steps[77]. Software packages that focus on the power system (electro-mechanical) dynamics of interest can accurately simulate wind power plant connected through voltage source converters (VSC)-HVDC[78]. Adopting a combined simulation strategy, i.e. stability simulation for AC grid dynamics, and electro-magnetic transient simulations for DC grid dynamics, provides an acceptable simulation speed and accuracy.

Finally, (dynamic) load modelling is a topic that historically has received limited attention, partly due to practical difficulties in obtaining widespread data for model validation, and the time-varying nature of the models themselves, as the load composition varies diurnally and seasonally, as well as evolving annually[79-81]. With increased wind penetrations, however, leading to 'lighter' systems, and with wind plants located at sub-transmission voltage levels, load characteristics are likely to play a greater role in the dynamic performance of the system.

FREQUENCY CONTROL AND INERTIAL ISSUES

As wind penetration levels rise, conventional generation will gradually be displaced, with implications for the frequency regulation capacity. At lower wind penetration levels, system flexibility may actually be enhanced, as conventional units are backed off but remain online, enhancing the headroom or manoeuvrability of the system as a whole. However, if such generation is displaced offline the fraction of generation participating in governor control is likely to reduce, along with the inherent inertia of the system, resulting in faster frequency dynamics following a major network fault or load-generation imbalance[13,82-84]. Wind turbines can, of course, provide a governor droop response, similar to conventional units, and such capability is mandated in many grid codes. However, while a high-frequency response can be readily achieved, i.e. a sustained reduction in output, a low-frequency response requires the turbines to have been curtailed in advance, i.e. a period of reduced production. In some jurisdictions, e.g. ERCOT, wind turbines which have been curtailed (for network reasons) can contribute to the frequency response capability[85], but, for many systems, wind governor controls remain an untapped resource, and the implications for unit commitment and reserve policies are not resolved. The frequency response may also depend on the type (synchronous or wind generator) and location (transmission connected or distributed generation) of the generation loss. For example, a study on the US Western Interconnection identified that the frequency response for a distributed generation (DG) outage was improved over that for a transmission connected outage[86], as shown in Fig. 3. The difference follows from the fact that the DG loss results in a depressed (local) distribution voltage, such that a low load voltage reduces (local) power consumption, and hence, the post-disturbance system demand.

Fixed-speed wind turbines do naturally provide an inertial response akin to that provided by a synchronous machine[87]. However, variable-speed wind turbines decouple the rotating mass of the turbine from the power system, which offers a number of operational and quality benefits to the turbine, but removes any intrinsic inertial capability. At times of high non-synchronous penetration, and the resulting displacement of synchronous generation, the on-line inertia will be reduced, altering the system response for both faults and contingencies[17,29]. For smaller power systems, or those linked together by asynchronous HVDC links, the effect can be particularly important and may be of concern[25,88]. The resulting high rate of change of frequency may, for example, cause anti-islanding RoCoF (rate of change of frequency) protection to mal-operate, further increasing the generation-demand imbalance in the system[89]. Low inertia has not, as yet, caused a problem for larger power systems, but is being investigated[63,90]. For example, as previously shown in Fig. 1, a significant reduction in synchronous inertia (stored energy) is estimated for the year 2020 compared to 2009 for the All Island (Ireland) system, which presents a major bottleneck to higher levels of wind penetration, as all generating units are (only) required to withstand a maximum RoCoF of 0.5 Hz/s following a load-generation imbalance. RoCoF limits are also defined as part of anti-islanding protection schemes for distribution-connected generation, with ≈50% of wind generation so connected in Ireland. Based upon a unit commitment for the year 2020, the maximum RoCoF, assuming that the largest infeed / outfeed is tripped in each hour, is shown in Fig. 4. It can be observed that both the current maximum RoCoF generation limit (0.5 Hz/s) and relay threshold (0.55 Hz/s) value would be violated for numerous events, and hence increasing the risk of additional unit outages and possible cascading events. Consequently, EirGrid and SONI (TSOs of Ireland and Northern Ireland) are currently exploring various measures, such as raising the RoCoF limit from 0.5 to 1 Hz/s for all units[91], modified and selective plant protection strategies, improved plant monitoring to ensure that conventional generators provide appropriate reserve in a timely manner following an energy imbalance, through alternative operational strategies (operational measures, load management, parking of machines, i.e. plant operation at low output but with reduced (or none) capability to provide system support services) or infrastructure reinforcement (synchronous condensers, construction of AC interconnections), or a combination of the above. Hawaii also faces the issue of high RoCoFs inducing gas unit tripping, which has led to a change in plant temperature control settings[14]. The same lean burnout phenomenon has also been seen in Florida, with multiple gas turbines tripping in one occasion[92,93]. For larger systems, high RoCoFs are of less concern, although at high renewable (wind and solar) penetrations, low frequency nadirs can occur: a reference incident (3500 MW generation loss) on the European Continental synchronous area could result in the security level of 49.2 Hz being at risk for 18% of the time, Fig. 5, assuming ≈35% annual renewable energy contribution[28,29]. The study conclusions were based on 814,680 'reference incident' dynamic simulations covering over 8760 hour time steps and 93 annual scenarios representing different wind profile years[94]. It is also noted that the load self-regulating effect, incorporated within the study, contributes strongly to frequency stability, and is a key parameter for characterising the “critical” variable renewable penetration rates.

