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Review of AEMO's Power System Model Guidelines and System Strength Impact Assessment Guidelines

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1. Executive Summary

The Australian Electricity Market Operator (AEMO) contacted Power and Energy, Analysis, Consulting and Education, PLLC (PEACE®) requesting that PEACE® make an evaluation of two guideline documents prepared by AEMO, namely the:

1) Power System Model Guidelines, May 14th 2018, and the

2) System Strength Impact Assessment Guidelines, May 14th 2018.

This report presents technical comments, thoughts and suggestions after a review of these two documents. In general, the documents are in line with good industry practice relative to modeling and analysis of power systems, and reflective of the needs of the Australian power system. For example, similar type standards and regulations are applied in North America and Europe. Thus, in spirit these documents are in keeping with good industry practice to ensure good modeling practices, efforts to ensure modeling adequacy and validity, and methods to identify when more sophisticated modeling (i.e. electromagnetic transient type modeling) is needed for specialized studies.

Care should be exercised, however, not to attempt to make a direct technical comparison of standards between those developed by AEMO and those developed elsewhere in the world. This is because there are marked differences among power systems on the various global continents, and thus the technical needs are, and should, be quite different. For example, the Australian power system by global comparison (e.g. compared to continental Europe, or the North American power systems) it is a relatively smaller system (in terms of peak load served), and more importantly the Australian power system is a longitudinal system rather than a densely meshed system. The Australian power system – the interconnected part on the Eastern part of the country – is a long and slender network of extra-high voltage (EHV) lines that run from Queensland to South Australia, with the major load centers then being essentially fed radially from the EHV-backbone. This is in contrast to systems such as for example the North America Eastern Interconnection, where the system is a heavily meshed network of EHV-lines, noting that geographically the 48 contiguous states of the US are almost exactly the same size as Australia. Thus, this longitudinal nature, combined with the relatively smaller-size, makes the system more susceptible to system wide oscillatory stability and other dynamic problems, and with the continued increase of power electronic interfaced generation, makes it quite susceptible to issues related to control interactions between power electronic interfaced generation and the network, due to low short-circuit strength (e.g. similar to the Texas panhandle network).

2. Introduction

The Australian Electricity Market Operator (AEMO) contacted Power and Energy, Analysis, Consulting and Education, PLLC (PEACE®) requesting that PEACE® make an evaluation of two guideline documents prepared by AEMO, namely the:

1) Power System Model Guidelines, May 14th 2018, and the

2) System Strength Impact Assessment Guidelines, May 14th 2018.

This report provides PEACE®'s technical review of these reports and offers thoughts and comments for AEMO's consideration. The comments and review provided herein is focused only on technical aspects of these documents and offers no commentary on the procedural or commercial aspects of the documents.

The remainder of this report is organized as follows:

Section 3 – gives a high-level overview of the PEACE®'s technical assessment of the two documents and provides a discussion on some evolving modeling considerations related to synchronous generator modeling and load modeling, which AEMO may wish to consider for future reference.

Section 4 – provides detailed technical comments and thoughts on the *Power System Model Guidelines* document.

Section 5 – provides detailed technical comments and thoughts on the *System Strength Impact Assessment Guidelines* document.

3. High-Level Overview of two AEMO Documents

At a high-level the two documents prepare by AEMO provide a solid frame work for power system model development and for considering one of the emerging issues world-wide concerning the massive integration of power electronic interfaced generation resources into the bulk electric power system – namely, the impact of system strength (short circuit capacity) on the control-loop stability of power electronic interfaced generation. In the next two sections of this brief report, some specific technical comments are offered on each of the two documents, respectively. However, here in this overview, some general thoughts are presented on the subject of modeling and model validation. Also, some other aspects of modeling are presented, which are not covered in the AEMO documents, which may be worth consideration in future efforts by AEMO.

A *model*, in the context of power systems, is a set of mathematical equations, typically a combination of algebraic and differential equations, which can be used to emulated the response, over time, of a real physical system. For example, a generating plant or an element of the transmission system, such as a static var systems. With this definition in mind, the process of model validation is then typically embarked on to establish a level of confidence in the ability of the model to faithfully emulate the response of the actual physical system. This is typically achieved by comparing the simulated response of the mathematical model to the measured actual response of the equipment to either a staged test in the field or a monitored disturbance event that occurs on the power system. This process assumes that the model to be used has adequate bandwidth to represent the phenomena to be simulated, and it has been properly coded into software free of any programming errors. Thus, these two issues aside, let us consider some of the other aspects of modeling and model validation, at a high-level.

First and foremost, no model can possibly claim to be completely accurate nor to cover all possible phenomena and conditions of a physical system. A model, by definition, is an emulation and not an exact representation of physical reality. Thus, all models, incorporate some simplifying assumptions and limitations. In the context of power systems, we can perhaps list the hierarchy of models as follows:

- **Real Time Simulators/Hardware in-loop:** These are typically factory and laboratory-based simulation platforms where a very simple model of the power system, together with a detailed model of the physical system of the equipment (e.g. thermodynamics and mechanical aspects of a gas-turbine) are incorporated into a dedicated computer simulation tool, which is then interfaced with the actual control system hardware used on the real equipment. This is often the ultimate factory testing mechanism for design and testing of the equipment by the equipment manufacturer. In the case of power electronic interfaced generation, the majority of the hardware may actually be incorporated into the real-time simulator, i.e. the converter controls, the actual converter power electronics, etc.
- **Electromagnetic transient (EMT) models:** These are detailed 3-phase vendor-specific models, which are highly proprietary and used by vendors for their internal control design and other applications. They may often be implemented in various software platforms such as PSCAD™, MATLAB® Simulink®, EMTP-RV, etc.

- **Reduced-order EMT models:** These models are based on the detailed EMT models above but may have some aspects of the mechanical and other components simplified or hard-coded as dynamically linked libraries. Again, these are typically proprietary models, owned and maintained by the equipment vendor.
- **Reduced-order vendor-specific RMS/positive-sequence stability models:** These models are typically benchmarked by the original equipment manufacturer against the higher-level models described above, within the bandwidth of stability analysis tools (typically 0.1 to 10 Hz or so). These models are typically developed in native programing code associated with commercially available software platforms such as Siemens PTI PSS®E, GE PSLF, PowerWorld Simulator, PowerTech Labs TSAT^{TM}, and again are proprietary and owned and maintained by the equipment vendor and shared under non-discloser agreements.
- **Generic RMS/positive-sequence stability models:** These are open source, publicly available model structures, developed through broad industry efforts (e.g. the North American second generation generic renewable energy system models[1] or the IEC standard models for wind turbine generators[2]). These models have the benefit of being public and open source and readily transferable across most major commercial software platforms. Their disadvantage is that they are the most limited in their range of applicability.

