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# Concepts of Model Quality Testing for Inverter Based Resources

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# ABSTRACT

With the ever expanding portfolios of renewable energy systems worldwide, the is a steady influx of inverter-based resources coming into power systems. The vast majority of these renewable resources are wind and solar-photovoltaic (PV) power plants. All such resources are connected to the bulk power system through power-electronic converters and thus referred to commonly as inverter-based resources (IBRs). The example used in the current report is that of a solar-PV plant, however, the concepts discussed could be equally applied to any IBR, including type 3 & 4 wind turbine generator based plants, energy storage systems, and hybrid power plants with any combination of such IBRs.

In the context of this continued large influx of IBRs into the bulk electric power systems around the world, many utilities, and independent system operators (ISOs), have struggled with the quality of the dynamic simulation models that are often submitted by power plant owner/operators for the purposes of planning studies performed by utilities. Whether these models are of a generic (standard library models in simulation tools) or vendors specific user-written black-box type, they still may be subject to such concerns of model quality. Moreover, the same is true whether the models are used in commercially available positive-sequence phasor-domain software tools, or electromagnetic transient simulation (EMT) tools. Many utilities, and ISOs, have thus developed their own so-called model quality tests to screen models that are submitted to them to try to catch such potential issues upfront and to thus work with the power plant owner/operators to try to resolve such issues prior to incorporating the models into their planning process. In this report we will not attempt to do a thorough review of any of the current used methods by various utilities and ISOs, nor make reference to any of them. This report instead explores the concept of model quality testing, proposes some reasonable procedures for model quality testing that could be applied to all the types of models (generic, user-written, positive-sequence or EMT), and expounds on the various limitations and issues that can arise in the process of model quality testing and thus the need of the engineer(s) performing such tests to exercise a level of judgment and balance in interpreting the results of model quality tests.

## Keywords

IBR modeling
Model quality testing

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# 1 INTRODUCTION

This report discusses the concepts of model quality testing for inverter-based resources (IBR). With the continued large influx of IBRs into the bulk electric power systems around the world, many utilities, and independent system operators (ISOs), have struggled with the quality of the dynamic simulation models that are often submitted by power plant owner/operators for the purposes of planning or interconnection studies performed by utilities. Whether these models are of a generic (standard library models in simulation tools) or vendors specific user-written black-box type, they still may be subject to such concerns of model quality. Moreover, the same is true whether the models are used in commercially available positive-sequence (fundamental-frequency) phasor-domain software tools, or electromagnetic transient simulation (EMT) tools. Many utilities, and ISOs, have thus developed their own so-called model quality tests to screen models that are submitted to them to try to catch such potential issues upfront and to thus work with the power plant owner/operators to try to resolve such issues prior to incorporating the models into their planning or interconnection study process. In this report we will not attempt to do a thorough review of any of the current used methods by various utilities and ISOs, nor make reference to any of them. This report instead explores the concept of model quality testing, proposes some reasonable procedures to model quality testing that could be applied to all the types of models (generic, user-written, positive-sequence or EMT), and expounds on the various limitations and issues that can arise in the process of model quality testing and thus the need of the engineer(s) performing such tests to exercise a level of judgment and balance in interpreting the results of model quality tests.

Section 2 gives some brief background on power system modeling to set the stage for the discussions in this report.

Section 3 presents an example procedures for model quality testing through the use of a simple example PV plant model.

Section 4 provides a brief discussion on what model quality testing is not, that is, how it relates to other activities for which the same models are to be used and are thus being quality tested to prepare them for use.

Section 5 gives an overall summary and conclusions of the report.

# 2 SOME BRIEF BACKGROUND ON POWER SYSTEMS MODELING

Before an attempt is made to suggest a proposed procedures for model quality testing, first let us consider the types of dynamic simulation models that exist in various software platforms and briefly review their purpose and use.

