Renewable Models and Issues for Dynamic Analysis

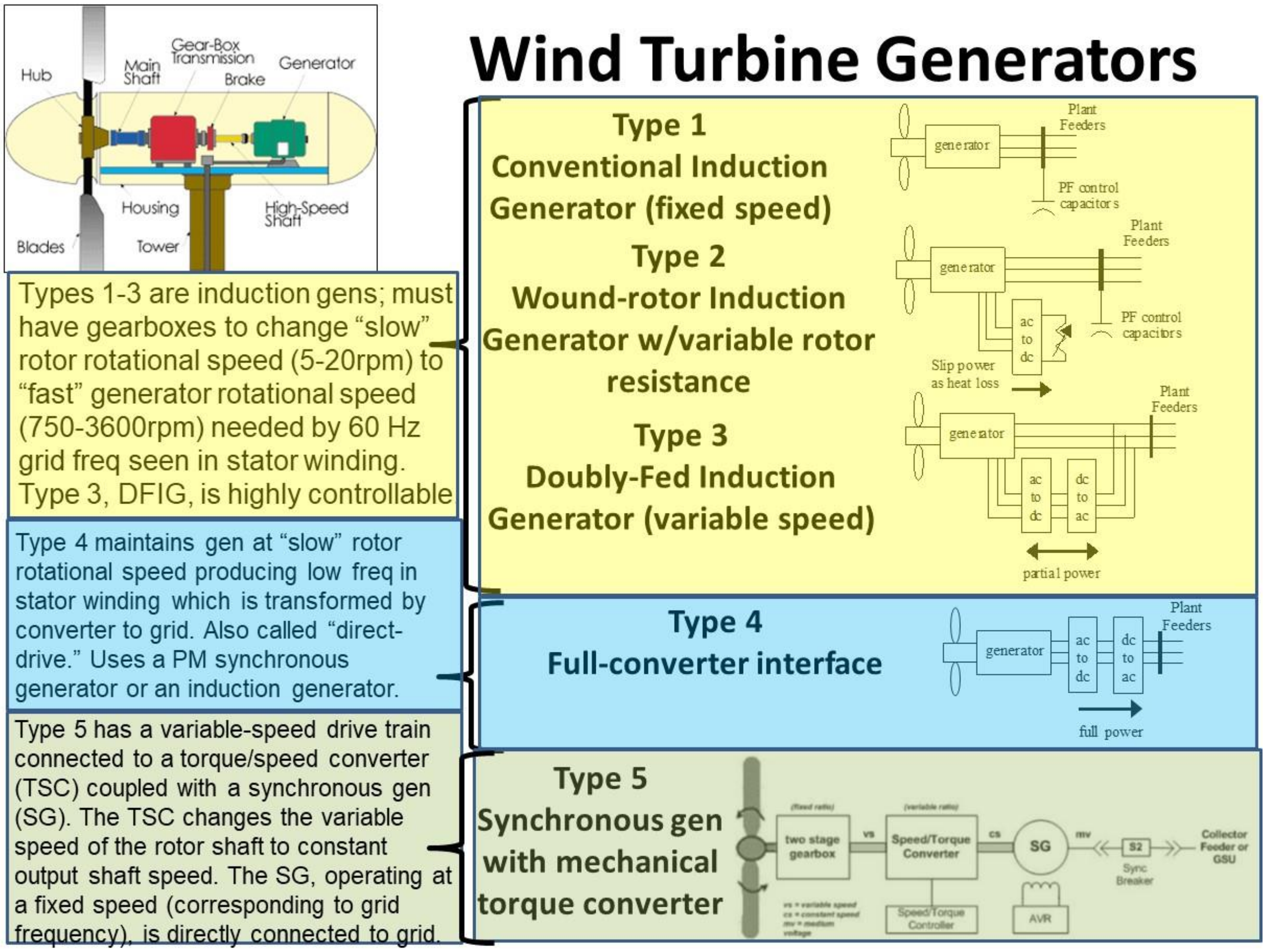
1 Dynamic models

These notes complement Chapter 11 in VMAF; they summarize features of models used for representing wind and solar PV for dynamic performance analysis.

