Model Validation of Large Utility Connected Wind and PV Power Plants Based on Staged Testing

3002012428

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Technical Update, January 2018

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ACKNOWLEDGMENTS

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Model Validation of Large Utility Connected Wind and PV Power Plants Based on Staged Testing. EPRI, Palo Alto, CA: 2018. 3002012428.

ABSTRACT

Model validation of large conventional power plants in North America has been in effect for several decades in the Western Interconnection of the US. More recently, the requirement to perform model validation for all types of power plants connected to the bulk electric system has become a mandated activity by the North American Electric Reliability Corporation (NERC). In recent years, the Electric Power Research Institute (EPRI), and others, have developed several approaches for performing model validation of power plants using on-line disturbance monitoring, where a good baseline model for the plant exists as a starting point. This approach has been successfully applied to both conventional and inverter-based (wind and photovoltaic) power plants. However, in many cases disturbance monitoring has not yet been established on large power plants, so the approach of field testing for model validation remains an important avenue for verification of power system stability models used for representing power plants in commercial positive sequence power system simulation tools. In the case of conventional power plants, such field testing techniques are well established and have been in use for decades. For wind and photovoltaic (PV) power plants, this is a new endeavor. Nonetheless, in recent efforts, a quite similar approach has proven to be an effective means of field testing these newer technologies. This report presents a brief account of the approach to field testing and model validation of large utility connected wind and PV power plants.

Keywords
Wind power plant
PV power plant
Model validation
Staged testing

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1

INTRODUCTION

Model validation of large power plants is presently a North American Electric Reliability (NERC) standard requirement, under NERC Modeling Data and Analysis (MOD) Standards 026-1 and 027-1. These standards require that the volt/Var (MOD-026-1) and frequency response (MOD-027-1) capabilities of all power plants, of certain MVA rating and above, connected to the bulk electric system be validated. The method of validation is left to the generator owner operator, who may choose to perform such validation using any technique that will show a reasonable match between the simulated and measured field response of the plant. Thus, the measured response may be from a suitable disturbance recording or staged tests performed by experienced field engineers. These requirements apply equally to conventional synchronous generator power plants, and inverter based asynchronous generation such as wind and photovoltaic (PV) generation. There is significant literature on both disturbance based and staged testing approaches for validating synchronous generation, and we refrain from referencing them as the list of references is enormous and some of the techniques date back to the 1970's. The focus of this brief report is on inverter based generation, wind and PV primarily.

With wind and PV generation, EPRI has already worked on developing tools for model validation using disturbance monitoring [1] and [2], and such work is on-going as new learning continues to occur. A few demonstrations of using this so-called play-back approach for model validation using disturbance data is shown in [3].

In this brief report, the intent is to describe an approach to model validation of wind and PV power plants using staged testing. The most recent publication in the literature on a comprehensive account of such an approach is [4]. This report is based primarily on that and similar experience.

The remainder of the report is laid out in the following sections:

Section 2 – discusses briefly the 2nd generation generic models for wind and PV, which are the only open, public and well documented models presently available for use in commercial power system simulation tools. These are the models used for parameterizing, when performing model validation.

Section 3 – presents the data collection needs and process for performing staged testing in large inverter based generation power plants, together with a few illustrative examples of model validation based on staged testing.

Section 4 – gives a brief conclusion and summary of the report.

2

MODELING OF WIND AND PV POWER PLANTS USING GENERIC STABILITY MODELS

A detailed account of the usage of the 2nd generation generic stability models for modeling wind and PV plants may be found in [5]. Here we give a very brief overview for the sake of completeness and to illustrate a few items related to model validation of these models.

In this report, the focus is on modern wind and PV technologies, all of which are inverter based generation. We will not discuss type 1 and 2 wind turbine generators (WTGs), which used passive conventional induction generators. The reason for this is as follows:

1. Most major vendors for large transmission connected wind power plants have moved away from these technologies. Almost none of them manufacture type 2 WTGs, and type 1 WTGs are likely only used for small distributed applications.
2. These are essentially passive WTGs, that is they operate at a fixed speed (type 1) or a relatively small variable speed range (type 2) and have no means of controlling their reactive output other than through other external equipment such as shunt capacitors, SVCs and STATCOMs installed in the collector system. Therefore, there is perhaps more need to validate the model of such devices (i.e. SVC or STATCOM in the plant) than the electrical generators of the WTGs. For validation of SVC/STATCOMs see [6].
3. Type 1 and 2 WTGs are essentially modeled using a conventional induction machine model together with an appropriate model of the shaft-dynamics and if appropriate the active-stall pitch controls [5]. The electrical parameters of the generator, the inertia of the shaft, etc. are thus best derived from the original equipment manufacturer data sheets, then attempting to validate them through tests in the field. This is briefly discussed in Appendix A.

Thus, let us focus on the inverter based generation. Namely, type 3 WTGs, type 4 WTGs and PV.

2.1 Type 3 Wind Power Plants

A type 3 wind power plant (WPP) may be modeled using the 2nd generation generic models with a combination of the models shown below in Figure 2-1. The models are in three (3) groups:

1. Mechanical aspects of the WTGs: the torque controller (*wtgtrq_a*), the pitch controller (*wtgpt_a*), the aero-dynamic model (*wtgar_a*) and the drive-train model (*wtgt_a*). The parameters of all these models are primarily physical quantities (e.g. inertia of the generator and turbine) and limits (e.g. limits on the movement of the turbine blade pitch) associated with the mechanical components of the WTGs. These parameters should all be based on the original equipment manufacturer (OEM) supplied numbers and do not lend themselves to being identified during tests or disturbance monitoring.
2. The Model of the Electrical Generator/Converter: the *regc_a* model represents the electrical interface (the generator/converter interface) with the network model in the power system simulation tools. This is a current source model, and the bulk of the parameters in this model

(see [5] or [7] for a detailed explanation) are associated with numerical stability of the model and appropriately establishing that interface. Again, they do not lend themselves to testing or validation. They must be based on OEM provided data.

3. The Electrical and Plant Controls: the heart of the WPP are the *reec_a* and *repc_a* models. This is where the volt/var and active-power controls for the whole WPP are implemented. It is on the functionality of these models that testing must focus.