Broadly, dynamics simulation models, used in commercial power systems analysis software, can be categorized into four categories:

1. 3-phase electromagnetic transient (EMT) vendor specific models,
2. Parameterized generic 3-phase EMT models [1],
3. Vendor specific user-written/developed positive-sequence (fundamental-frequency) phasor-domain models,

Parameterized standard-library positive-sequence phasor-domain models – these are typically referred to as “generic positive-sequence” models. Here, we will not go into a deep discussion of the use and efficacy of each of these model categories. It is sufficient to say that all these categories of models are used by various utilities, independent system operators (ISOs) and reliability entities (REs) both in North America and around the world. A brief overview, however, will be given of the broad application of each type of model as this will help with the model quality test (MQT) discussion.

Consider Figure 1, it is certainly not unique and various versions of this figure have appeared in various presentations and publications (e.g., Fig. 1 in [3]). The figure is not to be interpreted as all encompassing, nor to be taken as absolutely precise. Whenever, and wherever, it has been used the intent has been to convey a simple message. That is, in power systems analysis there are phenomena of interest that range from very fast transients (e.g., switching phenomena in gas insulated switch gear and lightning phenomena [4]) in the nano-second time frame to very slow phenomena such as economic dispatch of generation equipment that occur over many hours to a day time frame. It would be an insurmountable task to try to model all of these phenomena in a single software platform, which would faithfully model all the necessary components. The feasibility of such a task aside, the data management alone for a large interconnected system, such as those in North America, would be impractical. Some might suggest that with the power of modern computers this should not be impossible. However, consideration must be given to the many practical aspects that make such a viewpoint infeasible, such as data management, computational time and complexity for simple tasks that could be easily done with simplified model (e.g., power flow analysis), post-processing and interpretation of results for low frequency phenomena (e.g., trying to do small-signal stability analysis in an EMT environment versus eigenvalue analysis), etc. Here a detailed elaboration of this will not be presented, as it will divert from the main theme of the report. However, it should be quite evident to practicing engineers in the power and energy community that using the most appropriate model and modeling tool for each type of study is the most efficient and effective way to analyze the system. Thus, when looking at Figure 1, (i) EMT tools and models are used to analyze phenomena from very fast transients (VFT) to control interactions, (ii) while positive-sequence phasor-domain tools are used to analyze phenomena from low frequency (e.g., several Hz) localized control loop stability to system wide stability phenomena such as small-signal stability and frequency stability as well as long-term voltage-stability, and (iii) very slow phenomena such as economic dispatch and production simulations are performed in production simulation tools.

Thus, the common practical approach to power system analysis is that depending on the phenomena of interest, different simulation platforms and models are used. For example, when performing economic dispatch a production simulation tool is used, which uses extremely simplified models for generation and transmission equipment as compared to simulations models and tools used for studying higher frequency phenomena such as EMT or positive-sequence tools.