We describe dynamic models used for wind turbines and solar PV plants. In both cases, the parameters of the newly installed wind and solar plants are set based on the existing renewable plant of the same capacity.

1.1 Types of wind turbine generators

There are five types of wind turbine generators, as summarized in Fig. 1.



Types 1-3 are induction gens; must have gearboxes to change “slow” rotor rotational speed (5-20rpm) to “fast” generator rotational speed (750-3600rpm) needed by 60 Hz grid freq seen in stator winding. Type 3, DFIG, is highly controllable

Type 4 maintains gen at “slow” rotor rotational speed producing low freq in stator winding which is transformed by converter to grid. Also called “direct-drive.” Uses a PM synchronous generator or an induction generator.

Type 5 has a variable-speed drive train connected to a torque/speed converter (TSC) coupled with a synchronous gen (SG). The TSC changes the variable speed of the rotor shaft to constant output shaft speed. The SG, operating at a fixed speed (corresponding to grid frequency), is directly connected to grid.

Fig. 1: Types 1-5 Wind Turbine Generators

1.2 Historical development

Some of the earlier work published on wind turbine models for dynamic analysis was by performed by GE engineers[1] [2], as they and others expected wind growth, necessitating available models to be able to perform dynamic analysis in GE's PSLF software. A CIGRE group, led by EPRI's P. Pourbeik, published similar material shortly thereafter[3], dedicating chapter 6 to what was then state-of-art wind turbine modeling for power system studies, including Section 6.3 which focused entirely on generic models for time domain simulations. This section was very well done, and it is useful to include here its opening subsection 6.3.1. I have highlighted what I think are especially important parts.

> "It is pertinent to first present a brief discussion of the use of generic models versus more detailed (and manufacturer specific) models. In spirit, this discussion is applicable to any power system component (synchronous generators, SVC, STATCOM, HVDC etc.).
>
> The purpose of **generic models**, which constitute a generic structure based on physical principles, as opposed to detailed (typically 3-phase) component level and often manufacturer specific equipment models is to facilitate a means of performing power system studies that often incorporate tens of thousands of models. The aim is to have a simple yet comprehensive enough model structure to be able to faithfully capture the most important dynamics aspects and then by simply changing appropriate parameters (e.g. inertias, impedances, gains etc.) to facilitate emulation of different manufacturer designs.
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> Of course, such generic models have their limitations. When studies are focused on improving or assessing details of equipment design, such generic models are typically not adequate. For example, when evaluating the detailed performance of fault-ride through systems (see section 3.2.6.1, and to some extent some discussions in Appendix E) 3-phase component level models are necessary. In the end some engineering judgment and consultation among the parties involved (manufacturer, consultants, developer and host utility) are necessary to identify the correct level of modeling detail for each stage of a study. Also, as presented in section 4.2.3, in some cases (e.g. installation of a wind farm near a series compensated line or HVDC converter station) specialized studies may be necessary to evaluate the

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[1] Miller, N.W., Sanchez-Gasca, J.J., Price, W.W., and Delmerico, R.W. Dynamic Modeling of GE 1.5 and 3.6 MW Wind Turbine Generators for Stability Simulations. PES2003-000590, Panel Session on Wind Generator Modeling and Control for Power System Dynamics, IEEE PES GM2003, Toronto, Jul. 2003.

[2] Miller, N.W., Price, W.W., and Sanchez-Gasca, J.J. Modeling of GE Wind Turbine Generators for Grid Studies. General Electric International, Inc., Schenectady, Technical Report, Version 3.4b, Mar. 2005.

[3] Cigré Report 328. Modeling and Dynamic Behavior of Wind Generation as It Relates to Power System Control and Dynamic Performance. Working Group C4.601, Aug. 2007.