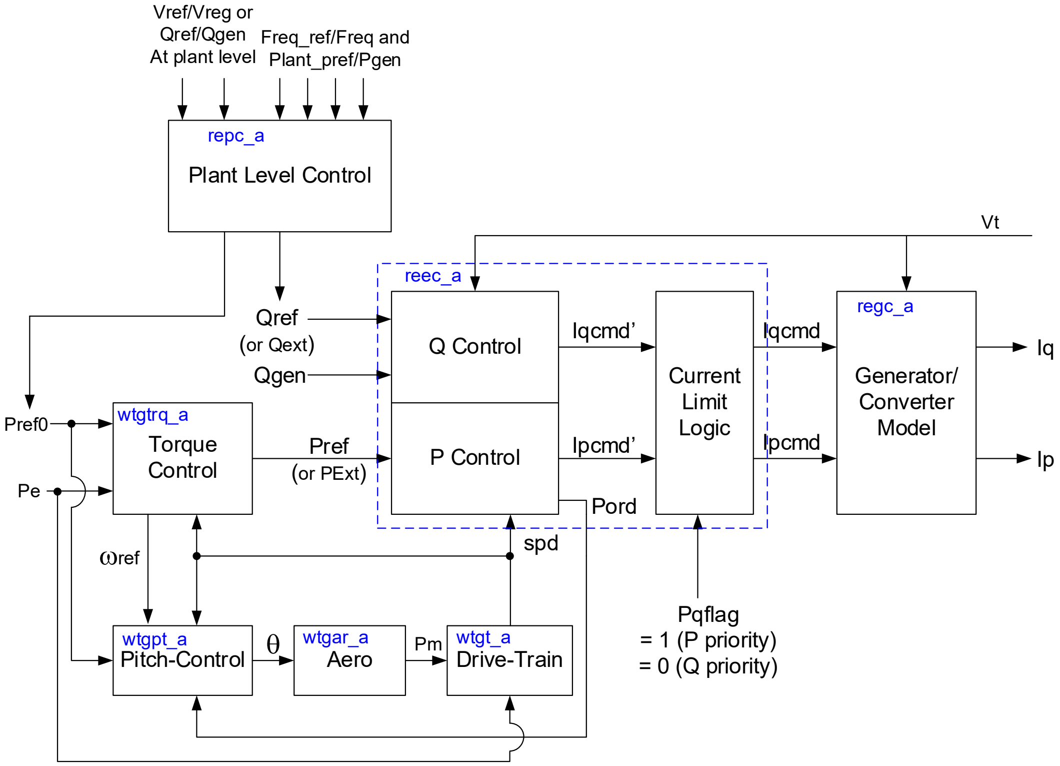
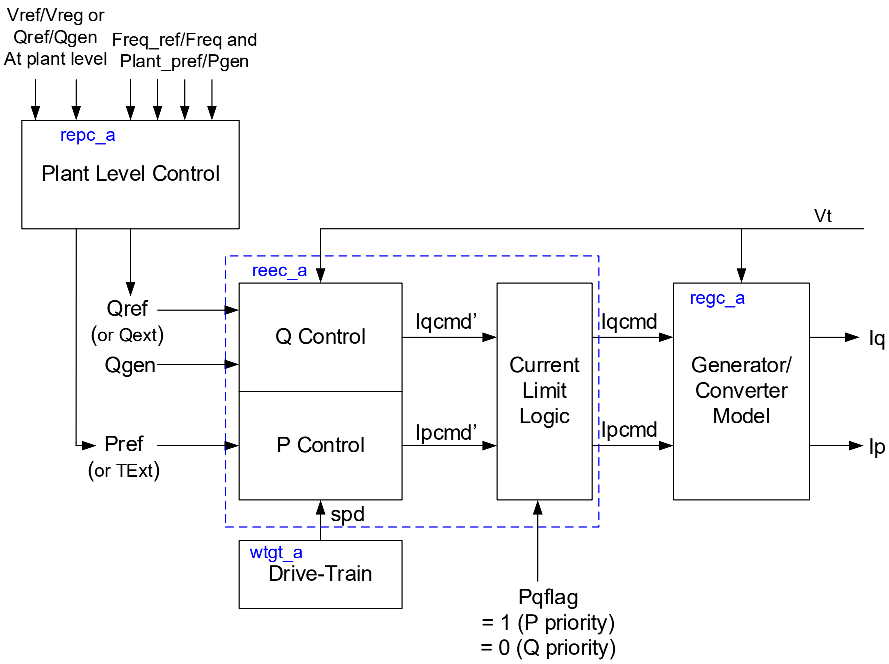


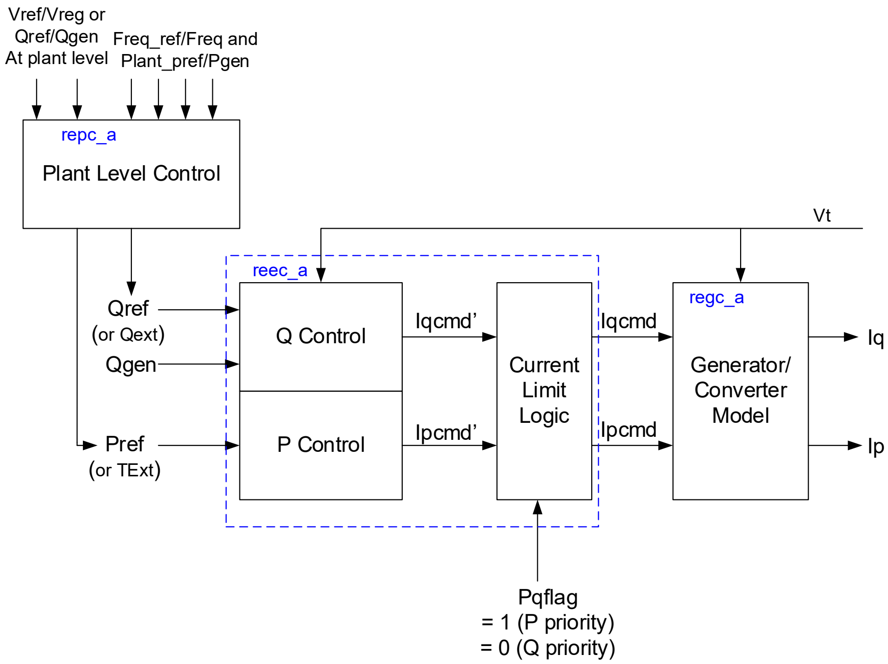
Figure 2-1
Model structure for the type 3 WPP

2.2 Type 4 Wind Power Plants and PV Plants

Figure 2-2 shows the model structures for a type 4 WPP or PV plant. The argument is much the same as above, except in this case there are little to no mechanical side models, since a PV plant has no mechanical parts (other than solar tracking systems on the panels, etc. which are not modeled for the purposes of power system studies) and in the case of a type 4 WPP previous work has shown that there is little value in modeling the mechanical side for power system studies [8].



Type 4 A



Type 4 B (or PV)

Figure 2-2
Model structure for a type 4 or PV plant.

3

FIELD TESTING OF WIND AND PV POWER PLANTS FOR MODEL VALIDATION

The field testing of a wind or PV plant should focus on determining two factors: (i) the volt/var control functionality of the plant, and (ii) any frequency response capability. Presently, in the United States of America, with the exception of the Electric Reliability Corporation of Texas (ERCOT) no other region mandates that wind and PV plants have primary frequency response capabilities. This may change in due course. That said, with the exception of plants in ERCOT, more than likely in all other regions in the USA the plants will not have frequency response capabilities activated and so testing/validating this aspect of the plant will likely show no results.

3.1 Base-Line Data

The first step for model validation, which equally applies to any equipment, is to establish the base-line model data. That is, starting with the verified original equipment manufacturer (OEM) provided model parameters for the plant model. Most of the major OEMs should be able to provide parameters for the 2nd generation generic models presented in the previous section. This would form the basis and starting point for the work. Also, as stated previously, many of these parameters would never be changed (e.g. limits on current, pitch-angle, turbine/generator inertia, switches/flags that determine the appropriate control strategy, etc.). This then establishes the starting point for the dynamic model of the WTGs or PV array.