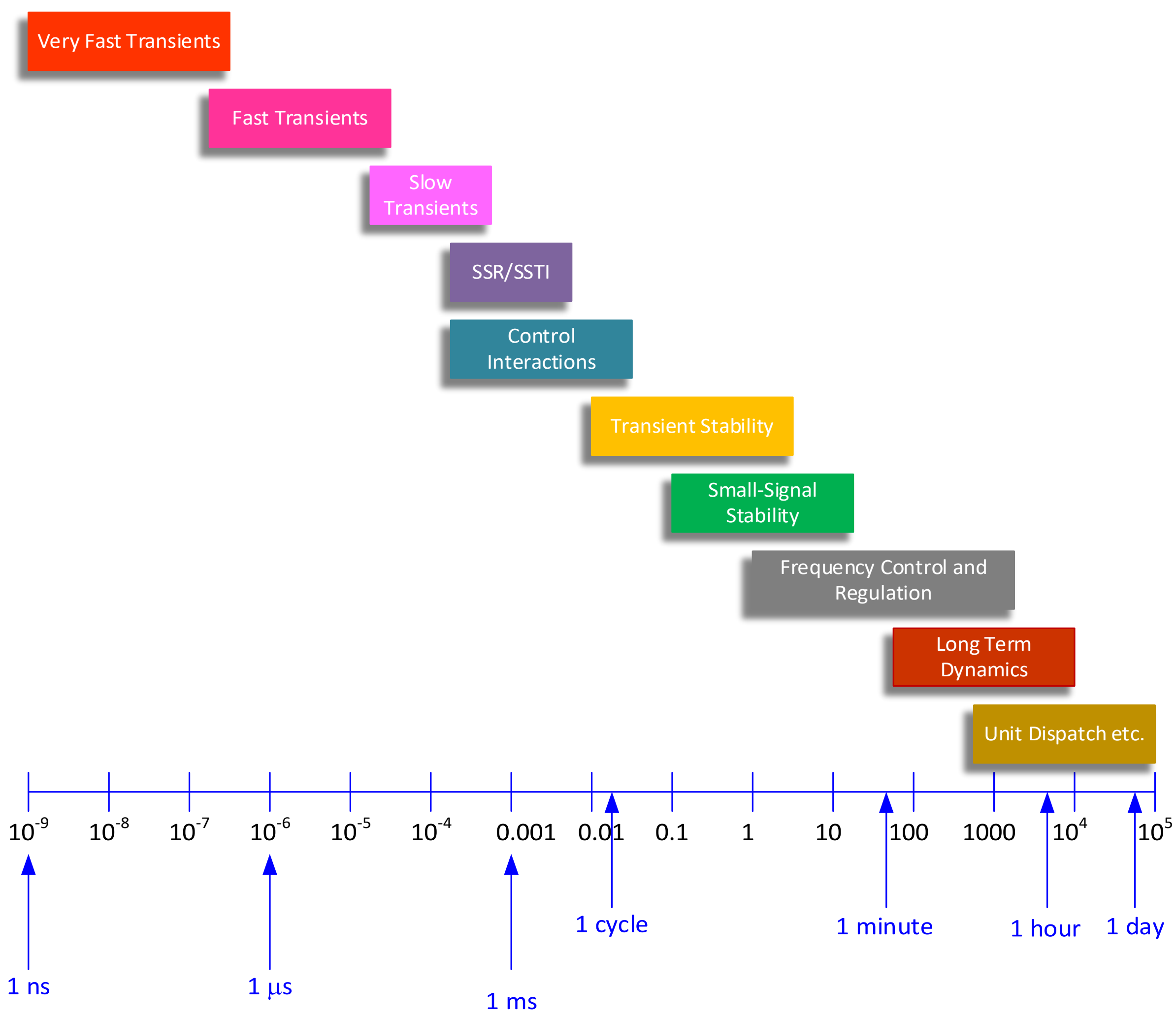


Figure 1. Power system phenomena of interest. (Source: PEACE® [2])

With above background given then, time-domain dynamic simulations are performed in EMT and positive-sequence (fundamental-frequency) simulations tools, and the models used and phenomena investigated are quite different. That said, when a model is developed in either tool, they can potentially be developed in one of three ways:

1. To use the actual source code of the control system and to compile that into the model as a dynamically linked library (DLL). This is becoming a more common practice.
2. To develop a so-called user-written dynamic model in the native programing language of the software tool, which is based on the actual details of the vendor specific controls.
3. To parameterize a standard library model in the commercial software tool (so-called "generic" models).

One further important note should be made. It is common practice in some regions to use parameterized generic positive-sequence (fundamental-frequency) models for stability analysis in the lower-frequency domain (e.g., power system frequency stability and control), even for existing IBR plants. However, when studying existing equipment, or a specific vendors equipment, in the context of high-frequency phenomena or specialized studies (e.g., studying subsynchronous resonance phenomena), then vendors specific EMT models must be used to ensure the highest fidelity possible. Generic EMT models are typically only used when studying futuristic scenarios where the equipment vendor is yet not determined, and there is still a need to make an assessment of potential issues related to high-frequency domain phenomena and control interactions. In the end, all applications of models and modeling require the proper level of engineering judgment to ensure the models and parameterization is suitable for the task.

So given all of the above context, if a model is then provided to a utility, ISO or other entity for use in power system simulations, how should the model be checked to ensure it is of good quality?