Modern wind turbines can provide a fast frequency (emulated inertial) response with its own characteristics. Due to the fast response time of wind farm controllers and the energy stored in wind turbine rotors, it is technically feasible to provide a rapid, but temporary, power injection, given that otherwise the wind turbines would lose too much rotational speed and therefore also aerodynamic torque[95]. The implementation strategies can differ between manufacturers and academic studies, however, in general, such controls cause the power output of an individual turbine, or farm, to temporarily increase in the range of 5 to 10% of the rated turbine power, following a significant under-frequency excursion, for several seconds[96-98]. Typically, the response consists of a fixed power injection signal, triggered once the frequency deviation exceeds a defined threshold, or, alternatively, a power setpoint trajectory is defined based on the actual frequency deviation, again triggered after a deadband is exceeded[99-101]. Several studies based on meteorological or power measurement data[102-104] indicate that the aggregate supply of rotational energy at a national scale can assist the frequency response, but it is not always available and changes with turbine operating point, as well as being dependent on turbine electrical and mechanical constraints and controller tuning[105,106]. Time delays associated with frequency measurement, activation deadbands and centralised farm communications may encourage local turbine controls. A good compromise should be made for appropriate controller parameter settings, which allow wind turbines to satisfy the grid code but do not seriously impact their own stability and lifetime. However, the added instrumentation implies a trade-off between increased cost and improved wind plant response. Particularly, in the Quebec system, operational experience has been gained for both type 3 and type 4 wind turbines[107,108], which has raised confidence in the technology that a suitably shaped and sustained response can be achieved[95], but also highlighted the opportunity to further improve the control strategies, enhance existing dynamic wind turbine (and farm) models, and also to revise system operator specifications and requirements (particularly considering the recovery phase of the response). Alternatively, fast-acting response from various load categories (water/space heating, air-conditioning, refrigeration systems, municipal water pumping, swimming pools)[109-114], electric vehicles[115,116] and storage devices, such as batteries and flywheels[117-119] are also beneficial options.

One future alternative to currently proposed fast frequency responses may be a virtual synchronous machine approach, whereby power electronics converters are controlled in order to emulate, within a certain degree, the characteristics of a synchronous machine. Several implementations have been proposed in the last decade, e.g. VISMA (virtual synchronous machine), synchroverter[120], but the concept is relatively immature, and, in particular, control tuning and stability assessment for a power system containing several such units is particularly challenging[121]. Additionally, with the emergence of large-scale offshore wind farms, interconnected through offshore trans-national DC grids, opportunities may exist for sharing of primary frequency reserves between asynchronous power systems, e.g. North Sea offshore grid, the mechanisms being similar to an onshore wind farm being connected through a power electronics converter.

TRANSIENT STABILITY AND FAULT RIDE-THROUGH

Transient stability studies examine the operation of power systems during severe fault contingencies, e.g. a fault on a transmission line, and their ability to maintain synchronism, with times of high wind penetration being relevant here. Wind turbines can contribute to system restoration with low / high voltage ride through (LVRT / HVRT) capabilities[122,123], as indicated by Fig. 6, showing the LVRT grid code regulations for various countries. The priority given to active or reactive power recovery, as part of LVRT controls, may also be a system specific decision, with the former approach more likely to be appropriate for smaller systems[27,124]. It should be noted, however, that current grid code requirements regarding wind turbine fault behaviour do not represent a guarantee of transmission system stability. The level of support provided is network sensitive, and proper representation of the impedance connecting the wind farms is crucial. Transient stability performance also strongly depends on the employed wind turbine technology and the grid code regulations in place, such that power systems with a significant proportion of older fixed-speed (FSIG) technology, not equipped with fault ride through (FRT) capability, are likely to observe a large proportion of wind turbine outages during a fault-induced voltage dip. For example, in Portugal and Spain, a significant share of the total installed wind turbines were previously not equipped with FRT capability, and therefore, large numbers of wind turbines were often tripped during a voltage dip[125]. This finding resulted in the introduction of FRT requirements, whereby decade old wind turbines were required to remain connected without reactive power support during a fault, while all new wind turbines were required to provide reactive power support during a fault. Fig. 7 shows the fault ride through certified wind power in Spain, reaching 97% of the installed capacity, according to Spain's TSO, REE. The number of (wind) power losses greater than 100 MW was ≈50 times (2005, 2006 and 2008), 87 (2007) and 30 (2009), but falling to 0 after 2009. As a result of the FRT implementations, the problem of significant wind generation tripping has been solved; therefore, wind plant curtailment due to FRT requirements has not been required since 2008 in the Spanish system.

A study on the New Zealand system, investigating the impact of wind power integration on transient stability, identified that stability-related constraints limit the power flow between different areas, due to FSIGs absorbing reactive power during and following a fault and eventually tripping off unless additional external dynamic reactive power support was available[21]. The Western Wind and Solar Integration Study (Phase 3) concluded that, with good system planning and power system engineering practices in place, transient stability should not be a bottleneck at higher levels of wind penetration[86]. However, a common-mode or sympathetic trip of distributed generation during a disturbance could result in a slower recovery and a sustained lower voltage, which in worst-case under-voltage DG tripping could lead to a system collapse. The challenges of simulating such, or other, behaviour are illustrated by the response to a three-phase fault at Midway-Vincet (500 kV) in California using alternatively a standard WECC load model and a composite load model, Fig. 8. The standard WECC load model assumes a 20% contribution from induction motors with the remainder represented by static components: the weighting of the static ZIP (constant impedance, Z, constant current, I, and constant power, P) terms vary by location, although in the majority of cases constant impedance is assumed for the reactive load and constant current is assumed for the active load. The composite load model, also known as the WECC composite load model (CMPLDWG), integrates distributed generation into the model with a variety of tripping characteristics, and also includes much higher contribution from induction motors. It can be observed that the responses are completely dominated by the load model, and, not surprisingly, the study also highlighted the importance of better load modelling for transient-stability analysis[86]. It was concluded that changing the load model had a greater impact on system performance over changing the level of renewable penetration.