The total wind/PV plant, for the purposes of large scale power system simulations, is typically modeled as a simple equivalent model as shown Figure 3-1. This approach has been shown based on research [9] and actual field testing [4] to be a reasonable means of representing a wind power plant for the purposes of capturing the electrical response at the point of interconnection (i.e. high-voltage side of the substation transformer) for the purposes of large scale power system simulation studies. It is therefore reasonable to assume, that it is equally valid for a PV plant (see e.g. [10]). There are two caveats to this:

1. In doing so, one is assuming that all of the WTGs (or PV inverters) in the collector system are identical. Therefore, this simple representation may not be adequate where a plant consists of a combination of different types of WTGs. In that case, a single equivalent may need to be built for each technology/type of generator.
2. It assumes that there are no other controlled devices in the plant (e.g. SVC, STATCOM, synchronous condenser, battery energy storage, automatically switched capacitor banks, etc.). In such cases, again a more complex model may be needed – see the latest *repc_b* model specification [11].

Putting the aggregated generator model (in blue) aside for the moment, the other parts of the model shown in Figure 3-1 can be derived at relatively easily:

1. The generator step-up transformer model should be based on the nameplate OEM data and simply scaled up in MVA – that is, resistance and reactance entered in per unit and the MVA

base of the aggregated step-up transformer set equal to the number of WTGs times the MVA of a single transformer.

2. The sub-station transformer should be modeled explicitly based on OEM nameplate data and the actual fixed-tap settings in the field.
3. The equivalent feeder impedance can be calculated from the collector system data using the NREL method [12].

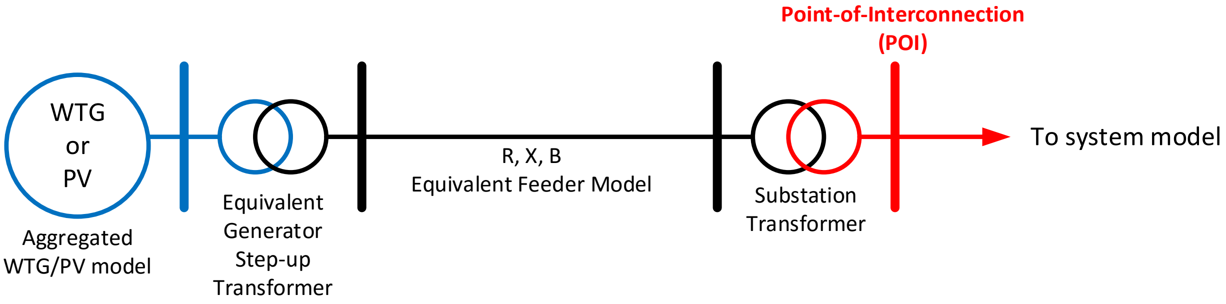


Figure 3-1
Single-aggregated generator equivalent model of a wind/PV power plant.

With the base-line plant model established, one is then ready to perform field tests, collect the necessary data and run simulations to compare, and tune, the model to match the field response.

3.2 Data Recording in the Field

For the purposes of field testing a wind/PV power plant, the same type of equipment that is used in the field testing of other generation equipment can be used. That is, any reasonably accurate digital measurement equipment (DME) that is able to record the necessary quantities for model validation. The goal is to capture the following quantities, at the following sampling rate, at the point of interconnection (typically high-voltage side of the substation transformer):

1. Real 3-phase power – P (MW)
2. Reactive 3-phase power – Q (MVar)
3. Positive-sequence rms line-to-line voltage – V (kV)
4. Frequency – f (Hz)

These quantities should be captured at a rate of at least 30 calculated samples per second or better, and recorded for a duration of several minutes for the various tests.

This can be achieved in many ways. One example is to use a dedicated DME to record all 3-phase voltages and currents at the POI and recorded the data at very high-sampling rates (e.g. 10 kHz or more – see [4]). Then the point-on-wave data can be easily post processed using well known digital signal processing techniques to calculate P, Q, V and f. Another equally valid approach is to, where available, use the digital recording capabilities of the wind power plant management system (see also [4]). Many of the newer wind and PV power plants have built into the software of the power plant management system, DME capabilities for recording the necessary data, and much more, for model validation during tests.

3.3 Validating Volt/Var Response of an Inverter Based Generation Plant

To validate the volt/Var capability of a wind/PV plant let us first consider the plant level controller model – *repc_a*, as shown in Figure 3-2. The reactive power control path of the model is the top part, which is what we are concerned with in this test. At the plant level, most, if not all, modern wind and PV plants are being installed with voltage control capability at the POI. Thus, the flag *RefFlag* should be set to 1. Also, it is more common to either have no droop/current-compensation in the controls or to employ reactive-droop (common particularly where there are multiple wind/PV plants in electrical proximity – see [4]). Thus, if reactive-droop is employed then *VcompFlag = 0* and the value of *Kc* should be set to reflect the actual droop settings in the controls. All these settings can be easily discerned from the digital controls, and/or discussions with the OEM. The reactive power limits of the power plant (Qmax/Qmin) can be tested if:

1. Conditions are favorable – i.e. it will not compromise the transmission system voltage to push the plant to its reactive limits, and
2. All the wind/PV inverters are on-line – due to the variability of the resource, this may be a challenge.

For smaller plants, the above can perhaps be achieved. But for larger plants it may not be feasible in the field, particularly due to operating limits on the transmission voltage, to push the plant to its reactive limits. Therefore, *Qmax/Qmin* may need to be calculated from the nameplate capability of the individual turbines, and then utilizing the simple model in Figure 3-1, in a simulation model. Thus, all that remains to be verified are *Kp, Ki, dbd (deadband), emax/emin, Tft* and *Tfv*. These controllers being digital controls, at least *Kp, Ki, dbd, emax* and *emin* can be looked up in the controls, or field settings requested from the OEM.

Voltage Reference Step Test:

Now the model can be validated. Through some iterative simulations, if necessary, these few parameters can be fine-tuned, by comparing the simulation results to measured test results. The simplest test to perform in the field is a voltage-reference step test. That is, a small (e.g. 1 to 3%) voltage-reference step is injected into the controls and the same is simulated (i.e. at the location of the green "Vref" in Figure 3-2). An example of such a test is shown in Figure 3-3 (from [4]). The recording should be long enough (typically minutes) to see the whole response.

One caution is that the step should not push the plant to its reactive limits, since for model validation purposes it may be wise to avoid hitting limits on the turbines. Also, at least 90% of the wind turbines/PV inverters should be on-line (or at least a majority).