The key here is that no single model can be valid and useful across all possible conditions and for all possible types of analyses. For example, using detailed EMT models to perform system wide small-signal stability analysis to determine the damping of oscillations would be a hugely burdensome task, and quite unfruitful, since the burden of computation, data management and postprocessing of simulation results to extract the necessary results well outweigh any potential benefits. AEMO's approach in its documentation appears to be focusing on what has been referred to above as EMT models, reduced-order EMT models and reduced-order vendor-specific RMS/positive-sequence stability models, and to attempt to identify when and where the complexity of EMT modeling is needed for localized studies, such as full assessment of system strength impact assessment or subsynchronous resonance studies. This is a reasonable approach. The only caveats here are to recognized that EMT models have their limitations too and so in all cases consideration should always be given to open consultation and communication among all the affected parties, including the equipment vendor. To illustrate the point with a simple example, when studying transient recovery voltage (TRV) across a circuit breaker for critical cases (e.g. in some gas insulated switchgear applications) it is exceedingly difficult, even with detailed EMT models, to account for all the possible sources of stray capacitance, which have a significant impact on the rate-of-rise of TRV. Thus, it may be necessary to collaborate closely with the breaker manufacturer to iteratively compare simulations results with actual

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[1] P. Pourbeik, J. Sanchez-Gasca, J. Senthil, J. Weber, P. Zadehkhost, Y. Kazachkov, S. Tacke and J. Wen, "Generic Dynamic Models for Modeling Wind Power Plants and other Renewable Technologies in Large Scale Power System Studies", IEEE Trans. on Energy Conversion, vol. 32, no. 3, September 2017. DOI: 10.1109/TEC.2016.2639050; http://ieeexplore.ieee.org/document/7782402/

[2] Ö. Göksu, P. Sørensen, J. Fortmann, A. Morales, S. Weigel, P. Pourbeik, "Compatibility of IEC 61400-27-1 Ed 1 and WECC 2nd Generation Wind Turbine Models", Conference: 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, November 2016.

breaker factory tests done during product development and design to come to a reasonable conclusion based on the simulation results.

Furthermore, when performing model validation for any one of these types of models, there will always be some discrepancy between simulation and measurement driven by factors such as unavoidably measurement errors, physical phenomena not represented in the models (e.g. magnetic hysteresis), interaction of other equipment on the grid with the validation tests, etc. Thus, some level of engineering judgment is always necessary in interpreting and understanding the results of validation work. The AEMO documents do allow room for such flexibility in interpretation, e.g. section 8 of the guide, and so this is commendable.

In the next two sections of this report, more specific comments are offered on each of the sections of both reports. For the remainder of this section two topics are presented, which are not explicitly covered in the AEMO documents, and may be worth considering in the future.

3.1 Load Modeling

The AEMO document on *Power System Model Guidelines* is focused on providing legally binding requirements for network service providers, generators and other registered entities, and thus it is focused on generation equipment and transmission equipment (e.g. HVDC). There is of course a third element to the dynamic and steady-state performance and behavior of the power system, namely load dynamics. Therefore, one suggestion is that AEMO might, in future efforts, consider investigating load modeling in more detail. In the past ten to fifteen years, there has been tremendous efforts in North America[3] on developing and using aggregated composite dynamic load models for transmission planning studies. It is out of the scope of this document to provide a detailed account of dynamic load modeling; however, the following high-level comments are pertinent:

1. Evidence in North America has shown that modeling the dynamics of the load, particularly a reasonable representation of the load composition, has a marked impact on the simulated transient and oscillatory response of the system.
2. Simple static load models are not adequate for capturing the full dynamic aggregated behavior of the load.
3. Load modeling is most critical for studies that involve voltage stability and voltage control but can also have a significant impact on power oscillations.

The so-called composite load model developed originally in the Western Electricity Coordinating Council's (WECC) Modeling and Validation Working Group (MVWG) is shown in Figure 1. The most complex component in the model, and the one that leads to the fault-induced delayed-voltage recovery[4] in the system, is the *motor D*, which represents the single-phase residential air-conditioning compressor induction motor. Perhaps, the

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[3] For a comprehensive coverage of most of the research and work over the past decade see the NERC Load Modeling Technical Reference: https://www.nerc.com/comm/PC/LoadModelingTaskForceDL/Dynamic%20Load%20Modeling%20Tech%20Ref%202016-11-14%20-%20FINAL.PDF#search=Load%20modeling%20technical%20reference

[4] https://certs.lbl.gov/initiatives/fidvr

saving grace for the Australian power system is that based on our understanding of the load profile in Australia (to be confirmed of course by AEMO and others), this component of the model (*motor D*) may not be needed. This is because, based on our understanding, unlike the US, most residential and commercial air-conditioning loads in Australia use variable-frequency drive (VFD) motors, which have a radically different dynamic behavior to single-phase cross-the-line induction motors. The VFD motors do not exhibit the stalling characteristics seen from single-phase induction motors.

The other complexity with using the composite load model is coming up with the aggregated load composition and component parameters. Again, it is outside of the scope of this document to delve into such details. It suffices simply to say that AEMO may wish to give due consideration in the future to the subject of more detailed load modeling. Furthermore, a more recent development in the US has been efforts to develop simplified aggregated models for distributed energy resources, such as residential roof-top PV, to be integrated into the composite load model[5].