Scenarios of particular interest are associated with reverse power flow situations, where conventional units have been displaced to accommodate wind power. With wind farms connected at lower voltage levels, fault critical clearing times can be determined to see how they may be affected, with implications for network protection schemes and relay settings[126]. Indeed, protection relay settings may need to recognise changes in the dynamic response of the system, dependent on wind instantaneous levels and geographical dispersion. Wind turbines could trip due to a widely-seen network fault, or the reduction in active power infeed could be significant, resulting in voltage depressions and frequency stability issues[127]. The operation of associated protection systems can, therefore, play a critical role, and its simulation may require sophisticated calculation methods[78]. Delayed active power recovery from (grid code compliant) wind turbines following a fault-induced voltage dip may also result in a short-term generation shortfall, resulting in frequency instability issues[128]. Offshore wind farms in DC grids can also pose fault ride through challenges, although plants consisting of mixed turbine types can improve the robustness to onshore faults with VSC-HVDC connection[129].

In order to mitigate stability problems, fast-acting reactive power response devices during and following the disturbance are required. A variety of options, or combination of options, can be considered including synchronous condensers and FACTS devices, in addition to the response obtained from wind turbines and conventional generators[45,130]. Co-ordinated wind turbine controls may also help to dampen oscillations, while VSC-HVDC can, to some extent, also be used for system stabilisation[76,126]. Traditional system reinforcement (e.g. transformers, shunt capacitors, line upgrades) may also be required to maintain adequate stability margins at higher levels of wind penetration. New wind turbine concepts, such as variable speed designs based on an electromagnetic coupler (synchronous generator directly connected to the grid, and able to generate reactive power up to 3 times rated) could also be considered[131].

VOLTAGE STABILITY

Voltage stability relates to maintaining an acceptable voltage profile in steady-state and following a disturbance, such as an increase in load or a network fault. It is mainly associated with an inability to meet (local) reactive power requirements, and so is dependent on the reactive power capability of generators and the reactive demand of loads, but is also influenced by implemented voltage control strategies, such as interactions with transformer tap changers. It may be appropriate, particularly in network regions where (conventional) generation has been displaced, to introduce static var compensators (SVCs), static compensators (STATCOMs), synchronous condensers, or similar equipment, or even to make certain generators 'must run' for voltage support reasons. Voltage instability may result in a loss of load, tripping of transmission lines and other elements, and so lead to cascading outages. Consequently, when assessing voltage stability at high wind penetrations, the potential to utilise the reactive power capabilities of the turbines is a key determining factor. In general, voltage stability is likely to be unaffected or enhanced by the presence of wind turbines[132], if the turbine reactive power control capabilities are deployed to manage voltage[63], and particularly if the turbines are connected at transmission level. However, this is largely true only for variable speed wind turbines, as FSIGs absorb reactive power during and following a fault, and, therefore, lower the voltage stability margin of the system. Moreover, wind-driven displacement of conventional power plants reduces the overall system-wide dynamic reactive power and short-circuit power capacity[133,134].

The Irish All Island Facilitation of Renewables study investigated steady-state voltage stability limits using PV and QV curves for a wide range of dispatches, with zero exchange across the HVDC interconnectors to Great Britain[25]. The analysis identified that distribution-connected wind power tended to reduce voltage stability, as such installations were not equipped with additional reactive power compensation, while reactive power compensation at distribution level could not resolve reactive power issues at transmission level. It was also identified that voltage instability may occur even close to the nominal voltage level in the worst cases, even with grid code compliant wind turbines, as shown by the solid lines in Fig. 9. However, with improved reactive power support deployment, voltage stability was found to be improved, as shown by the dashed lines. Subsequently, EirGrid has implemented an on-line wind stability analysis tool (WSAT)[30], which, amongst other functions, assesses the voltage stability for the current system condition and for a range of short-term demand and wind production increase scenarios.

A similar study using PV analysis to assess the wind integration impact on voltage stability was conducted by Transpower New Zealand[135]. One of the study assumptions was that wind generation, with limited voltage control ability, displaces other forms of generation. It was seen that at lower wind penetration levels, such that other generation was not displaced, the voltage stability of the system was improved due to the additional reactive power margin made available from conventional generators by relieving their active power output. However, at higher levels of wind penetration, with displacement of other forms of generation, the voltage stability limit was reduced by 10-34%. A case study on the Danish power system also suggested that the overall voltage security level was compromised at higher levels of wind penetration, considering current grid code compliance, but without deployment of any other reactive power sources, such as synchronous condensers and SVCs[136], as shown in Fig. 10. Traditionally, PV curve analysis is used to estimate the maximum power transfer at a particular bus. However, a basic assumption is that the generation is dispatchable. Since wind energy is not, a new approach has been proposed to assess the voltage stability of wind integrated systems[137], whereby, in order to include wind variability, a PV surface for secure operation known as a voltage secure region of operation (VSROp) is proposed. The method assumes a constant wind generation level for each PV curve in the 3-D surface.