Capacitor Switching:

An alternative test, where available, is switching in (or out) a large transmission shunt capacitor bank in the vicinity of the plant, to see the response of the plant to the sudden change in transmission voltage. An example of this is shown in Figure 3-4 (from [4]). In this case, the fast initial-response, upon switching of the shunt-capacitor, is driven by the turbine electrical controls (the *reec_a* model) and therefore verifies those OEM parameters, while the slower recovery of the POI voltage is again the action of the plant controller (the *repc_a* model) and verifies those parameters. It is therefore imperative that the numerous flags associated with the *reec_a* model also be appropriately set per the OEM’s actual control strategy. This is discussed in [5], and for completeness explained again in Appendix B.

PV and Other Inverter Based Generation:

The above types of test are equally applicable to PV plants. See for example Figure 3-5. Also, this could easily be extended to other technologies such as battery energy storage systems [14].

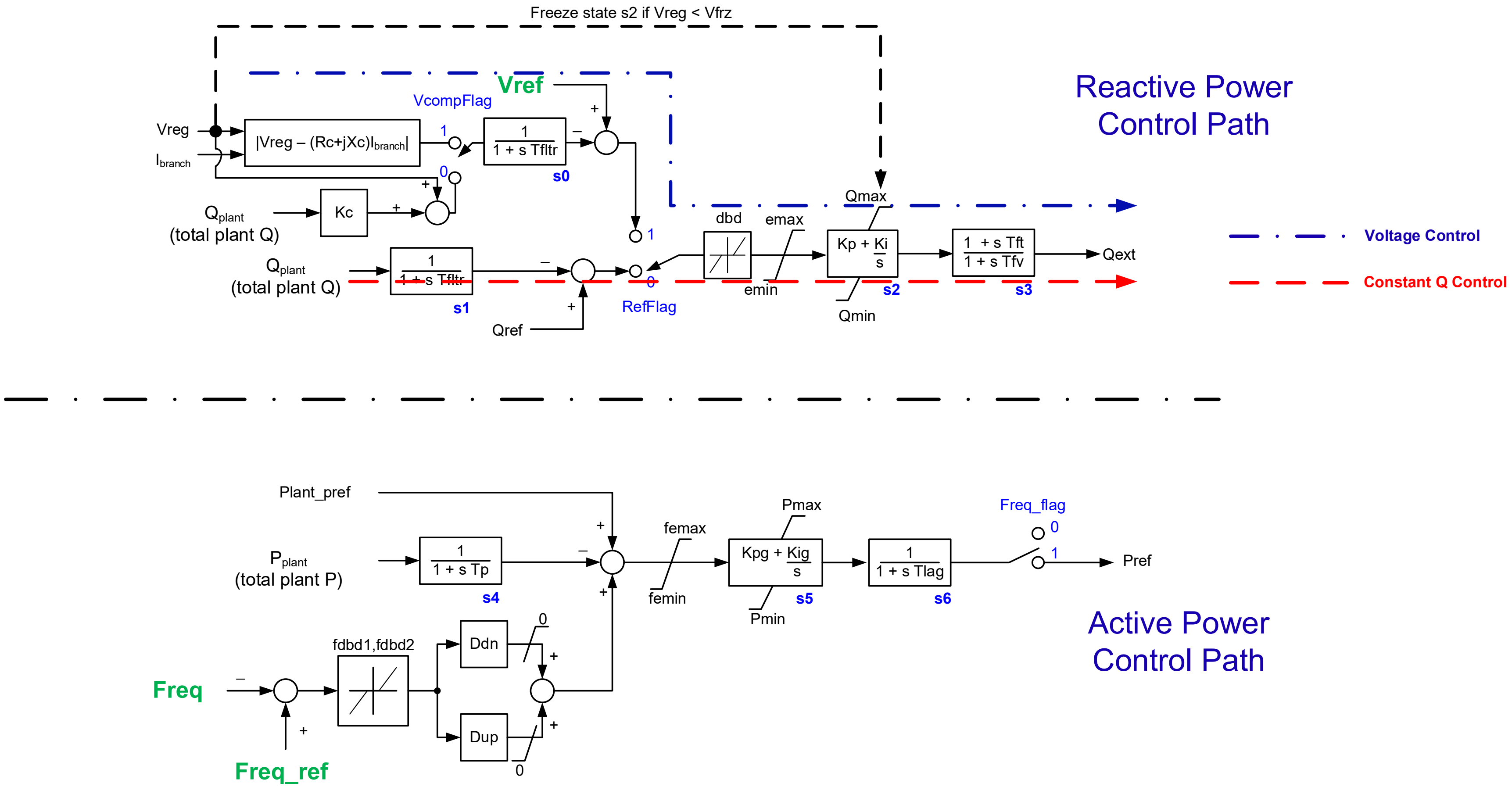


Figure 3-2
Plant controller model – *repc_a*.

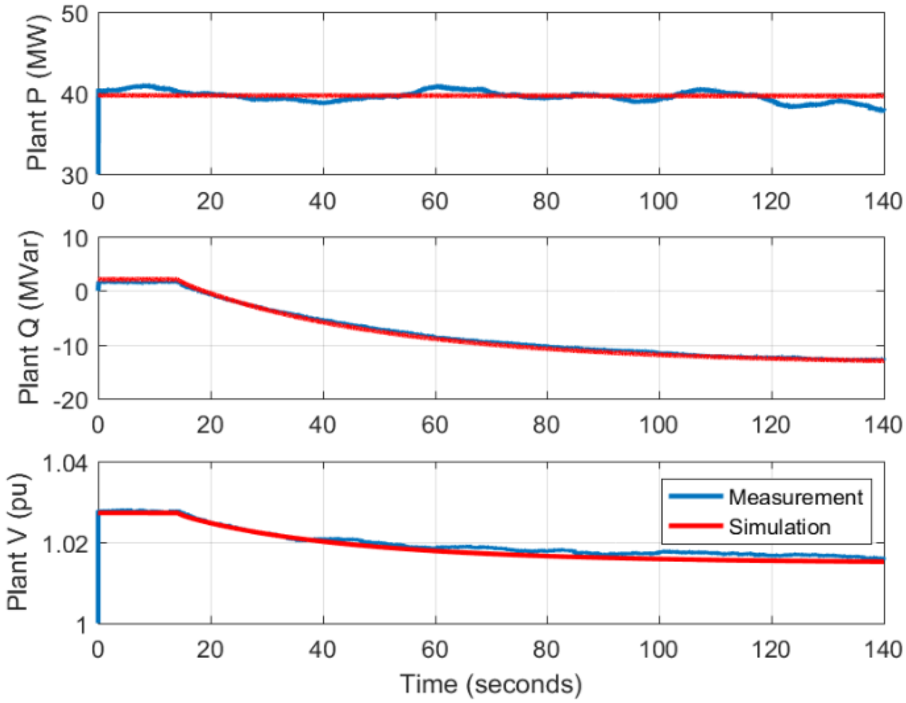


Figure 3-3
Example response of a large wind power plant at the POI to a voltage reference step test injected into the wind power plant controller (step-down in voltage). [<u>Source:</u> PEACE® [13]).