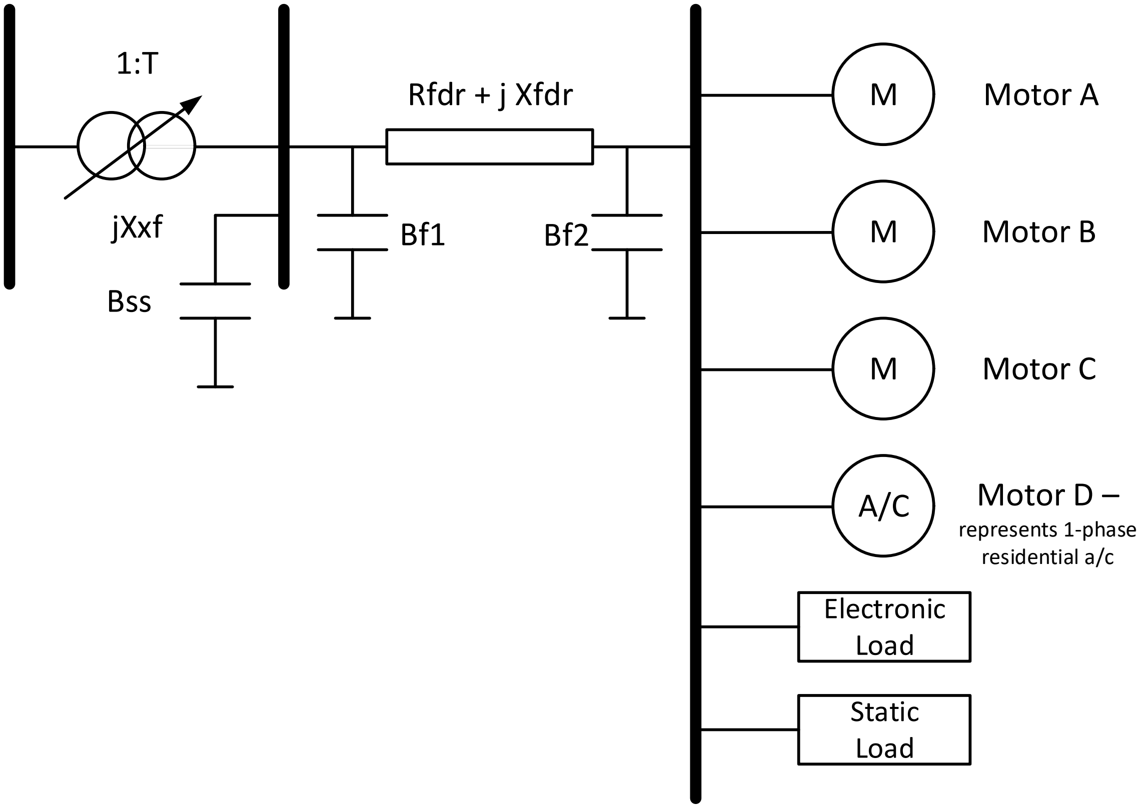

Figure 1: WECC developed composite load model structure.

3.2 Recent developments in Synchronous Generator Modeling

By far the dominant model used in all commercially available power system simulation tools, such as Siemens PTI PSS®E, for representing synchronous generators is the so-

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[5] The so-called distributed energy resource model A, the detailed of which may be found here: https://www.wecc.biz/Reliability/DER_A_Final.pdfThe model has already been adopted and tested across four of the major commercial power system simulation tools in North America, including Siemens PTI PSS®E.

called GENROU family of models (GENROU, GENSAL, GENROE, etc.). These models have been used to represent round-rotor (GENROU) and salient-pole (GENSAL) machines for decades. In WECC another family of models, called GENTPF, has been used for well over two decades. The GENROU family of models are based on the simplifying assumptions that (i) rotor saliency is ignored in the subtransient time frame ($X''q = X''d$), (ii) all the mutual-inductances between the windings on the same axis are assumed to be equal in deriving the operation impedance model, and (iii) saturation is modeled using the open-circuit saturation curve[6] and it is assumed that all the inductances saturate in the same way. By contrast, the GENTPF family is based on the assumptions that (i) rotor saliency in the subtransient time frame is not ignored and (ii) the following relationship is assumed, between the self and mutual inductances on the d-axis $\frac{L_{akd}L_{fkd}}{L_{kd}L_{af}} = 1$[7]. In the past decade it was found, initially in WECC, that neither of these family of models, when used with standard original equipment manufacturer data, could faithfully calculate the variation in field current and voltage over the full operating range of the generator. The issue being that as the machine is loaded these family of models both significantly under-estimate the corresponding per unit field current at higher loading levels as the machines reactive power also increases. The consequence of this for power system simulation studies is that the over-excitation limit (OEL) is reached in the simulation at a much higher value of reactive power output. Thus, the reactive capability of the machine is significantly over-estimated for severe conditions[8]. This is all due to the way saturation is modeled. Thus, nearly a decade ago the Bonneville Power Administration (BPA) sponsored the development of a new model, based off of the GENTPF family of models called GENTPJ[9]. Over a period of a decade or so, this model proved to be very effective in emulating both the dynamic and steady-state response of the generator field current over the entire range of the generator's response[10], requiring the additional of only one extra parameter (*Kis)* which can be fit using steady-state measurements[9]. This parameter augments the saturation function, by introducing a component in the saturation function which is proportional to the machines stator current (i.e. machine loading). Thus, for many years WECC no longer accepts the use of the GENSAL model for salient-pole machines, and both WECC and NERC[11] recommend the use of the GENTPJ model, were possible.

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[6] In Siemens PTI PSS®E, GENROE, is essentially identical to GENROU, except that saturation is modeled by an exponential, rather than quadratic, equation.

[7] P. Pourbeik, B. Agrawal, S. Patterson and R. Rhinier, "Modeling of synchronous generators in power system studies", CIGRE Science and Engineering, Volume 6, page 21-31, October, 2016. (available for free download at: www.e-cigre.org)

[8] B. Agrawal and D. Kosterev, "Model Validation Studies for a Disturbance Event That Occurred on June 14 2004 in the Western Interconnection", Proceedings of the IEEE PES GM, 2007.

[9] J. M. Undrill, "The GENTPJ model", WECC approved model specification for the GENTPJ model, November 19, 2007 (revised June 19, 2012).
https://www.wecc.biz/Reliability/gentpj-typej-model-specification.pdf

[10] S. Patterson, "GENTPJ Validation", Presentation made to the WECC Modeling and Validation Working Group, November 19, 2010. https://www.wecc.biz/Reliability/gentpj%20and%20gensal.pdf

[11] North American Electric Reliability Corporation, Modeling Notification on use of GENTPJ Generator Model, November 18, 2016.
https://www.nerc.com/comm/PC/NERCModelingNotifications/Use%20of%20GENTPJ%20Generator%20Model.pdf

With all this said, in 2017 some issues were identified with the GENTPJ model in BC Hydro for some salient pole generators, when using very high gain AVRs with no transient gain reduction[12]. Specifically, it has been found that for salient-pole machines, where T''do is quite small, and the AVR is high gain, and transient gain reduction is not employed, then the response of the GENTPJ model, particularly for open-circuit voltage reference step tests, is significantly less damped than the measured response of the machine. This is not true when using GENSAL. However, GENSAL suffers from the issues described above for the calculated values of field current over the entire range of the generator operating conditions. This problem with GENTPJ has not, however, been observed yet on round-rotor machines.

Thus, a recent new effort has been started in WECC, sponsored once more by BPA, to develop yet another model (GENTPW) to resolve both issues. This is a work in progress and the results are unlikely to be seen for another year or more.

The recommendation here is that AEMO might consider following some of this work, moving forward, and to explore the potential impact of the inaccuracies that may occur in the estimated dynamic reactive reserve of generators when using models such as GENROU, GENSAL, GENROE and GENSAE in conjunction with OEL models, and how this may impact voltage stability margins in parts of the Australian system that are susceptible to voltage stability. If voltage stability is not a major concern for AEMO, these issues with synchronous generator modeling may not present a significant concern.