SMALL SIGNAL STABILITY AND SUB-SYNCHRONOUS INTERACTIONS

In general terms, there are four major types of power oscillations[60,138]: i) intra-plant oscillations, where machines within the same power station oscillate against each other at a frequency of 2-3 Hz, while the remaining system remains unaffected, ii) local mode oscillations, where one generator oscillates against the rest of the system (1-2 Hz), iii) inter-area oscillations, where a set of coherent machines oscillate against another group of coherent machines (1 Hz or less), and iv) torsional mode oscillations, which are associated with the turbine generator shaft system (10-46 Hz). Variable speed wind turbines, similar to HVDC interconnection, do not generally introduce electromechanical oscillatory modes and hence do not directly contribute to system oscillations. However, depending on the wind penetration level and underlying wind turbine technology, system damping performance may change indirectly. For example, wind generation may displace individual synchronous units and hence impact the oscillatory modes and controller contributions: if a synchronous generator with an installed power system stabiliser is offline it can not contribute to system damping. Similarly, increasing wind penetration levels may significantly alter the direction and magnitude of power flows within the transmission network, with implications for small signal stability. Furthermore, wind power interactions with synchronous machines may change the damping torque induced on their shafts[139].

A considerable number of studies have been performed to investigate the impact of wind penetration on power oscillations. However, no clear and generalised conclusion can be drawn as to whether wind integration improves or decreases power oscillation damping. One of the earlier studies[140], investigating the impact of fixed-speed (type 1) and doubly-fed (type 3) wind turbine technologies, concluded that type 1 based wind farms improved damping more than type 3 based wind plants. It was also shown that both wind plant categories improved system damping more than synchronous generators. Similar results were reported in other time domain simulation-based studies considering only type 3 wind turbines[141-143]. Some other studies involving small signal stability analysis have also reported an improvement in system damping with wind integration[22,144,145]. However, other studies have concluded that increased wind penetration levels could have de-stabilising effects, and not necessarily at high wind penetration levels[22,146-149]. For example, a voltage dip due to a fault at the wind turbine terminal is likely to excite torsional oscillations in the wind turbine shaft, with the frequency of such mechanical oscillations tending to be around 1.7 Hz. The wind turbine system acts as a low pass filter to such oscillations, and, as a result, the frequency of the oscillations introduced in the voltage and power output of the turbine is ≈1 Hz, which is close to the natural frequency of power oscillations[127]. On the other hand, a third view point reports that, depending on wind farm location, fault location and turbine operating states, higher wind penetrations could be detrimental or beneficial to the system response[150-155]. In general, increased wind penetrations will reduce the number of oscillatory modes and improve system damping, particularly if turbine (damping) controls are introduced[88]. The latter may be achieved by modulating either the active and/or reactive power output, with the effectiveness of different control input(s) and damping output(s) dependent on the network properties and on where the wind plant is connected. Finally, it should be noted that system damping can be made worse without careful coordination between wind power plants providing power oscillation damping, i.e. when multiple wind power plants are required to simultaneously contribute damping support[22].

The impact of sub-synchronous interactions (SSI) has also been investigated, incorporating sub-synchronous resonance (SSR), sub-synchronous torsional interaction (SSTI) and sub-synchronous control interaction (SSCI), with the latter reported as the main concern for wind integration. For example, SSCI has been seen on the ERCOT system for a wind plant connected radially via a series compensated line, where, following a single-line to ground fault on the transmission line, the wind plant experienced a build-up of sub-synchronous oscillations, resulting in damage to both the series capacitor and the wind turbine[156], Fig. 11. Fixed-speed (type 1) and wound rotor fixed-speed (type 2) wind turbines, if operating close to synchronous frequency, generally do not see sub-synchronous interactions (SSI). However, due to their control response, doubly-fed (type 3) wind turbine based wind plants can be sensitive to SSI, while direct-drive (type 4) wind turbines are also reported to be SSI insensitive. A study from Elforsk, Sweden, investigating the impact of variable-speed wind turbines on SSI, obtained findings in agreement with the ERCOT study, suggesting that type 3 wind turbines were more susceptible to resonant conditions at low frequencies, while type 4 wind turbines have minimal impact due to the power electronic interface between the turbine and the transmission line[157]. A further study, investigating SSR in double-cage induction generator based wind plants connected through series compensated transmission lines, concluded that although torsional interaction does not seem to occur for the considered range of wind farm sizes and series compensation levels, the IG effect, i.e. electrical mode becoming unstable, may be experienced with large wind plants in the range of 100–500 MW at series compensation levels of 50–60%[158]. Analysis with various commercially available induction generators reveals similar potential for SSR oscillations. However, for any potential SSI found in a given system, adequate countermeasures, such as mitigation through FACTS devices, bypass filters, an appropriate level of series compensation or cost effective methods through auxiliary control (damping control) strategies[159] can help avoid any such interactions.

CONCLUSIONS

With increasing wind penetration, the stability of the power system will be affected. At low penetration levels the effects will be limited, and may indeed enhance system performance, with the existing population of conventional generators remaining online but operating at lower outputs. However, at higher wind penetrations, and as conventional (synchronous) generators are displaced, and offshore DC grids emerge, the nature of the power system will change from being largely synchronous to asynchronous. Stability issues are most likely to be seen first during low demand (and high wind) periods, but the nature of the stability challenge, i.e. frequency, voltage, transient or small signal stability, will depend on the underlying characteristics of the system. It follows that, as part of a wind integration study for a particular system, that a stability assessment should be performed, particularly for wind annual energy penetrations beyond 10%, recognising that the instantaneous wind penetration will at times be much higher. As part of such an exercise, adoption of operational (stability) tools embedded within energy management systems, coupling and interaction between distributed power electronic based (wind plant) controls, enhancements to grid codes and/or promotion of new (flexibility-based) ancillary services, changes in operational practice and electricity market structures, real-time wind plant telemetry and control capability, and so on, may also need to be addressed.