> potential for controls and torsional interactions – again these studies by their very nature demand more detailed equipment level models.
>
> The models discussed in this subsection are intended for time-domain, dynamic simulations of wind turbine generators for the purpose of power system stability studies. In such studies, the time frame of interest is typically a few seconds to tens of seconds following a disturbance and the power system network is represented by a constant positive-sequence impendence matrix. Thus, such simulation tools are intended for looking at system wide oscillations and phenomena such as between many generators spread out on the system (inter area modes of rotor oscillation) or frequency instability or fast and slow voltage decay. Thus, these power system models are limited to a bandwidth of up to 2 Hz or so, because the network model is static and not adequate for studies that go outside this range. For local control interactions between controllers that are in the same substation or very close by and thus not affected by the network impedance (e.g. potential interactions between the automatic voltage regulator on a generator and that of a nearby SVC) this can also be studied provided the respective control models are of high enough fidelity and so perhaps the range of simulation bandwidth for such local phenomena may be extended to 10 to 20 Hz. It is within this context that the model structures below are recommended. Furthermore, during such simulations, typically it is assumed that the wind speed is constant for the duration of the simulation."

The emphasis on generic models was in part to avoid dependence on vendor-specific models which were not always publicly available. This point is central to the 2nd paragraph of VMAF's Chapter 11 (p. 463). This paragraph also characterizes further development through an IEEE Power & Energy Society (PES) task force. I have again highlighted what I think are central and important parts of this paragraph.

> "Increased renewable resource integration has created the need to carefully examine the impact of all of the above resources on power system operation and planning. The dynamic performance of these resources has also received significant attention. Both wind turbine generators and PV converters include manufacturer specific features and characteristics that are proprietary. The mathematical models representing these features typically become available from the manufacturer only when the entity owning the renewable resource purchases the turbine generator and PV converter devices. The dependence on proprietary models imposes certain restrictions on the planning process specifically relating to the examination of the impact of these resources on the dynamic performance of the system. To address this concern, the IEEE Power and Energy Society (PES) formed a task force to examine and develop generic models for wind turbines. This task force has also developed and compared a set of proposed generic models against measurements from actual wind turbines [1, 2]. The contributions of the IEEE PES task force

> have then been further refined based on concepts and ideas introduced in [3, 4, 5]. A status report on this activity is provided in [6].

The work of this IEEE PES task force was reported in 2011 via references [4] [5] [6]. These are referred to in Chapter 11 of VMAF as [1, 2, 6]. Following this, a new effort commenced, referred to as "Phase II" that resulted in a second generation of models.

> "More recently, a Western Electricity Coordination Council (WECC) task force on modeling has extended the PES models and developed a set of second generation generic models for both wind and PV solar resources [7]. This chapter leverages many of these models to describe the characteristics and dynamic performance of renewable resources. Generic models for both wind turbine generators and solar PV systems will be detailed and discussed. The second generation models discussed in [7] are compared with test results obtained from actual wind turbines."

Reference [7] mentioned above is from 2017, here [7]. A key concept was modularity. Other motivations for the Phase II models are captured in this paper and quoted here:

> "In 2010, building on user experience with the first generation of WECC generic wind power plant models [4], the WECC REMTF started tackling the task of creating the second generation generic models, this time including both wind and photovoltaic (PV) plants. The main reason for the development of the second-generation generic models was
>
> - to make the models more flexible,
> - to allow for a wider range of control philosophies and for parameterization in order to allow for representation of a wider range of equipment, and
> - to thus resolve some of the limitations found in the first generation of generic models.
> - Furthermore, the second-generation models were developed on the basis of modularity to allow for future developments and to accommodate future technologies.
>
> The IEC and WECC REMTF model development efforts were closely coordinated, and the core of the resulting IEC and WECC models for wind turbine generators are essentially the same, with some modular differences. The WECC work culminated in 2014 with the release of the so-called second generation generic models for wind and PV in the major commercial software platforms used for power system studies throughout North America [5]. Some of the models have since been adopted in European commercial software tools also [6]."

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[4] Adhoc TF on WTG Modeling of the IEEE Working Group on Dynamic Performance of Wind Power Generation. Description and Technical Specifications for Generic WTG Models – A Status Report. Proceedings of the Power System Conference and Exposition (PSCE), 2011.

[5] Adhoc TF on WTG Modeling of the IEEE Working Group on Dynamic Performance of Wind Power Generation. Model validation for wind turbine Generator Model. IEEE Transactions on Power Systems, vol. 26, no. 3, pp. 1769-1782, Aug. 2011.