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[12] Q. Y. Wang and J. X. Zong, "GENTPJ Model Dynamic Performance", 2017 IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE); https://ieeexplore.ieee.org/document/7946628/

4. Comments on the Power System Model Guidelines Document

The *Power System Model Guidelines* document consists of eight (8) sections and several supporting appendices. Here the comments offered are organized, for easy reference, under these section titles.

4.1 Section 1 - Introduction

This section of the document is an introduction and in general it is quite well written. The only minor suggestions are as follows. In Table 1, under disturbances, what is defined as "*changes to the energy source*" probably require some further clarification. For example, the variations in the energy source for wind power plants occur constantly. From a power system performance stand-point, small variations of a few percent in output of a single plant is likely of little consequence. What is of importance are large variations due to extreme, or dominant weather patterns, that may lead to many tens of percent variation in the output of a large portion of the installed wind/PV base. Therefore, a "*disturbance*" in the context of changes to the energy source, are significantly large changes that lead to large and fast ramps up or down in a significant portion of the installed variable generation base.

4.2 Section 2 – Provision of Models and Other Information

This is a procedural section, and thus we have no technical comments to offer.

4.3 Section 3 – Models and Data Requirements

This is a concise section of procedural aspects for modeling and data requirements. The one observation is that the size requirements in Table 2 (i.e. EMT models not required if plant size is ≤ 5 MVA and no model required if plant is < 1 MVA) are quite small, however, this is perhaps reasonable for the Australian power system since (i) by global comparison (e.g. comparison to continental Europe, or the North American power systems) it is a relatively smaller system (i.e. load served), and (ii) more importantly the Australian power system is a longitudinal system rather than a densely meshed system. The Australian power system – the interconnected part on the Eastern part of the country – is a long and slender network of extra-high voltage (EHV) lines that run from Queensland to South Australia, with the major load centers then being essentially fed radially from the EHV-backbone. This is in contrast to systems such as for example the North America Eastern Interconnection, where the system is a heavily meshed network of EHV-lines. This longitudinal nature, combined with the relatively smaller-size, makes the system more susceptible to system wide oscillatory stability and other dynamic problems, and with the continued increase of power electronic interfaced generation, makes it quite susceptible to issues related to control interactions between power electronic interfaced generation and the network, due to low short-circuit strength (e.g. similar to the Texas panhandle network).

4.4 Section 4 – Model Adequacy

The following are some comments and thoughts offered on this section of the document:

1. In this section, and many other sections of the report the phrase "*reticulation network*" is used. We assume that by reticulation network is meant the *collector system* of for example wind and PV power plants. Namely, the medium voltage (typically 34.5 kV in North America) radial network of feeders, which collect the output of all the individual wind turbine generators (or PV inverters) and feed them to the substation transformer, which then steps up the total collective output of all the individual turbines and injects it at the point-of-interconnection into the EHV network. If so, we suggest that the phrase be defined in Table 1 of section 1(in the glossary section) since this is not a commonly used phrase.
2. In general, section 4.3 has a lot of excellent points and requirements that will help to ensure proper modeling for RMS and EMT models. However, there are many comments and requirements in this section that may need to be carefully considered and, in some cases, relaxed as they can be challenging at best, and not quite achievable in some cases. To give a few specific examples, consider the following:
    a. Section 4.3.1 discussed general requirements for model accuracy. In this section, under the tile "*Model composition and operating range*" there are several requirements around the need to have the models valid and functional for the entire range of possible operating conditions, e.g. from no-load to full-load. This may be achievable, to an extent, for equipment that are entirely based on power electronics and digital controls (e.g. an SVC or STATCOM). However, is an insurmountable task for equipment that incorporate mechanical and thermodynamics systems (e.g. gas-turbine, steam-turbine, etc.). Consider the example of a steam-turbine. Steam-turbines have both non-linear and complex thermodynamics that will result in significant variations in steam temperature and pressure as the unit is loaded from no-load to full load. Thus, to try to capture the response of a steam-turbine for a wide range of operating conditions one may need quite a complex model, which can be difficult at best to manage and validate for power system studies[13]. On the other-hand, properly parameterized and simplified models can actually reasonably emulate the behavior of the steam-turbine, even for real system frequency events[14], at typically load levels near base-load. Thus, it may be useful to acknowledge this.
    b. Another sentence in this section states, "*All changes to operating models should happen automatically.*" Again, it should be realized that all mode changes are not automatic, e.g. turning on or off the coordinated shunt capacitor switching function on an SVC. However, such functions can be modeled, and toggled by a flag in the model. Furthermore, some automatic mode changes in equipment cannot be easily incorporated into RMS nor EMT models, since they involved details of the thermodynamics and mechanical systems of the equipment, which would be too complex, and perhaps insurmountable, to be modelled in software platforms such as Siemens PTI PSS®E or PSCAD. An example, is the mode shifts in the combustion modes of a gas-turbine during load ramps.

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[13] *Dynamic Models for Turbine-Governors in Power System Studites*, IEEE Technical Report PES-TR1, 2013. http://sites.ieee.org/fw-pes/files/2013/01/PES_TR1.pdf

[14] See for example Figure 2-4 in the above public reference.

c. The document states that "*when initialized at a valid Steady State operating point for the plant …………….the model must correctly calculate state derivatives……… This will generally be the case when the derivatives calculated ………. are no greater than 0.00001….*" Although this statement is certainly true in the vast majority of cases, there are legitimate exceptions to this rule. For example, for a battery energy storage system, the model may be initialized from power flow with an initial battery state of charge of say 50% and with the battery initially charging (i.e. absorbing power from the grid). In this case, the derivative of the state of charge (which is energy being injected into the battery) will be equal to the initial power being absorbed, which will be non-zero and quite significant. This is not an error, it is a simple fact of the physics of the device.

d. The statement "*include models of generating unit mechanical components that would be affected by Disturbances*" is a slightly vague statement. A better statement might be: *include adequate modeling of the mechanical components of the plant, to the extent that such mechanical components have a significant effect on the stability of the plant and its response to power system disturbances*.

e. A general comment is that in a few places in the appendices reference is made to modeling torsional damping in EMT models. It should be noted that although it is possible, and common practice, to model the lumped-spring mass mechanical drive-train in EMT tools and to thus obtain a reasonable representation of the torsional modal frequencies, mode shape and initial transient-torques following a grid disturbance[15], for conventional power plants it is exceedingly difficult to properly model the inherent mechanical damping of the torsional modes, as it is a function of machine loading and many other factors. This is actually acknowledged by AEMO in a footnote in their document. However, it may be worth providing here a little more elaboration on this subject. Due to this difficulty in estimating inherent mechanical damping of the torsional modes for conventional generation, in many cases no-load damping is measured in the field and full-load damping is estimated[16]. Even so, such measurements and estimates have inherent errors associated with them. Thus, it is imperative in all such cases to carefully review the results of any analysis related to torsional stress with the equipment vendor and with experienced engineers who can reasonably interpret the results. Furthermore, the calculation of fatigue and loss-of-life of the drive-train components is quite complex and requires significant post processing and close collaboration with the equipment vendor, who will have the necessary information of the materials and endurance limits of the drive-train components. For wind turbine

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[15] P. Pourbeik, D. G. Ramey, N. Abi-Samra, D. Brooks and A. Gaikwad, "Vulnerability of Large Steam Turbine Generators to Torsional Interactions During Electrical Grid Disturbances", IEEE Trans. PWRS, August 2007.