There indeed may be other legitimate questions to be asked also, such as is the model a valid model, if it pertains to an existing and operational IBR plant. Such questions are outside of the scope of this present discussion. The question here is given a model of an IBR unit or an IBR plant in a given software environment, for a given study purpose, how can we reasonably check to ensure that the model is of a sufficient quality before proceeding with our simulation work?

The question of model quality comes down to three main factors (i) does the model behave in the expected way (e.g., if we expose the plant to a voltage dip, and the plant is supposed to be controlling voltage, do we see it respond by increasing reactive power in order to attempt to bring voltage back up), (ii) are the parameters of the model in a reasonable and physically meaningful range (e.g., do the transformers have a reasonable leakage reactance), and (iii) will the model be numerically stable for the range of conditions to be simulated.

Figure 2 is an attempt to diagrammatically depict how model quality testing might fit into the process of designing, interconnecting, and commissioning a new IBR plant. Namely, one round of IBR unit or supplemental IBR device model quality testing might be done briefly prior to embarking on the detailed IBR plant design evaluation phase. This might be to ensure that the IBR unit models provided by a vendor after their internal IBR unit type testing and IBR unit model validation has been completed is performing reasonably and thus ready for use in the IBR plant design evaluation. During IBR plant design evaluation further tests of IBR unit model sufficiency might be performed, or feedback given to the vendor to provide added information to verify sufficiency during the type testing, e.g., frequency scans of the EMT level models as well as frequency scans as part of factory type testing might be requested to be included in the IBR unit model validation reports when necessary for studies like subsynchronous resonance analyses. Then a second round of model quality testing on the whole IBR plant model would be pertinent after the IBR plant model has been verified through the design evaluation and/or validated[1].

[1] Presently, in North America, power plant model validation is done typically through field testing during commissioning, and then revalidated periodically through disturbance performance monitoring during operation. In Europe, some regions have adopted a slightly different philosophy where a plant model is considered validated compared to both (i) field tested during commissioning, and (ii) disturbance events captured during a so-called trial period of many months during normal operations. Here we deliberately refrain from going into a detailed discussion of the pros and cons of these two approaches and what constitutes validation. Such discussion is outside of the scope of this document.