[6] Ellis, A., et al, Description and technical specifications for generic WTG models – A status report," Proceedings of the IEEE Power System Conference and Expo, pp: 1-8, March 2011.

[7] Pourbeik, P, et al. 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, pp.1108-1116, Sep. 2017.

Phase II type 3 generic wind turbine generator model[8] is often used to represent future wind plants. This model is the second phase double-fed induction generator (DFIG) model for power system stability simulations. This model is widely used because most future wind plants are likely to employ DFIGS due to their low cost (relative to type 4 direct-drive units) and effective control capabilities (relative to types 1 and 2 squirrel-cage units). The Phase II type 3 generic wind turbine generator model consists of seven core sub-blocks:

- generator/converter model (*regc_a*),
- P/Q control model (*reec_a*),
- plant control model (*repc_a*),
- drive-train model (*wtgt_a*),
- aero-dynamic model (*wtgar_a*),
- pitch-controller model (*wtgpt_a*) and
- torque-controller model (*wtgtrq_a*).

These seven core control blocks are illustrated in Fig. 2a[9] (from 2017).

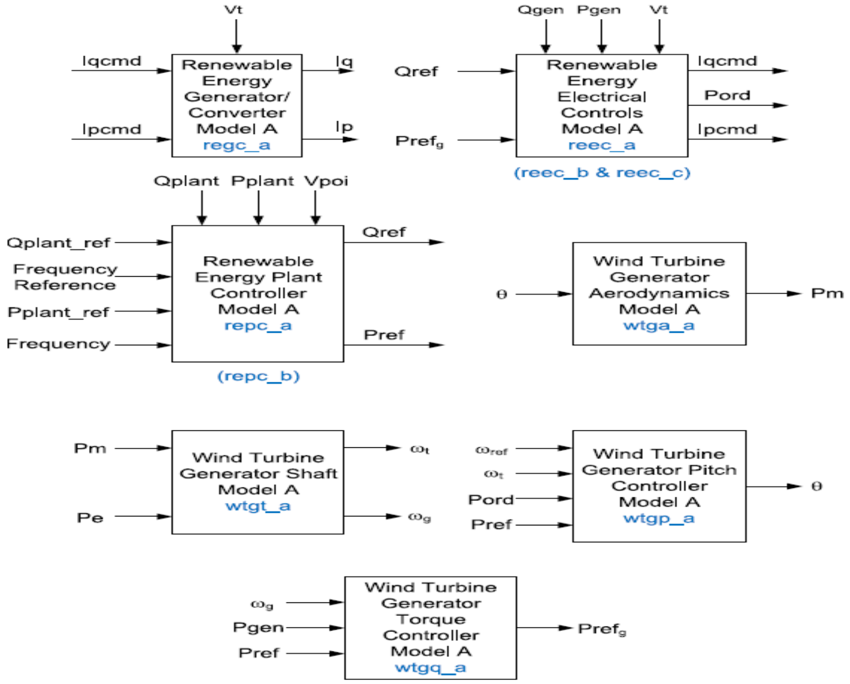

Fig. 2a: The seven core modular blocks that form the basis of the renewable energy system generic models

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[8] https://www.esig.energy/wiki-main-page/type-3-generic-wind-turbine-generator-model-phase-ii/

[9] P. Pourbeik, et al., "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, Sept, 2017.

Although not equipped with active control and wind inertia control of the GE WTG, the Phase II type 3 generic wind turbine generator model has many control strategies to select, including constant power factor control, constant Q control, and local V control. The overall structure of this model is illustrated in Figure 2b[8]; which shows how the seven core modular blocks fit together to represent a type 3 wind turbine generator.