[16] P. Pourbeik, C. E. J. Bowler and V. L. Crocker, "Model Validation Testing for the Purpose of Determining Generation Equipment Dynamic Performance and Torsional Mechanical Response", Proceedings of IEEE PES General Meeting, June 2004, Denver, Colorado.

generators, most modern technologies incorporate active-drive train damping controls for dampening the torsional mode on the shaft. The effects of this control in most cases likely far outweigh the inherent mechanical damping of the drive-train. Therefore, for wind turbine technologies, EMT models may more effectively model the damping of torsional modes through proper modeling of the active-drive train damping controller. Nonetheless, the vendor should be consulted in interpreting results.

   f. In the table in section 4.3.6, reference is made to the "*Quantity determining FRT activation*" for HVDC links and SVC/STATCOMs. In the context of HVDC what should be modeled is the voltage-dependent current-order limit (VDCOL) for line-commutated (LCC) technologies, as well as an emulation (in RMS models) and simulation (in EMT models) of commutation failure. Also, for both LCC and voltage-source converter technologies, if the converters are blocked below a certain voltage (and other conditions) then that blocking should be modeled. The term Fault Ride Through (FRT) perhaps is not as conducive or appropriate in the context of these technologies. Similarly, for SVCs and STATCOMs the issue is to properly model blocking and any over/under voltage strategies[17].

3. In section 4.7 on model aggregation, it is stated that *"… no more than four generating units of any one type*" should be modeled in a plant explicitly. We suggest clarifying this statement with the size of each individual generating unit. For example, in North America there are many plants that consist of six or more nominally sister units of gas-turbines or hydro-turbines. In all these cases each unit is explicitly modeled, as these are large units. While in the case of wind power plants, certainly all generators of the same type are aggregated into a single aggregate unit model. There is one subtlety here, which has no clear answer. There are many cases today, in North America, where older wind power plants (e.g. 10 to 15 years old) are upgraded in stages, e.g. a plant with 50 turbines may have turbines replaced or upgraded a few at a time over a period of several years. In these cases, it is hard to ascertain at what point, and in what fraction, to start splitting out the new and old turbines in the aggregated plant model. Such cases require some flexibility and engineering judgement.
4. In subsection 4.7.3 it is stated that "*For model validation purposes, both the individual generating unit and aggregated generating system response must conform to the accuracy requirements in Section 6.2.*" We offer the thought that some level of flexibility and engineering judgement must be exercised here. Take as an example the results shown in Figure 2, Figure 3 and Figure 4. Figure 2 shows the validated response of the aggregated wind power plant model for simulating a plant level voltage response at the point-of-interconnection (see Figure 5). Figure 3 shows the response, as measured at the same time, of two individual wind turbine generators (WTGs) in the plant and how this compares to the scaled down response of the aggregated WTG in the model (see Figure 5). In this case fortuitously the responses match well. Figure 4 shows an example of an individual WTG response

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[17] P. Pourbeik, A. Boström and B. Ray, "Modeling and Application Studies for a Modern Static VAr System Installation", IEEE Transactions on Power Delivery, Vol. 21, No. 1, January 2006, pp. 368-377.

where the actual measured response is quite a bit offset from the simulated aggregated WTG model, even though the response at the point-of-interconnection (POI) was just as good as that in Figure 2. The reason is simple. The equivalent feeder model, derived using the so-called NREL method[18], is able to give a reasonable representation for modeling the plant's response at the POI, however, it is unreasonable to assume that it will be able to adequately capture the exact steady-state voltage and reactive profile at every point in the collector system. Thus, in some cases one will be lucky and see a response such as Figure 3 and in others one will see an offset in voltage and reactive power as in Figure 4. Nonetheless, the dynamic response of the individual WTGs is adequately captured. This can be further illustrated by other tests too, such as a capacitor switching test which invokes a "true" grid voltage jump (see Figure 6). This is all said to illustrate the fact that an aggregated model of a wind (PV) power plant, which is typically what is needed for power system simulations (and actually specified in the AEMO document) cannot give the same level of accuracy at both the POI and the individual turbine/inverter level. Thus, there must be flexibility here in understanding the goal and objective of the model.

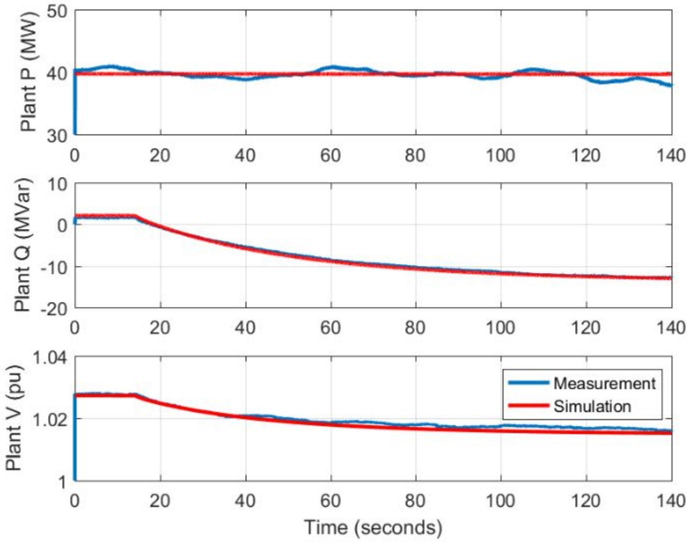

Figure 2: Simulation and measured response of a type 3 wind power plant at the point of interconnection (high-voltage side of the substation transformer) for a voltage reference step test on the plant controller. (© IEEE 2018[19], reproduced with permission)

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[18] E. Muljadi, C. P. Butterfield, A. Ellis, J. Mechenbier, J. Hochheimer, R. Young, N. Miller, R. Delmerico, R. Zavadil, and J. C. Smith, "Equivalencing the collector system of a large wind power plant," in Proc. IEEE Power Eng. Soc. General Meeting, Montreal, QC, Canada, Jun. 2006.