While stability analysis may well reveal new operational limits, following on from existing load flow, unit commitment, etc. imposed limits, the operating boundary of a power system with high wind penetration may actually depend on other factors. For example, in systems such as Portugal, instantaneous variable energy generation (wind, run of river hydro and small-scale CHP), combined with reserves, can at times exceed demand. Similarly, the total generation in Denmark often exceeds the total demand, with wind generation alone exceeding the demand on a number of occasions, reaching 136% instantaneous penetration in December 2013. No technical difficulties have been identified, but the business case for wind generation is clearly affected, as it competes with other energy sources, some of them also renewable, while others are made mandatory to provide reserves and short-term security of supply[125]. In the future, wind generation may well play a greater role in providing ancillary services to enhance wind energy value, while also reducing the technical (including dynamic) risks of operating power systems with a reduced share of dispatchable and synchronous energy sources. Several of these services, e.g. voltage control, fault ride through, frequency support, have been available from wind plants for years and have made their way into different requirements in transmission system operator (TSO) connection codes. A number of TSOs have requested certain functionality to be incorporated as a future feature: Hydro-Quebec and ERCOT request emulated inertia, ELIA (Belgium) and NGET (Great Britain) discuss power oscillation damping, while in Ireland a range of frequency and voltage support services are proposed. Key questions remain to be addressed for wide-scale (commercial) adoption of such capabilities: is provision truly available when needed by the power system - how much & how fast & for how long - and can they be efficiently traded? Numerous efforts are underway around the world to better understand and address these issues. However, it is increasingly clear for many power systems across the world that while large-scale wind integration can present system stability challenges (in addition to existing market-related, environmental-related, and other challenges), technical solutions and commercial opportunities are eminently available, and the limits for further wind expansion aims remain to be reached.

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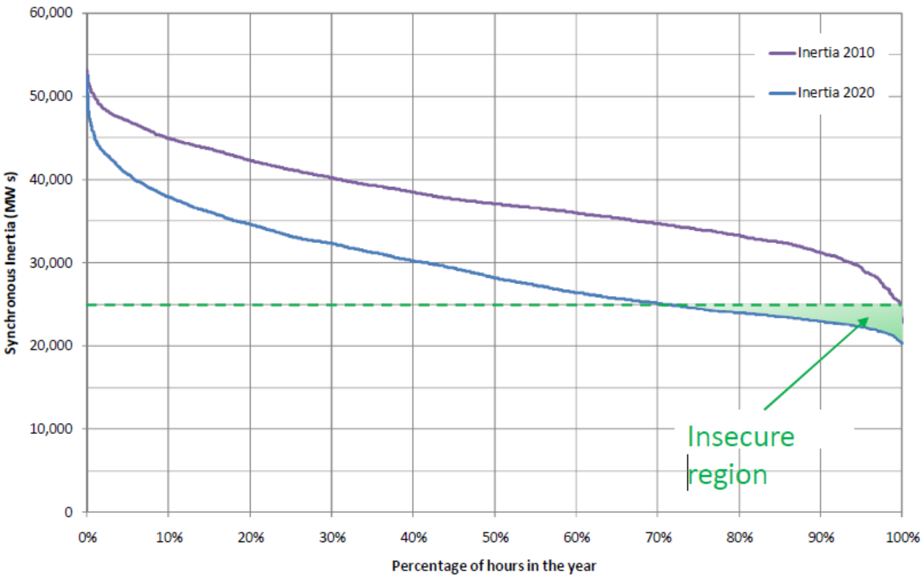

Fig. 1: Inertia duration curves for All-Island system of Ireland. Source: EirGrid