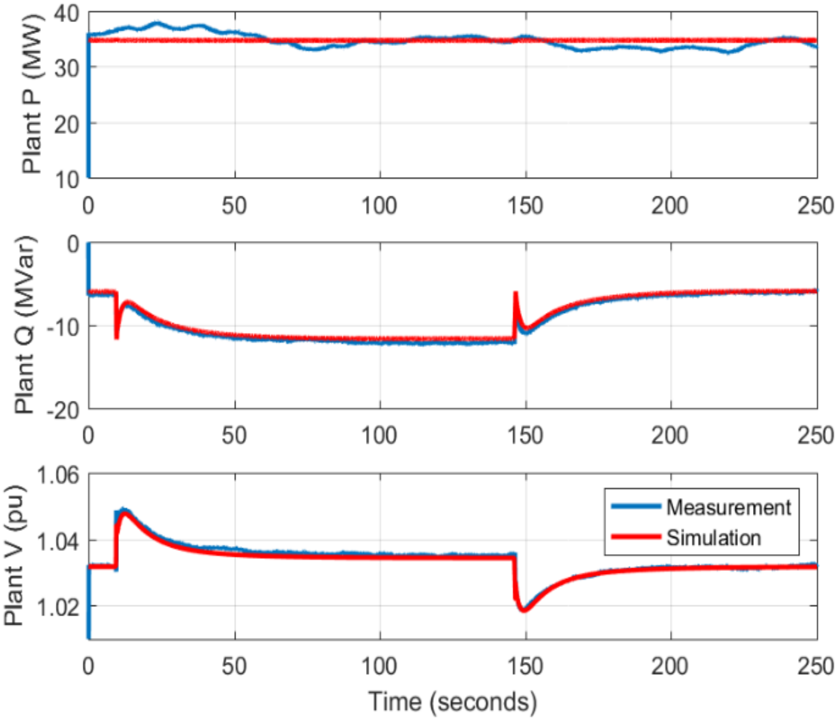


Figure 3-4
Example response of a large wind power plant at the POI to the switching in and out of a transmission shunt-capacitor bank in the vicinity of the plant [<u>Source:</u> PEACE® [13])

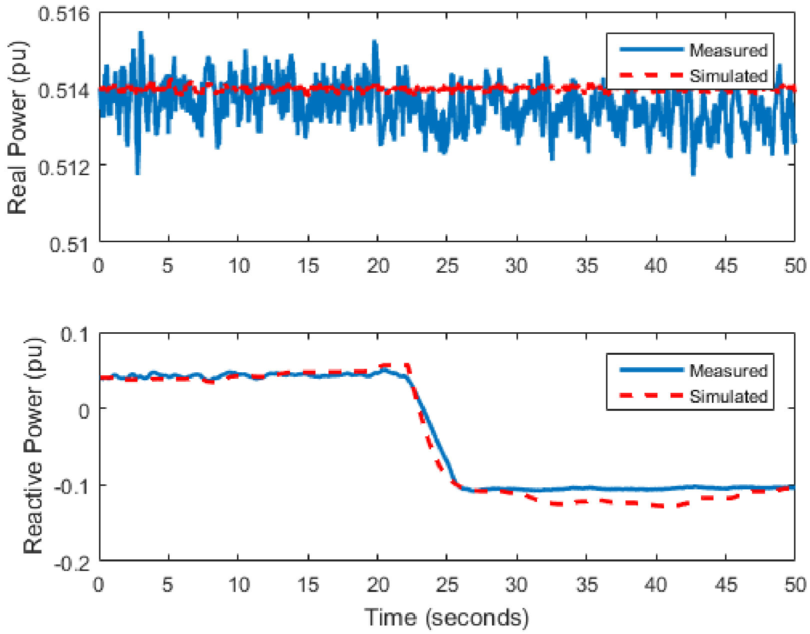


Figure 3-5
V-reference step test (step down) response, showing simulation versus measured response in MW and MVAr of a PV plant. Plant in voltage control mode [10].

3.4 Validating Frequency Response for Inverter Based Generation Plant

The active-power control path of the plant is independent of the reactive control path, and is shown in the bottom half of the *repc_a* model in Figure 3-2. In the majority of wind and PV plants in the USA as of the writing of this report (with the exception of those in ERCOT), this control path is disabled and so it is enough to set *Freq_flag = 0* in the model and one is done. Disturbance monitoring can then be used to confirm this fact (see for example [4]).

Now it is possible for a wind power plant to provide primary frequency response. In such a case, the *Freq_flag = 1*in the *repc_a* model. Furthermore, the parameters *fdbd1, fdbd2, Dup, Ddn, femax, femin, Pmax, Pmin, Kpg, Kig* and *Tlag* need to be set properly. Clearly, *Pmax/Pmin* must be set in accordance with the actual plants rated capability from the OEM data. Again, all of these values can be typically looked up in the digital controls (or obtained from the OEM). Then it suffices to perform model validation one of two ways:

Disturbance Monitoring:

By monitoring the response of the plant to an actual system frequency event, as captured by a phasor measurement unit (PMU) at the POI, or other DME. One example of this is shown Figure 3-6.

Frequency Reference Step Test:

By placing a small frequency reference step (at *Freq_ref* shown in green in Figure 3-2) into the plant controller. One example of this is shown in Figure 3-7.

In this case, a more sophisticated approach can also be taken. Namely, a synthetic frequency signal – e.g. mimicking an actual system event – can also be played into the plant controller (Freq shown in green in Figure 3-2) and the simulation model. An example of this is shown in Figure 3-8 and Figure 3-9, for a PV plant from reference [10].

One caution is to implement a step (or play-back signal) in the field that would result in a change in the plant output that is not more than 5 to 10% of nameplate rating. Also, the primary frequency response controls need to be in-service and have been properly tuned and commissioned by the OEM. Finally, note that there needs to be adequate wind/solar resource to have enough of the WTGs/PV inverters on-line and have some of the resource in reserve in order to allow for frequency response for this test to be performed. Also, for type 3 WTGs, the model parameters need to be appropriately adjusted to allow for this to be simulated – e.g. the initial blade pitch angle in the aero-dynamics model (*wtga_a*) should be set to a non-zero value (e.g. 10 degrees) to emulate this condition (i.e. blades not optimally pitched, to hold power in reserve) to be able to simulate this response. Other slight refinements of the model parameters, may also be necessary.