[19] Figures 2, 3, 4 and 6 are from: P. Pourbeik, N. Etzel and S. Wang, "Model Validation of Large Wind Power Plants Through Field Testing", *IEEE Transactions on Sustainable Energy*, July 2018 (http://ieeexplore.ieee.org/document/8118170/)

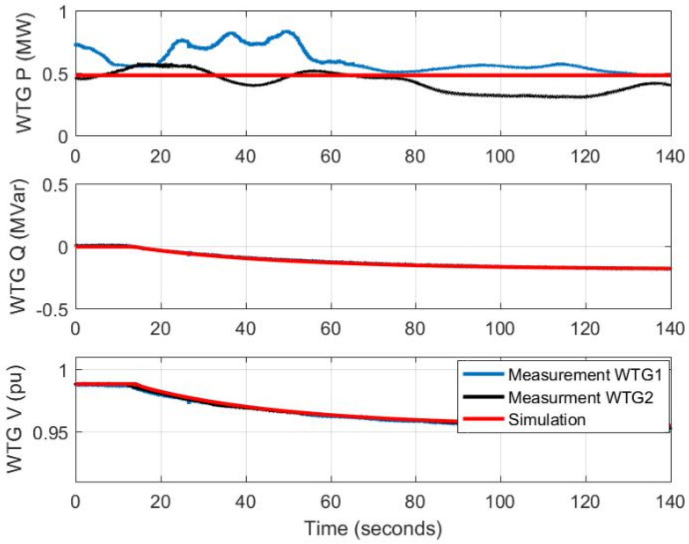

Figure 3: Simulation and measured response of two individual wind turbine generators in the wind power plant for the same case as Figure 2. (© IEEE 2018, reproduced with permission)

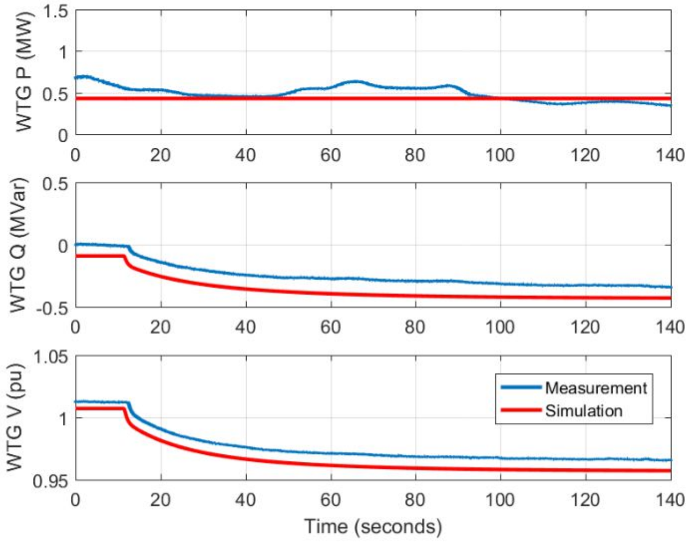

Figure 4: Simulation and measured response of an individual wind turbine generator in another wind power plant where the same test as shown in Figure 2 was performed. (© IEEE 2018, reproduced with permission)

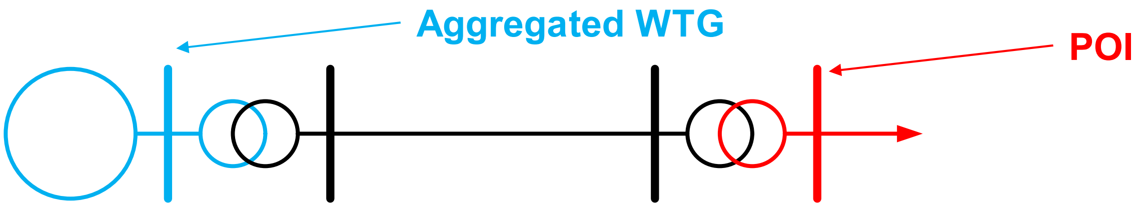

Figure 5: Aggregated wind power plant model.

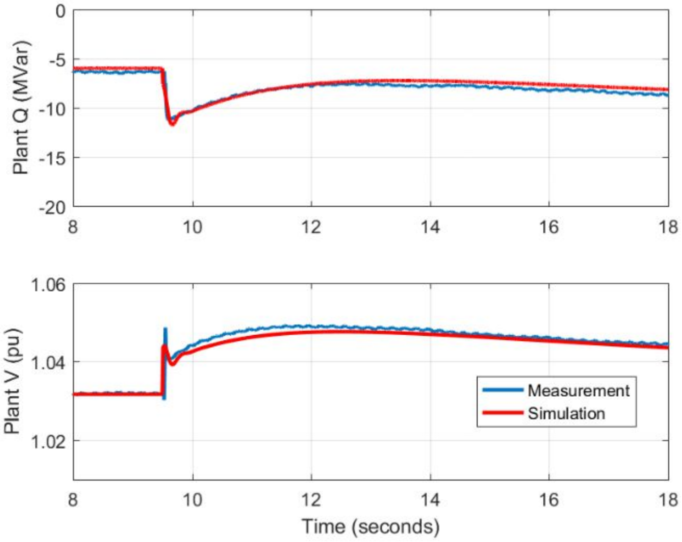

Figure 6: Simulation and measured response of the same wind power plant as in Figure 2 for the switching of a near-by large EHV shunt capacitor bank. The response in the immediate second or after the event is driven by the volt/var controls on the individual WTGs. (© IEEE 2018, reproduced with permission)

4.5 Section 5 – Model Documentation

This is also a well written section with much valuable information. The following minor comments and thoughts are offered:

1. In section 5.2.2 on RMS models it is stated that "*The transfer function block diagram must be described by Laplacian transfer functions.*" This is certainly necessary for RMS modeling, since RMS tools (e.g. Siemens PTI PSS®E) by their very nature require modeling to be developed in the s-domain. However, it is likely understood that many actual controls (such as HVDC, SVC, STATCOM, VSC converters in wind/PV etc.) will have digital controls (z-domain) which will need to be converted to s-domain. Such conversions will introduce some approximations and errors.
2. In the same section it is stated that "*Dynamic data must be provided as 'per unit' quantities on the machine MVA base.*" One thought, and suggestion, is that particularly in the case of conventional generation (gas-turbines, steam-turbines, etc.) experience has shown that it is better to model the turbine-governor on the turbine MW rating, while modeling the other components on the generator MVA rating[20]. Many software tools have done this for well over a decade (i.e. the turbine-governor models have their own rating), and Siemens PTI PSS®E has recently also introduced the TRATE (turbine rating) parameter in most, if not all, of its turbine-governor models for the same reason. The reason can be easily illustrated by an example. Consider a steam-turbine which is rated 100 MW connected to a 120