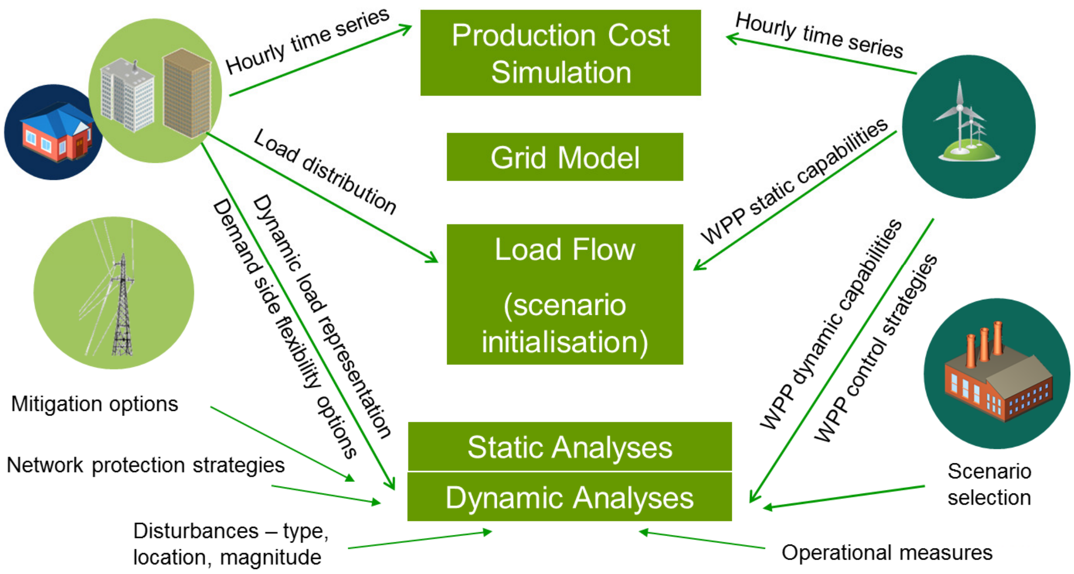

Fig. 2: Representative schematic of power system operational analysis

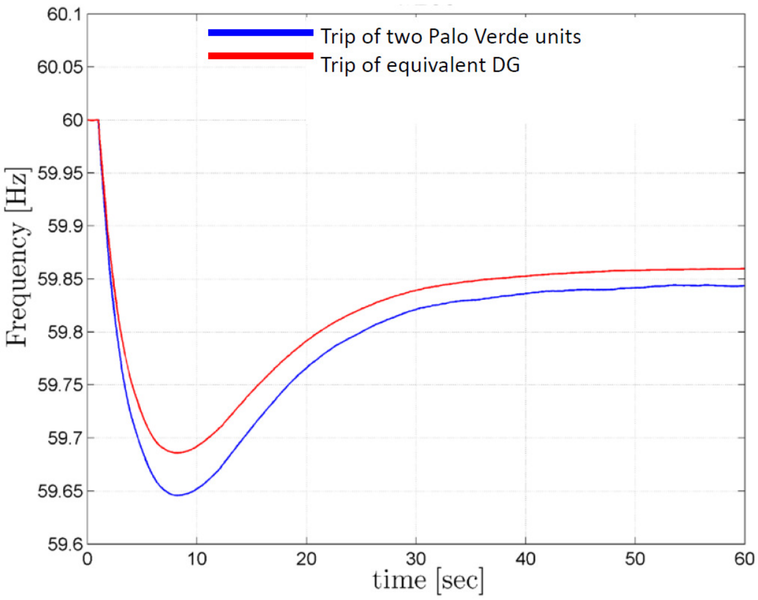

Fig. 3: Frequency response of Light Spring Hi-Mix case – DG trip vs. two Palo Verde unit trips. Source: GE Energy

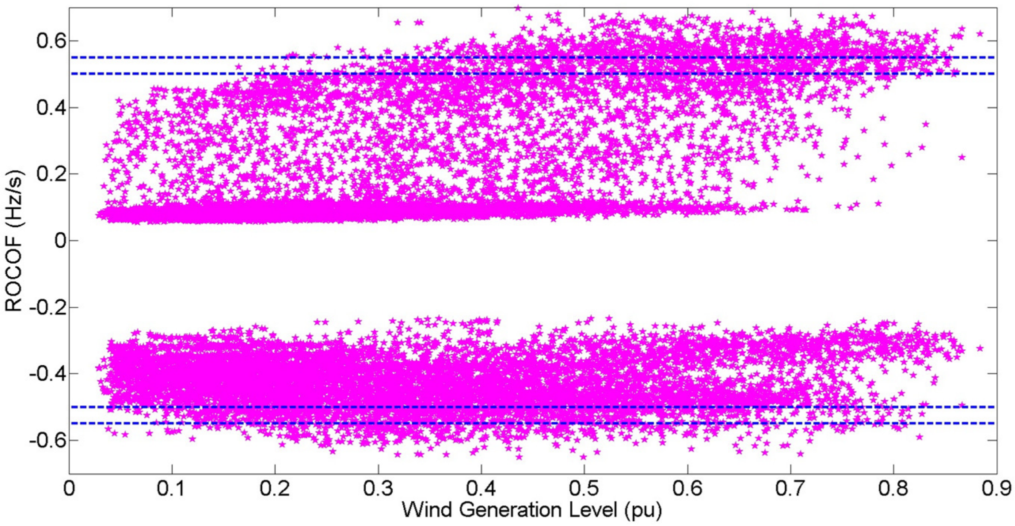

Fig. 4: Maximum RoCoF for All Island (Ireland) System for the year 2020 following tripping of the largest infeed / outfeed

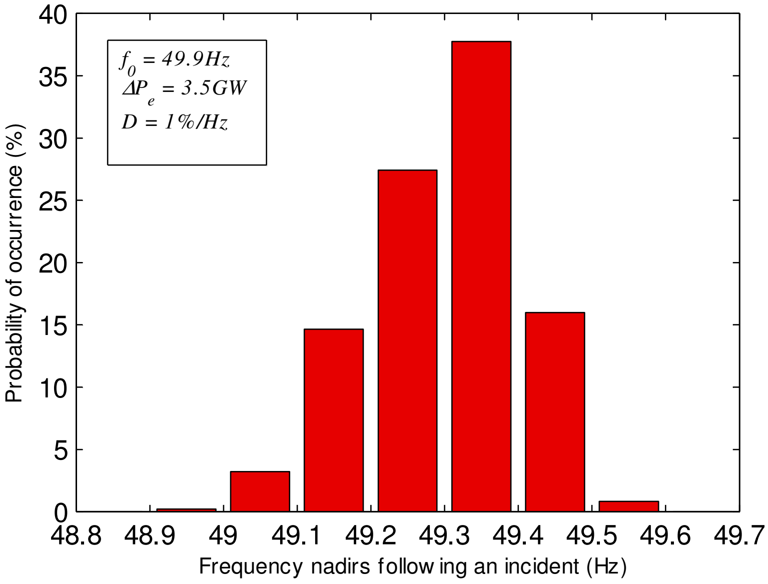

Fig. 5: Distribution of frequency nadirs of European Continental synchronous area following a reference incident