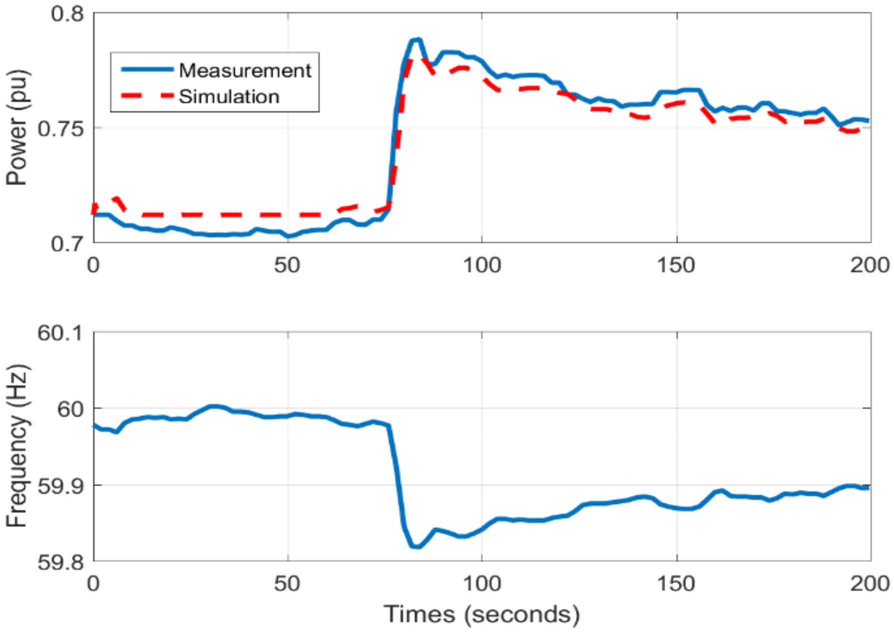


Figure 3-6
Aggregated single equivalent generator representation of a wind power plant, and the comparison of the simulated model response to actual measured response of the plant to a frequency event on the system. The plant consists of type 4 wind turbine generators, with primary frequency response controls. (© 2017 IEEE. Reprinted with permission from reference [3])

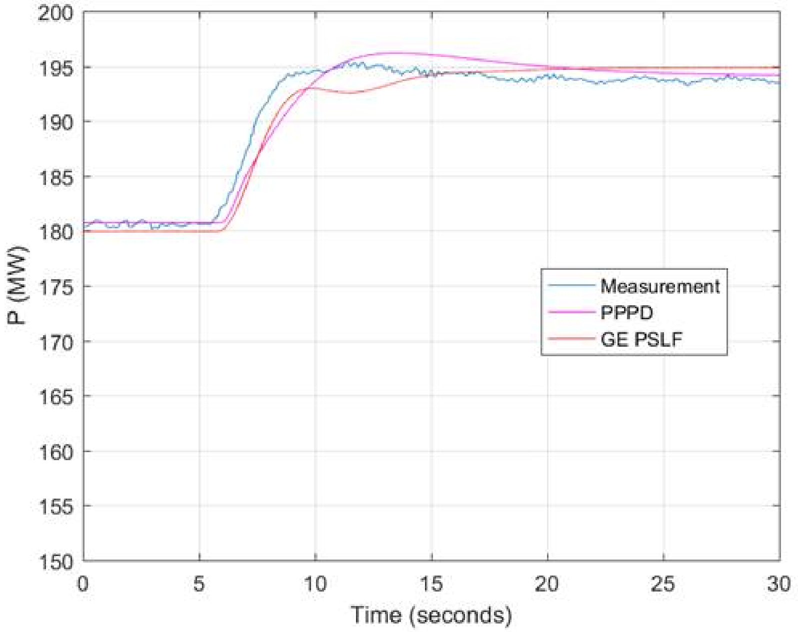


Figure 3-7
Aggregated single equivalent generator representation of a wind power plant, and the comparison of the simulated model response to actual measured response of the plant to a frequency reference step-test on-line. The plant consists of type 3 wind turbine generators, with primary frequency response controls.

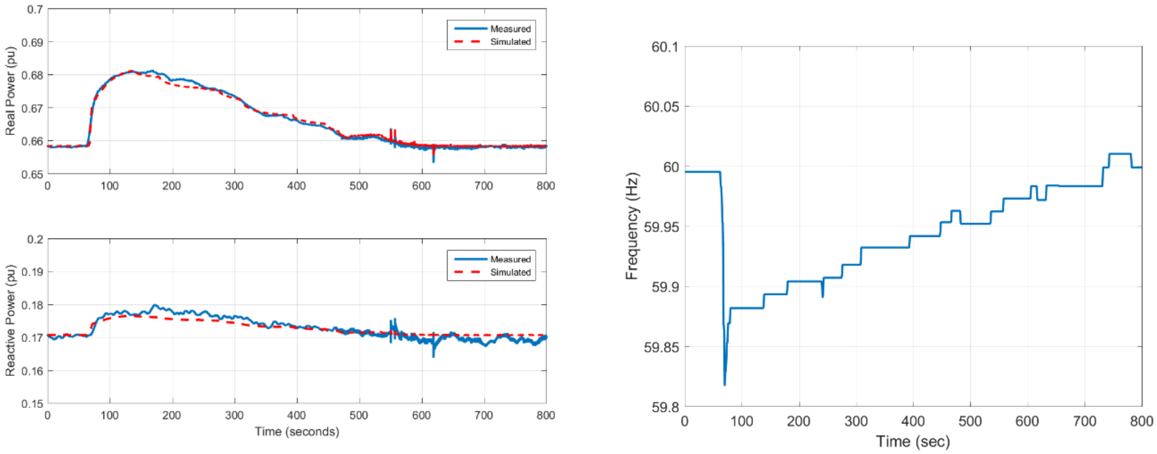


Figure 3-8
Under-frequency response for the 250 MW PV plant, showing simulation versus measured response in MW and MVAr of the plant. Plant in frequency responsive control mode, with head-room [10].

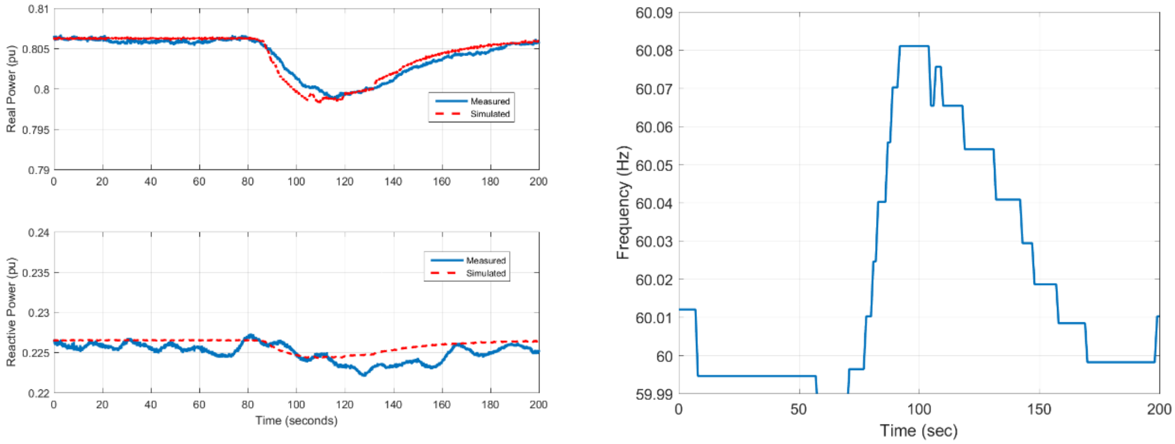


Figure 3-9
Over-frequency response for the 250 MW PV plant, showing simulation versus measured response in MW and MVAr of the plant. Plant in frequency responsive control mode, with head-room [10].