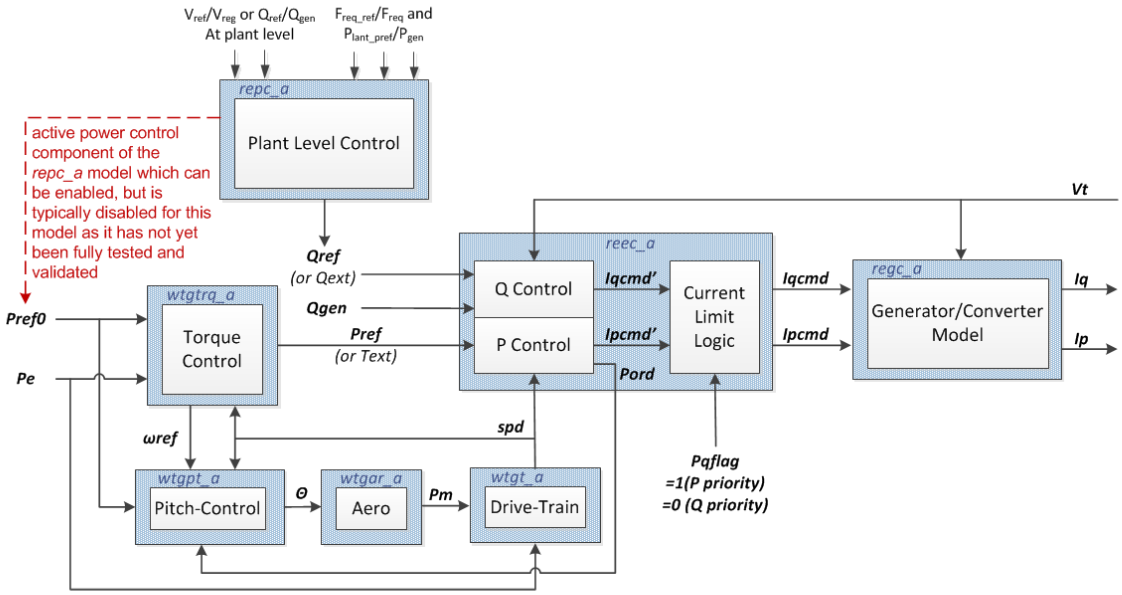

Figure 2b: Structure of the phase II type 3 generic wind turbine generator model

Table 1 shows how to convert the old (1st generation) generic stability models for type 3 WTGs to the new (2nd generation) models. The 1st generation models are a subset of the more general 2nd generation models, with a few exceptions.

Table 1: Conversion of 1st generation models to 2nd generation models

2nd gen model	1rst gen model
regc_a	wt3g
reec_a	wt3e (part of)
repc_a	wt3e (part of)
wtgp_a	wt3p
wtgt_a	wt3t (part of)
wtga_a	wt3t (part of)
wtgq_a	wt3e (part of)

1.3 Solar PV plants

There are three choices for models to use in representing solar PV plants: generic models, *PVD1* model, and modified generic model. Generic models[10] [11] are often used to represent future large PV plants because they are considered to be a better representation of utility-scale solar PV; in addition, they are more advanced then the *PVD1* model. VMAF, Section 11.2.2, reports on the modified generic model for representing PV solar.

Here, we focus on the generic model, which consists of

- generator/converter module (*regc_a*, a 2nd generation model),
- inverter control module (*reec_b,* a 3rd generation model), and
- plant control module (*repc_a,* a 2nd generation model).

It is of particular interest that of the above three modules, two of them (*regc_a* and *repc_a*) were also used in the type 3 generic WTG model described in the previous section. *Repc_a* provides control signal to *reec_b* to achieve volt/var control and active power control. With these models, the available solar power is constant throughout the duration of simulation. The model is considered to be valid for analyzing electrical phenomena in the frequency range from 0-10 Hz and for systems having a short circuit ratio of at least 3 at the point of interconnection. The solar PV plant dynamic model corresponding to this particular choice of modules is shown in Figure [11].