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[20] *Dynamic Models for Turbine-Governors in Power System Studites*, IEEE Technical Report PES-TR1, 2013. http://sites.ieee.org/fw-pes/files/2013/01/PES_TR1.pdf

MVA generator[21]. The *Pmax* (maximum power output) parameter in the turbine-governor model by definition is 1 pu on the turbine rating of 100 MW, while if we were to place the turbine-governor model on the generator rating and forget to change *Pmax* to 100/120 = 0.833 pu, then in simulations one would see the turbine respond to under-frequency simulations and produce more output than it is capable of. Furthermore, most turbine-governors are tuned to have a drop of 4 to 5%, this again is tuned in the field based on the turbine rating. Therefore, again if the turbine is placed on the generator MVA base, the droop parameter must be appropriately scaled. These, and other factors, can lead to inadvertent errors. It is thus best to model each component on its own proper rating.

4.6 Section 6 – Model Accuracy Requirements

This section of the document goes into significant detail on the accuracy requirements of the models. There are many other similar quantitative approaches to determining modeling accuracy and validity, most notably the validation standards in Germany, and those begin developed by the IEC TC88 WG27. In contrast, to date the approach in North America has been to take close and detailed look at model performance, but to reserve the ultimate decision of model accuracy and validation to engineering judgement based on the intended use. Both approaches have their benefits and weaknesses. The quantitative approach has the advantage of appearing to be unbiased and objective, but by the same token is hampered with the disadvantage of not being able to cater to exceptions to the rule. Furthermore, the criteria derived for such quantitative evaluations are often established through a process of trial and error and compromise and cannot be precisely linked to a given technical fact or criterion. By contrast, the approach of using engineering judgement can be much simpler and cater for exceptions or addressing measurement errors etc., but its disadvantage is that it relies on the engineers who are making the decisions to have a high-level of expertise and experience with the equipment, testing, model validation process and the intended use of the model. This later approach can also have an appearance of a level of subjectivity. In the end all these approaches have their strengths and weaknesses, as mentioned above and none is superior to the other. Thus, each entity must make a choice of approach and proceed accordingly.

With the above said, there are no further detailed comments on section 6, other to say that some level of flexibility may be needed in some cases when assessing model accuracy. It is noted that such flexibility appears to be granted in the AEMO document, particularly by the introduction of section 8 on alternative processes, so this is commendable.

In general, section 8 of the document is an excellent addition, since it offers an avenue for market participants to have a means of address potential exceptions to the rule for both the model accuracy piece (section 6) and the mode adequacy piece (section 4).

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[21] Typically, the name-plate rating of steam-turbines and gas-turbines are always lower than the MVA rating of the generator connected to them. This is not necessarily true of hydro-turbines. In the case of a hydro-turbine, in many cases the opposite can be true.

4.7 Section 7 – Confidentiality of Information and Models Provided

This section of the document pertains to legalities and thus we have no comments to offer here.

4.8 Section 8 – Alternative Process

Our only comment on this section is that we commend AEMO for providing this alternative process definition section, since there will always be some legitimate cases that will not be able to follow all the processes and requirements set forth for various reasons, and thus it is always important to offer this possibility for an entity to present its case, for consideration, for an alternative means to fulfill the needs of AEMO from a modeling and model validation perspective.

4.9 Appendices

The only comments on the appendices are a few minor comments:

1. Under C.1.1 mention is made of torsional stress protection. Such protection is relatively rare, and typically only implemented on a case-by-case basis where there is a significant risk of SSR (e.g. some synchronous power plants in North America and elsewhere in the world, which are in close proximity to series capacitors). Furthermore, modeling such protection in RMS models would be inappropriate, since the phenomena for which the protection is in place cannot be simulated nor adequately captured in RMS simulation platforms (e.g. SSR).
2. Similarly, modeling of negative phase sequence and unit transformer and generator differential protection is likely not applicable for RMS simulation.
3. In Table C.2.1, under transient stability, for EMT and RMS models an asterisk (*) is placed on these for the mechanical drive train model, indicating that the application should determine if the full mechanical drive train model is needed or not. To be consistent, an asterisk should then also be placed on the EMT and RMS models under the "*torsional damping*" title, since without the mechanical drive train model, there is no meaning to modeling torsional damping. So, if the applicant decides not to model the mechanical drive train, then he/she cannot model torsional damping either.
4. Under Table C.6.1 one of the columns is titled "*Turbine flywheel*". It is not entirely clear what this means. The second column entitled "*Mechanical drive train*" presumably embodies a lumped mass model of the turbine, any couplings, and the generator. So, the applicant would make the decision as to whether to provide a detailed lumped spring-mass model representing each lumped mass on the drive-train or a single lumped-mass equivalent for the entire mechanical drive-train assembly. So, it is unclear what then AEMO's intent is with the separate "*Turbine flywheel*" designation.

5. Comments on the System Strength Impact Assessment Guidelines Document

The *System Strength Impact Assessment Guidelines* document consists of five (5) sections and several supporting appendices. Here the comments offered are organized, for easy reference, under these section titles.

5.1 Section 1 - Introduction

The introduction of the document is concise and clear, there are no comments to be offered on this section.

5.2 Section 2 - Background

In general, this is a well written section on the general background on the subject of this document.

5.3 Section 3 – Adverse System Strength Impact

This section defines what is meant, in the context of the document, by adverse system strength impact, and how it is to be identified. The only rather minor comment that is offered is that although the section is well written, there is a lack of clarity as to what exactly is meant by a "*credible contingency event*" and a "*protected event*". For example, are credible events only N-1 and N-2? Perhaps these are defined in more detail elsewhere in the rules and regulations documents.

5.4 Section 4 – System Strength Impact Assessment Process

This section defines the process proposed by AEMO for the investigation of system strength impact assessment. In general, it is well written and reasonable. A few high-level comments are offered:

1. Although perhaps obvious, it may not hurt to explicitly state in the document that the system strength impact assessment issues are primarily a concern with the interconnection of new power electronic interfaced generation into potentially weak parts of the network, and not with the interconnection of large conventional synchronous generation plants, which would improve short circuit strength.
2. We note that for harmonic distortion analysis, load modeling and consideration of the existing background harmonic distortion in the system can play a significant role. Presently, an ongoing CIGRE effort, CIGRE JWG C4/B4.38, is looking at these and other issues and is likely to publish it final findings latter in 2018.