3.5 Low/High Voltage and Frequency Ride-Through Capability of the Plant

The low/high voltage and frequency ride through capabilities of wind and PV inverters (and power plants) are “emulated” in positive-sequence stability models using the *lhvrt* and *lhfrt* generic models, respectively. These models are very simple relay models that each have up to ten (10) break points. The parameter list of the two models is shown below. As an example, if vref = 1, and dvtrp1 = -0.9 and dttrp1 = 0.1, this means that if the voltage at the terminals of the WTG model drops by 1-0.9 = 0.1 pu voltage for more than 0.1 seconds, then the model will trip. If alarm = 1.0, then the model will not trip but only issue an alarm in the simulation. Thus, for each of the two models up to ten trip points, in sequence, can be provided.

The parameters for these models should be obtained from the OEM. It is not recommended that any tests be performed in the field to attempt to validate the low/high voltage and frequency ride-through capabilities of the plant or individual turbines/inverters as performing such test can risk damaging the equipment. In Europe, per IEC testing procedures, such tests are often done in the field on an individual WTG or inverter. This is not done in the US. We believe it is far more suitable to rely on factory tests from the OEM, and thus OEM provided numbers.

4

CONCLUSION AND SUMMARY

In this brief report it has been illustrated how the 2nd generation generic models can be parameterized and validated to represent the dynamic performance of wind and PV plants for the purposes of large scale power system simulations using staged testing. As illustrated the process has three main steps:

1. Collecting the base-line original equipment manufacturer data/parameters for the models and choose the suitable models to represent the wind or PV plant.
2. Performing a combination of:
    a. on-line voltage-reference step tests (1 to 3% step up or down) in the plant controller, and
    b. frequency-reference step-tests (small step, in order not to change the plant output by more than say 5% of nameplate),

   and record the response of the plant at the point of interconnection (MW, MVar, kV and frequency).
3. Performing simulations of the same tests and comparing the results between measurement and simulations to establish validation, during which some small tuning of the key parameters may be needed.

Table 4-1 summarizes this whole process.

Table 4-1
Summary of testing process.

Step	Actions	Results
Collecting Base-Line Model Data	Obtain from the original equipment manufacturer (OEM) the parameters associated with the 2nd generation generic renewable energy system models	1. Identify the models needed 2. Identify the control strategy and model flags (e.g. voltage control - yes/no, frequency control - yes/no, LHVRT settings etc.)
Perform Field Tests	1. Data Recording - set-up to record P (MW), Q (Mvar), Voltage (kV) and Frequency (Hz) at the point-of-interconnection of the plant (typically, high-side of substation transformer). Record the 3-phase calculated P/Q, and line-to-line rms kV at a rate of 30 calculated samples per second or better. Record for a few minutes for each test.	Obtain measured response of the plant to field tests.
	2. Voltage-refence step-test - perform a 1 to 3% step up/down in voltage reference on the plant level controller (of the POI voltage). Avoid hitting plant reactive limits. Make sure at least 90% of turbines/inverters are on-line	
	3. Frequency-refence step-test - if the plant has primary frequency response capability enabled, then make sure it is at a point where it can deliver primary frequency response and the controls have been properly tuned and commissioned by the OEM. Then perform a small frequency reference step test (to effect a 5 to 10% change in the plants output, on nameplate rating).	
Perform Simulations	Simulate the above tests in a commercial simulation platform and compare the results to the measured field tests. Tune parameters as needed.	Validation of the models

5
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A

MODEL PARAMETERS FOR A CONVENTIONAL INDUCTION MACHINE

For type 1 (and type 2) WTGs the electrical generator is typically modeled as a conventional electrical induction generator model. In most cases, the OEM will provide the single-cage equivalent circuit parameters of the machine (see Figure A-1). These equivalent circuit model parameters can be converted to the operational impedance parameters required in the typical induction machine models in commercial power system simulation tools, with the following equations.

$$Ls = Lm + La$$

$$Lp = La + 1/(1/Lm + 1/L1)$$

$$Ll = La$$

$$Tpo = (L1 + Lm)/(2\pi 60.R1)) \qquad \textbf{Eq. A-1}$$

In most commercial software tools, the sub-transient circuit in the model may then be eliminated by setting Tppo = 0 and Lpp = Lp.

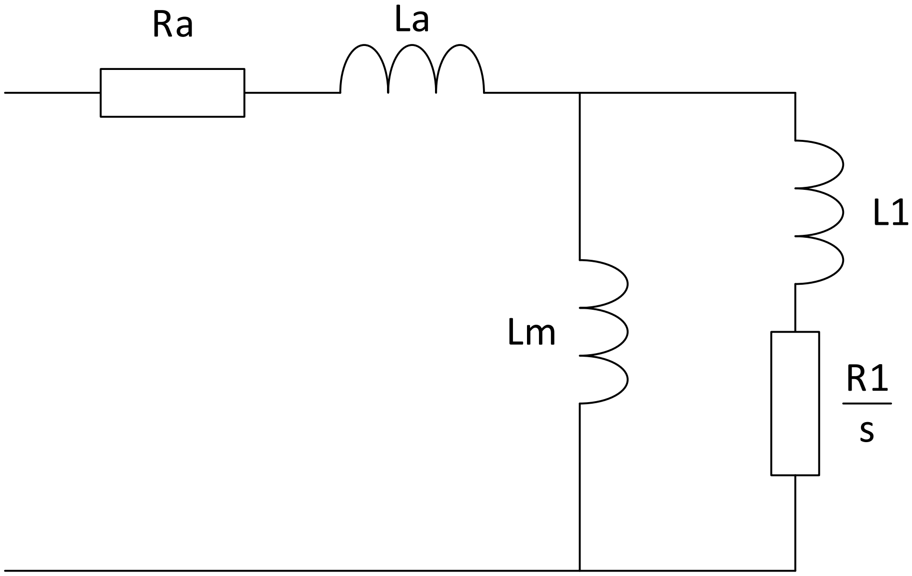

Figure A-1
Single-cage equivalent-circuit model of an induction machine.

B

THE CONTROL OPTIONS IN THE REEC_A MODEL

Consider the model *reec_a* (Figure B-1). There are three parts to the model:

- active current controls which develop the active current command *Ipcmd*
- reactive current controls which develop the reactive current command *Iqcmd*
- the converter current limit logic which limits the active and reactive current to within the ratings of the converter[1]

Active Power Control: Let us first look at the active power control (Figure B-1). In this part there are two options *PFlag* = 1, or *PFlag* = 0. For type 3 WTGs *PFlag* must equal 1, because the power developed by the turbine is modulated by perturbations in the shaft speed since the electrical generator is directly coupled to the grid. In this case, the *wtgtrq_a* model develops electrical torque, and so torque times speed yields power. ***EXTREMELY IMPORTANT NOTE:* *in many commercial software tools, such as GE PSLF and Siemens PTI PSS®E, the output of the torque model is multiplied by speed within the torque model, thus the output of the wtgq_a model in GE PSLF is already equal to power and so PFlag must be set to 0 in GE PSLF for otherwise one would be multiplying torque by speed squared which is of course incorrect. This is still the exact same model, it is just that the vendor for internal software reasons, decided to place the torque × speed calculation in the torque model. THIS MAY ALSO BE TRUE IN OTHER SOFTWARE PLATFORMS. SO PLEASE DOUBLE CHECK THIS IN THE SOFTWARE USER'S MANUAL.***

For type 4 WTGs either option may be valid depending on the type of unit. For a type 4A WTG the electrical power output of the unit is perturbed by the torsional oscillations of the turbine-generator shaft and so *PFlag* can be set to 1 and the *wtgt_a* model used to approximately emulate this behavior[2]. For type 4B WTGs there is no appreciable observation of electrical power perturbation due to torsional oscillations in the turbine generator shaft, due to the converter design, and so PFlag is set to zero and no *wtgt_a* model used.