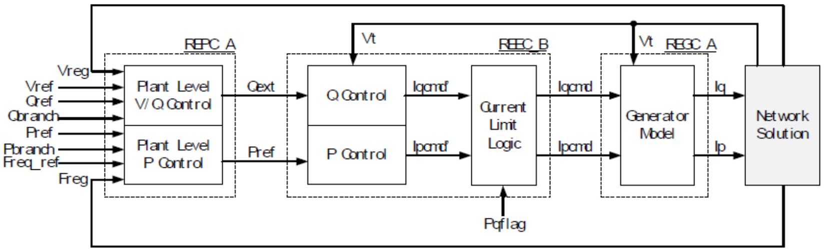

Figure 2: Structure of the solar PV generator model

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[10] https://www.esig.energy/wiki-main-page/pv-systems/

[11] https://www.esig.energy/wiki-main-page/generic-models-pv-plants/

2 Weak Grid Conditions

When the electric impedances between a bus in the network and synchronous machines are low, i.e., when the bus is electrically "close" to synchronous machines, the point is considered to be "stiff." This means that the voltage magnitude at that point does not vary much as network loading conditions change. Such "stiff" conditions at a bus are characterized by a high short-circuit current at the bus. This is because, when the bus is faulted, by Ohm's Law, the short circuit current is high when the electric impedances between the bus and the synchronous machines in the network are low. A bus that is densely connected (many transmission connections) to many nearby synchronous generators will be a voltage-stiff bus. Power systems having many stiff-buses are said to be "strong grids." Power systems having many non-stiff buses are said to be "weak grids."

The dominant contribution to short circuit currents is made by synchronous generators, as synchronous generators have an internal voltage with magnitude that is unaffected by fault conditions, so that the internal voltage remains essentially constant during a fault. A similar thing can be said for synchronous motors, and to a lesser extent induction motors. Indeed, wind turbines with no or partial converter interfaces (typically referred to as Type 1, 2, and 3 turbines) fall into this category as well.

However, the short-circuit current contributions of Types 4 and 5 wind turbines, and of solar PV plants, are different in that the short circuit contribution depends on the inverter design and settings. Whereas conventional resources like synchronous generators and motors, induction motors, and types 1-3 wind turbines have behavior during short-circuit conditions that is well-represented by a constant voltage behind a reactance, inverter-based resources have behavior during short circuit conditions that is better modeled by current sources[12]. An important

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[12] An excellent source of information on these issues is a recent white paper developed by the North American Electric Reliability Corporation (NERC) called "Short-Circuit Modeling and System Strength," February 2018, available at www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/Short_Circuit_whitepaper_Final_1_26_18.pdf.

observation is that inverter-based resources typically contribute significantly less short-circuit current than do conventional resources, reported to be between 15% and 40% of equivalently sized synchronous resources[13].

This means that as more and more synchronous machines are retired, replaced by inverter-based resources, short-circuit current decreases. Under the short-circuit current/grid strength equivalence, high inverter presence leads to a weak grid[14]. Weak grids are more inclined to have the familiar problems such as voltage instability, transient voltage dips, and fault-induced delayed voltage recovery. (A well-known related issue is that line-commutated converter (LCC) based HVDC transmission is especially vulnerable to weak grid conditions, resulting in malfunction due to commutation failures at the converters[15]). In addition, some types of inverters (particularly grid-following inverters) may not function adequately due to instability associated with inverter dynamics, influenced by the phase-locked loop (PLL)[16]. The function of the PLL is to synchronize the inverter with the grid, i.e., to orient active and reactive components of injected currents, by tracking the phase angle of the grid-side voltage. Although the PLL-related instability may be addressed during design[17], most grid-following inverter systems in operation today are vulnerable.

Positive sequence stability programs currently in use today do not capture instability related to converter controls. A recent tool from EPRI called

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[13] D. Turcotte and F. Katiraei, "Fault contribution of grid-connected inverters," IEEE Electrical Power Conference, Oct. 2009, Montreal.

[14] It may be that short-circuit current is not a good indicator of voltage stiffness in a grid having a large number of inverter-based resources. The reason for this is that inverter control under faulted conditions is very different than inverter control under steady state conditions, as articulated in the following reference: T. Ackermann, T. Prevost, V. Vittal, A. Roscoe, J. Matevosyan, and N. Miller, "Paving the way: a future without inertia is closer than you think," IEEE Power and Energy Magazine, Vol. 15, I6, 2017.

[15] J. Khazaei, P. Idowu, A. Asrari, A.B. Shafaye and L. Piyasinghe, "Review of HVDC control in weak AC grids." Electric Power Systems Research, 162 (2018), pp.194-206.