5.5 Section 5 – Mitigation Measures

This section defines the various potential mitigation measures for solving issues relative to the impacts of low system strength on the control loop stability of power electronic based generation. The solutions and schemes proposed are all reasonable, and AEMO also legitimately states that given the relatively limited experience still world-wide with remedial action schemes (RAS) and some other approaches, there still needs to be research and development done to truly proves some of the potential solutions. One such proposed solution in the research literature is what is presently referred to as "grid-forming converters" as discussed in AEMO's Draft System Strength Impact Assessment Guidelines. The terminology is somewhat at variance across researchers. At a high-level the concept is as follows. Presently, power electronic interfaced generation systems almost predominantly use voltage-source converters (VSC) with some form of a phase-lock loop (PLL). The PLL locks into the grid voltage phasor, thus establishing the reference phasor based upon which the VSC controls then determine the voltage phasor that the converter needs to create in order to inject into the grid the required real and reactive current (power). This is a highly simplified explanation, there are of course many detailed nuances here, and variations on control and converter design. At a high-level, however, the concept is as described. Where the connection point to the system is relatively weak (low short-circuit ratio) the stability of the PLL and so-called inner-current control-loops that effect the current control can suffer significantly following a nearby fault or other disturbances. Thus, a proposed alternative is to create an internal voltage reference, rather than having to lock unto the grid voltage phasor with a PLL. A similar concept is used in VSC-HVDC when it is used to black-start one end of the link. How such a concept will work when extended to large numbers of individual wind/PV inverters and plants, spread across a region is yet to be seen. In general, for now the most plausible solutions and mitigation strategies are as described in section 5 of the AEMO document.

5.6 Appendices

The appendices of the document provide various practical examples. The details and calculations were not checked. In general, the examples presented seem reasonable and are a good addition to the document to illustrate the issues at hand.

One comment is offered here for further elaboration on the issues related to low short-circuit strength and power electronic interfaced equipment. Although there are many factors that can lead to concerns with low short-circuit ratio (SCR) and the application of power electronic interface generation, the problems in general, typically fall into two main[22] categories:

1. <u>Post fault recovery of PLL/inner current control loop</u> – this is driven by the dynamics of the phase-lock loop (PLL) and the inner-current control loops that regulate the current injected by the converter based on the active and reactive current commands developed by the high-level controls. At a high-level, the concept here is that the PLL locks into the network phasor to provide a reference for the inner-current control loops, which then regulate the converter current. As the system strength weakens, the gains of these feedback paths may need to be relaxed to avoid instability during post-fault recovery as the PLL tries to lock into the grid phasor after fault-clearing. Thus, both the PLL and inner-current control

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[22] It should be noted that there are other issues that may lead to control interactions and stability concerns when interfacing power-electronic interfaced generation to a node of the network with relatively low short-circuit strength. However, here the two most common concerns are discussed. Also, this document and the AEMO documents have not discussed issues related to fault-current levels and protective relaying and how protection systems and relays are impacted by reduced short-circuit levels in the system as power-electronic interfaced generation penetration increases – these issues are outside of the scope of the present discussion.

loops need to be tuned considering the range of possible short-circuit strength of the system.

2. <u>Instability of the plant level voltage control</u> – as the SCR at the point of interconnection (POI) of the plant reduces, the closed-loop voltage-control of the inverter-based generation can become small-signal unstable. This can be understood by a simple example. As SCR reduces, the effective Thevenin impedance seen by the inverter-based generation (IBR), looking into the system, becomes large. Thus, a small change in current injected into the system by the IBR plant results in a relative large change in voltage. The voltage control loop sees this and acts again to change injected reactive current. If the gain is too high, particularly proportional gain, the control-loop becomes small-signal unstable and thus oscillatory. The solution is to reduce the gain. This is the very reason why SVCs have a gain-scheduler, which adaptively reduces the SVC AVR gain if oscillations are detected due to reduce system strength.

Ultimately, if the SCR becomes too low (e.g. < 1.5 or so) the only viable solution presently may be to add elements to the power system to increase SCR. A common practice now in many systems around the world under such conditions is to employ synchronous condensers. There is also ongoing research and development on the concept of so-called grid-forming inverters, which was mentioned earlier in the report. This is yet to be fully proven and to be offered commercially for inverter-based generation.

Appendix – Engineering Resume

At the specific request of AEMO, attached here is the mission statement of PEACE® as well as a brief resume of the principal consultant of PEACE®.

Company Mission:

To be of service to the power and energy industry and help advance the technology, design and utilization of energy generation and transmission systems in an effort to safe guard our environment, while serving the energy needs of the community in the most sustainable, effective and efficient means possible.

Experience:

Dr. Pourbeik has served the electric power and energy industry as a consultant and a researcher since 1997. He completed his Bachelor of Electrical and Electronic Engineering and PhD in Electrical Engineering in 1993 and 1997, respectively, at the University of Adelaide, Australia. He worked for GE Power Systems Energy Consulting from 1997 to 2000, as an application engineer. From 2000 to 2006 he was with ABB Inc. in the Electric Systems Consulting group. From 2006 to 2016 he worked for the Electric Power Research Institute. In March 2016, Dr. Pourbeik founded Power and Energy, Analysis, Consulting and Education, PLLC (PEACE®).

Throughout his career, he has lead and performed numerous consulting and research projects spanning a wide range of electric power system technical performance issues. He has also extensively performed generator model validation and field testing in North America and overseas. He has lead and performed studies related to power flow analysis, transient and small-signal stability analysis, voltage stability analysis, modeling and model validation of generation and transmission equipment, integration of renewable energy systems, subsynchronous resonance and torsional interaction issues, application of FACTS and HVDC, electromagnetic transients associated with line/cable switching, shunt capacitor switching and shunt and series reactor switching, overvoltage protection of series capacitors, and many other aspects of power systems technical performance. He has been, and continues to be, a major technical contributor to the development of numerous dynamic models that are presently standard library models in the most popular commercial power system planning software tools, including models for wind generation, photovoltaic generation, battery energy storage, HVDC systems, SVC and STATCOMs, dynamic load models, turbine-governor models for gas turbines and combined-cycle power plants, and several other models associated with conventional synchronous generators.

Dr. Pourbeik has authored or co-authored over eighty technical publications, including one text book on small-signal stability analysis of power systems, which has been released as an e-book and downloaded by thousands of readers worldwide.

Dr. Pourbeik is a Fellow of the IEEE, a Distinguished and Honorary Member of CIGRE and a license professional engineer in the States of North Carolina and Texas. He is also a past chairman of both the IEEE Power & Energy Society's Power System Dynamic Performance Committee and the CIGRE Study Committee C4 – System Technical Performance. He has also been an active member, and in some cases also chairman or co-chairman, of numerous international task forces and working groups within IEEE, CIGRE, NERC, WECC and IEC.