The rest of the parameters associated with the active power control are the maximum and minimum power ratings of the unit (*Pmax/Pmin*), the maximum and minimum rate of change of power reference (*dPmax/dPmin*) and the time constant associated with the controls (*Tpord*).

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[1] It assumes a full-converter unit. For the sake of simplicity, it was decided, during the development of this model, by the WECC MVWG to not make a distinction between stator current limits for the type 3 WTG and converter current limits for the type 4 WTG.

[2] The *wtgt_a* model when used with the type 4 WTG is intended solely for emulating the observed torsional oscillations post-fault in some type 4 equipment, where this occurs. In these cases, the mechanical power (*Pm*) of the *wtgt_a* model is assumed to be constant. Therefore, this model should not be used for cases where the primary frequency response feature is used or other external models that change *Pref*, since keeping *Pm* constant while *Pe* is being change is not realistic.

Since this model is for use with WTGs (or PV) the minimum active current command is clearly zero (*Ipmin = 0*), and this is not changeable by the user.

The maximum active current command limit is determined by the current limit logic (*Ipmax*).

Reactive Power Control: There are several options for reactive power control. This is shown diagrammatically in Figure B-1. These are:

- Local constant Q control – PfFlag = 0 and QFlag = 0; VFlag = 1 or 0 (irrelevant)
- Local constant power factor (pf) control – PfFlag = 1 and QFlag = 0; VFlag = 1 or 0 (irrelevant)
- Local terminal voltage control – PfFlag = 0, VFlag = 0 and QFlag = 1
- Local coordinated Q/V control – PfFlag = 0, VFlag = 1 and QFlag = 1

In addition to all this, there is a separate proportional, with deadband, current injection control which can be used either as proportional voltage control during a voltage dip (deadband set to zero) or a proportional current injection with deadband during a voltage dip. To disable this path, *Kqv* can be set to zero. The parameters *Iqfrz* and *Thld* can be used in association with this current injection loop to create various state transitions (see [5] for details).

For the local voltage control option, the user-defined reference bias *Vref1* is typically set to the default value of zero (0). This bias was provided again at the request of one OEM. It should only be used if so instructed, otherwise we advise always setting it to zero.

Thus, the various control options are summarized in the table below.

Table B-1
Reactive power control modes for the *reec_a* model.

Control Mode	PfFlag	VFlag	QFlag
Local constant Q control	0	0 or 1	0
Local constant power factor (pf) contorl	1	0 or 1	0
Local voltage control	0	0	1
Local coordinated Q/V control	0	1	1

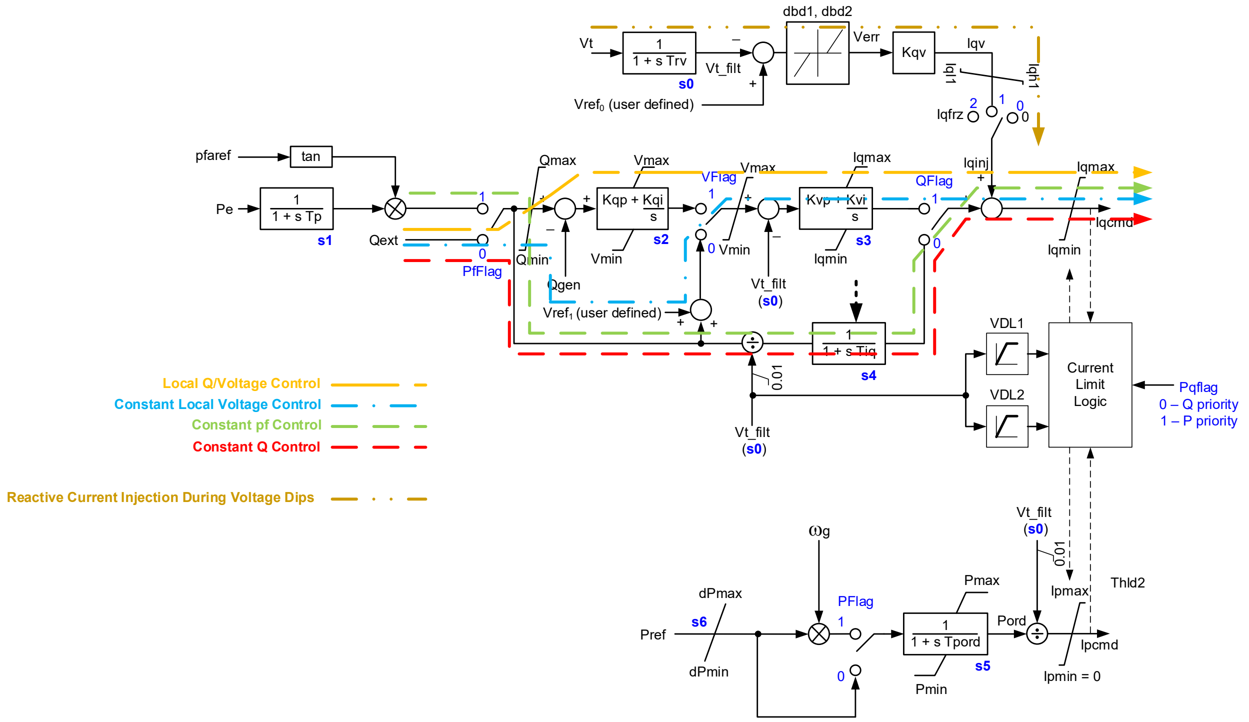

Figure B-1
Options for the reactive power control path in the *reec_a* model.

<u>*Current Limit Logic:*</u> The current limit logic implementation is discussed in detail in [5]. In its most basic form the current limit is a semi-circle. That is, only positive active current is allowed (*Ipmin* = 0) since this is a model for a generator, and the total current must be less than or equal to *Imax*. The selection of the *Pqflag* determines whether priority is given to active or reactive current. The *VDL1* and *VDL2* tables are two look-up tables with four pairs of numbers that define a piece-wise linear curve. These tables define the reactive and active current limits, respectively, as a function of voltage. Therefore, in addition to the basic current limit, the *VDL* tables can be used to effect further limits on either active or reactive current as a function of voltage. The values of these tables need to come directly from the OEM, or based on fitting the values from factory tests. To disable these tables (or if data is not available) then simply set all the values to *Imax* for four different voltage settings, e.g. Vq1 = 0, Iq1 = Imax; Vq2 = 0.2; Iq2 = Imax; Vq3 = 0.5, Iq3 = Imax and Vq4 = 1.0, Iq4 = Imax etc.

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