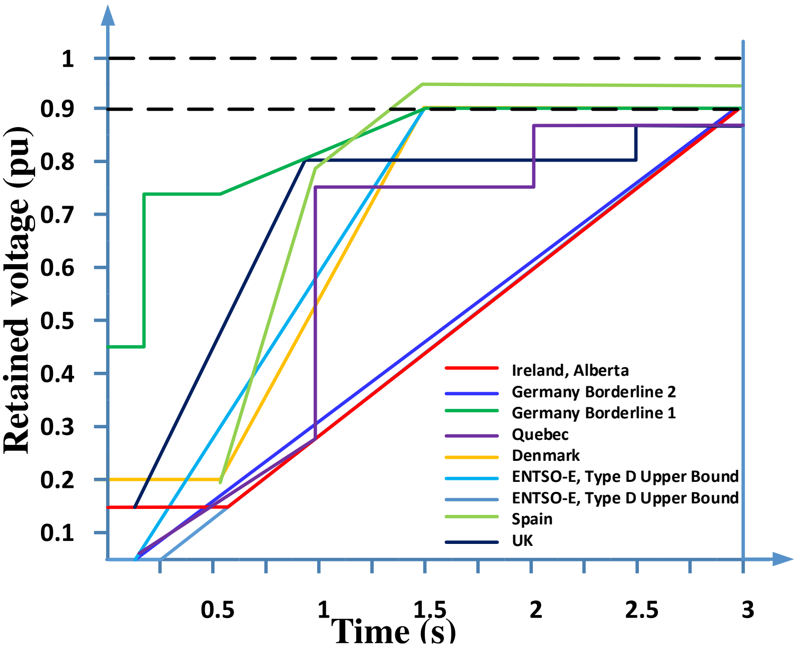

Fig. 6: Low voltage-ride through requirement from WPPs in various countries

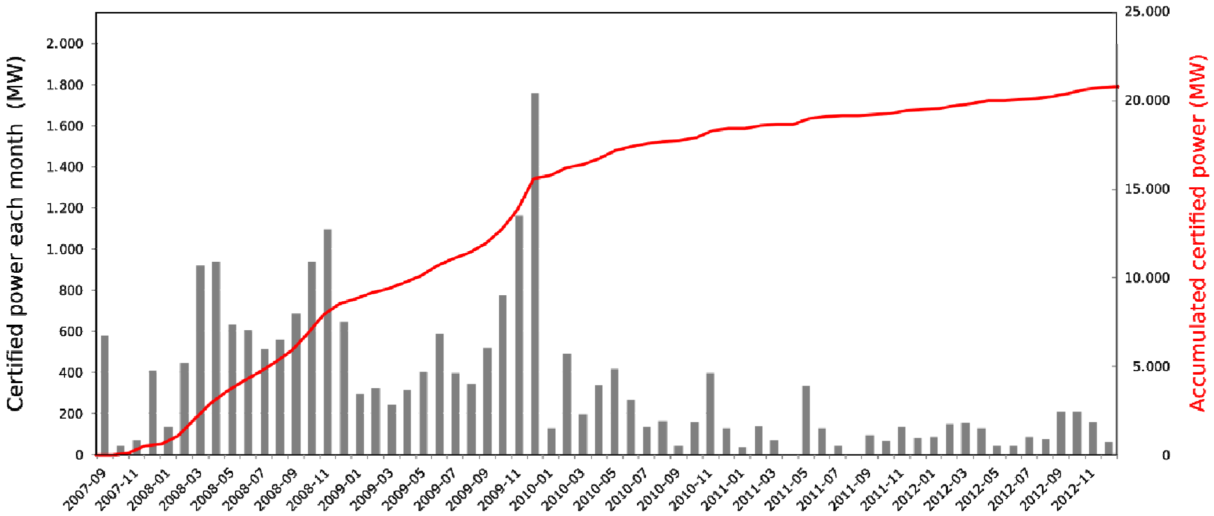

Fig. 7: Fault ride through certified wind power in Spain. Source: Spanish Wind Energy Association (AEE)

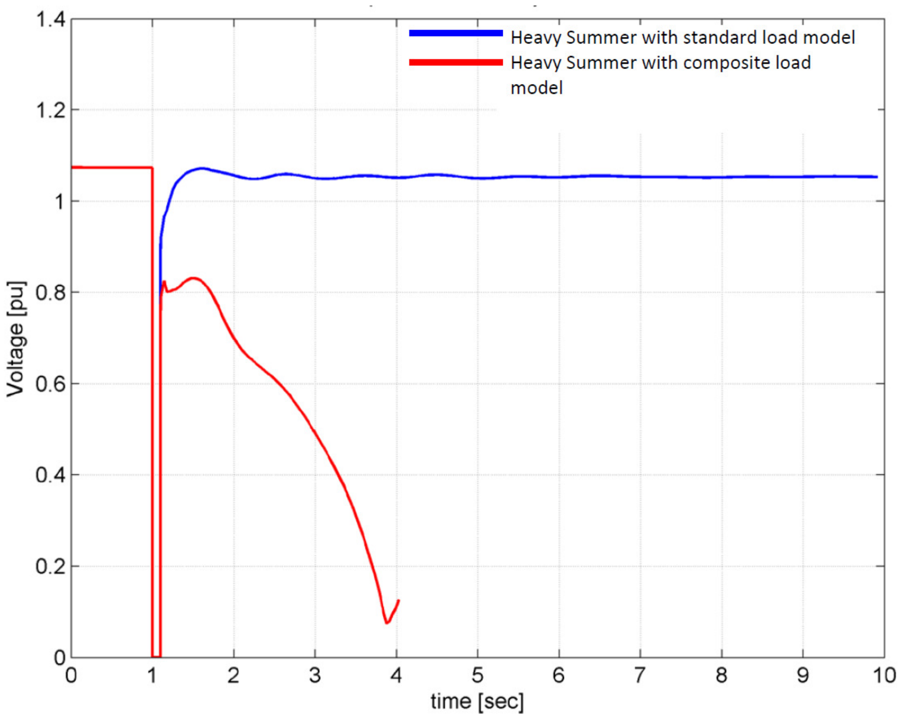

Fig. 8: Load-induced voltage collapse in heavy summer base case, Midway-Vincet (500 kV), California. Source: GE Energy