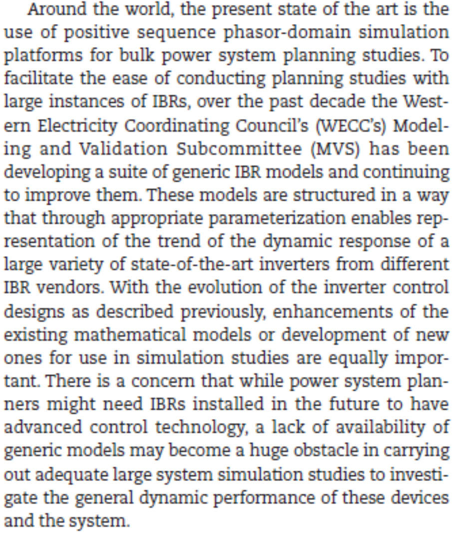
[16] D. Zhang, Y. Wang, J. Hu, S. Ma, Q. He, and Q. Guo, "Impacts of PLL on the DFIG-based WTG's electromechanical response under transient conditions: analysis and modeling," CSEE Journal of Power and Energy Systems, Vol. 2, I2, June, 2016.

[17] M. Davari and Y. Mohamed, "Robust vector control of a very weak-grid-connected voltage source converter considering the phase-locked loop dynamics," IEEE Trans. on Power Electronics, Vol. 32, No. 2, Feb., 2017.

"GSAT"[18] performs such analysis by identifying potential weak locations by calculating system strength indices such as short-circuit ratio (SCR). The SCR is the ratio of the short-circuit MVA at a bus to the nameplate rating of a resource considered for installation at that bus. SCRs below about 3.0 are considered to be characteristic of weak-grids. Alternate (but related) indices have been suggested by ERCOT and GE as well. GSAT is also able to characterize stability performance of the PLL. A recent industry report provides insight into how GSAT was applied within a portion of the Southwest Power Pool's region of the Eastern Interconnection[19]. Although GSAT is an effective and useful tool, analysis of inverter dynamics and associated stability performance is conclusive only after analysis performed with an electromagnetic transient program (EMTP) such as PSCAD (see https://hvdc.ca/pscad/).

3 Next step

We have not done justice to this topic as it is an ongoing area of research for me. My next step is to continue probing the literature. One paper that may nicely summarize where we are with respect to modeling is [20]; I have copied out the front page of it below. Here is a quote from it:



Around the world, the present state of the art is the use of positive sequence phasor-domain simulation platforms for bulk power system planning studies. To facilitate the ease of conducting planning studies with large instances of IBRs, over the past decade the Western Electricity Coordinating Council's (WECC's) Modeling and Validation Subcommittee (MVS) has been developing a suite of generic IBR models and continuing to improve them. These models are structured in a way that through appropriate parameterization enables representation of the trend of the dynamic response of a large variety of state-of-the-art inverters from different IBR vendors. With the evolution of the inverter control designs as described previously, enhancements of the existing mathematical models or development of new ones for use in simulation studies are equally important. There is a concern that while power system planners might need IBRs installed in the future to have advanced control technology, a lack of availability of generic models may become a huge obstacle in carrying out adequate large system simulation studies to investigate the general dynamic performance of these devices and the system.

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[18] "RES modeling & planning tools for weak grids," Electric Power Research Institute, available: www.npcc.org/Standards/commRegStand/Documents/May%2016%202019%20RSC%20Meeting%20-%20DER%20Forum%20Presentations.pdf

[19] D. Bowman et al., "SPP 2019 Inverter Based Generation Integration Study (IBIS)," report/slides obtained from D. Bowman, dbowman@spp.org, available at www.spp.org/documents/60618/twg%20minutes%20&%20attachments%2020190904.pdf.

[20] D. Ramasubramanian, P. Pourbeik, E. Farantatos and A. Gaikwad, "Simulation of 100% Inverter-Based Resource Grids With Positive Sequence Modeling," in IEEE Electrification Magazine, vol. 9, no. 2, pp. 62-71, June 2021.

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Simulation of 100% Inverter-Based Resource Grids With Positive Sequence Modeling