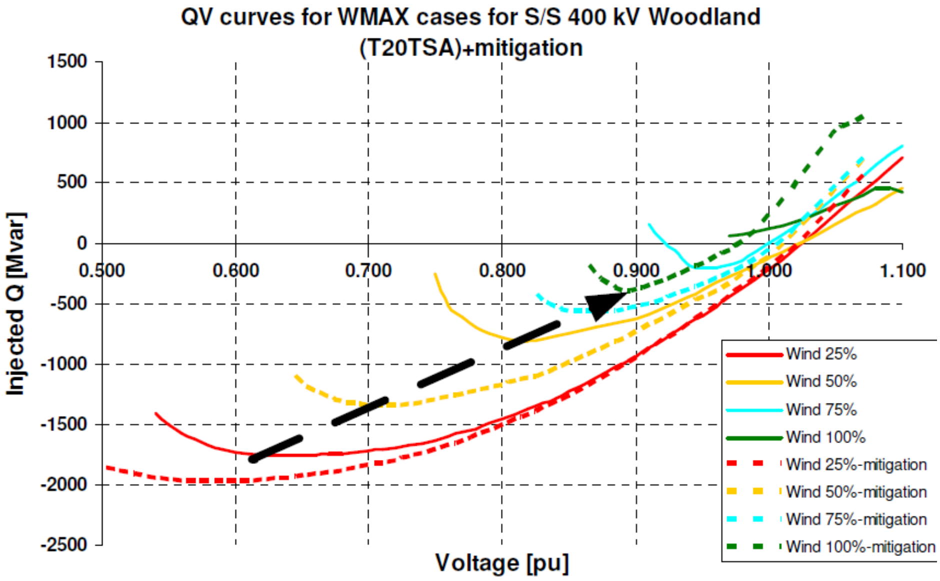

Fig. 9: Reactive power versus voltage analysis (QV curves) for 400 kV busbar Woodland for winter maximum load and various wind power levels in the All Island System. Source: EirGrid

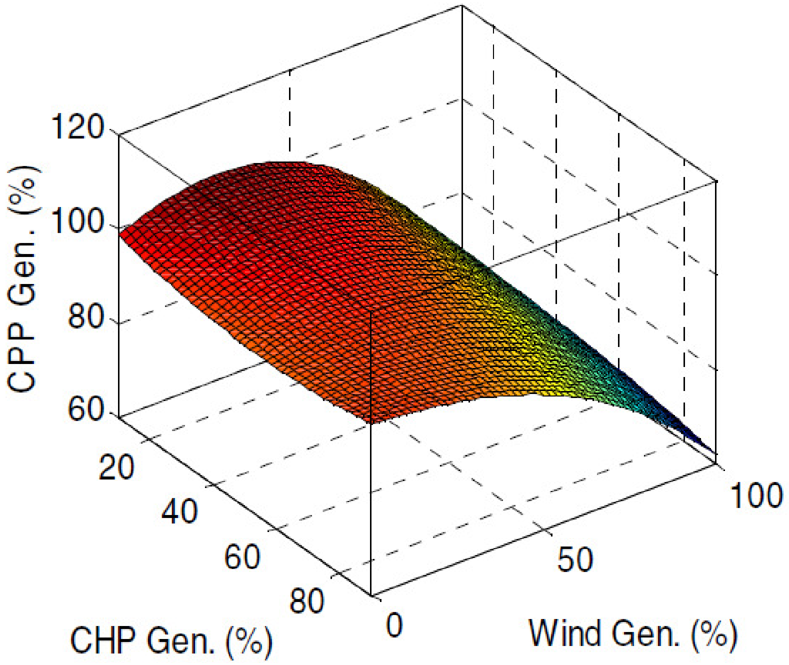

Fig. 10: Voltage security boundary of the Western Danish power system, dependent on conventional power plant (CPP), combined heat and power (CHP) and wind generation mix.

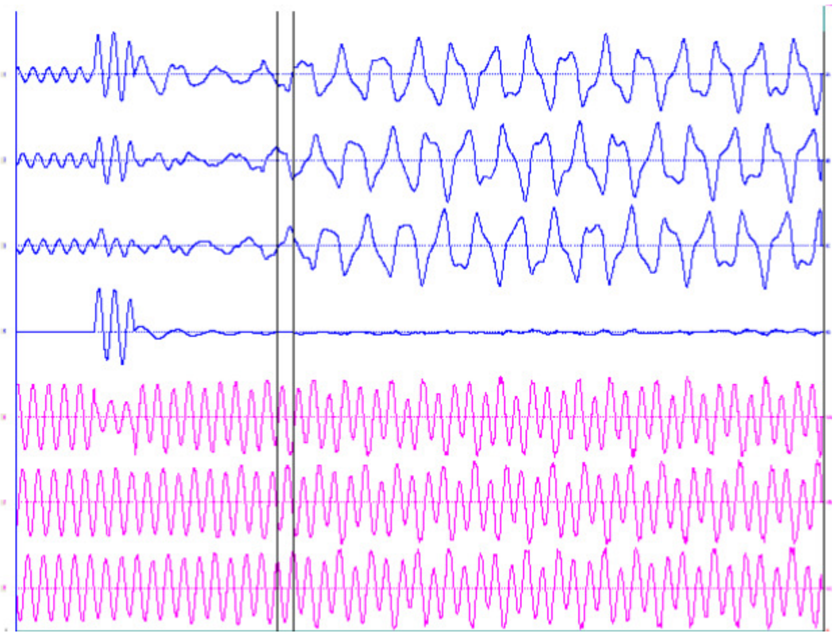

Fig. 11: Measured quantities (phase currents (top - blue) and voltages (bottom - magenta)) at receiving end of transmission line in ERCOT system. Source: Electranix