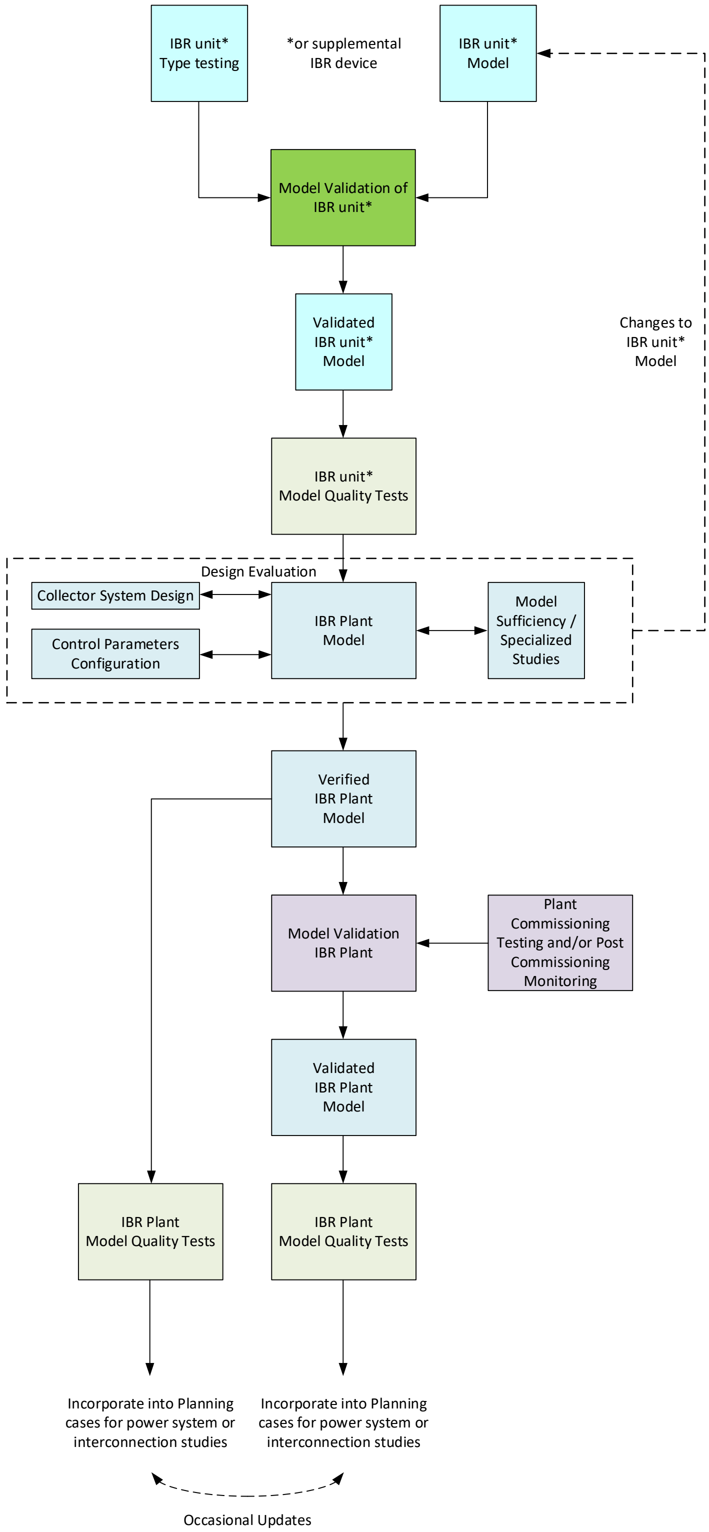


Figure 2. Where model quality testing might fit in the process of designing, interconnecting and commissioning of an IBR plant.

# 3 MODEL QUALITY TESTING

When a dynamic model is received by an entity from an equipment vendor, the first expectation is that the model is bug-free. Though obvious, let us now reflect on this for a moment. All computer simulation dynamic models are software code compiled into a software program, whether they are of the (i) real-code DLL type, (ii) user-written native programing language type, or (iii) standard-model library type. All models need to be coded one way or another and integrated/linked into the software tool. Thus, all these models are susceptible to software bugs. That is, an unintentional error or flaw in the code of the models that can result in an incorrect, unexpected, or unintended response under certain circumstances. The main goal of model quality testing, when done on the part of the model recipient (e.g., utility engineers) is not to check to see if the model software has bugs or not. Certainly, it is always a goal to produce bug free software. But that responsibility should be placed upon the model developer, whether it is the equipment vendor or the software vendors, or both working in collaboration. Moreover, despite all efforts to test and verify code in software, it is quite possible that some bugs may go unnoticed. Bug fixes for software is a common occurrence in all software development. Thus, the main goal of model quality testing is to:

- ensure that the model initializes properly in the software and for a no-disturbance run the model's output remains in steady-state and does not change noticeably nor diverge,
- ensure that the model responds in an orderly and expected fashion to reasonable voltage and frequency events,
- ensure that the model responds in an orderly, and well damped fashion to transmission level faults[2], and
- ensure that the model behaves well numerically for a reasonable range of system strength at the interconnection point.

With the above in mind, an example is given here of possible procedures for model quality testing, using an example IBR plant model. Everything discussed here is equally applicable to models of similar type in any commercial software tool such as Siemens PTI PSS®E, GE PSLT™, PowerTech Labs TSAT™, PowerWorld Simulator, DIgSILENT PowerFactory, etc. For the sake of simplicity, and having open-source models, the standard ("generic") library models have been used here, however, all of the types of tests and simulations presented here would be equally applicable to user-written black-box models. Thus, the example case is provided with the report.

Figure 2 shows the example IBR plant model used. It is a single aggregated IBR unit model, with a single aggregate unit step-up transformer, with an equivalent collector feeder model, and an explicitly modeled substation power transformer. The model is a fictitious photovoltaic (PV) power plant. It does not represent any actual plant or entity's data. None-the-less, it is a

[2] In the case of EMT models this may involve simulating not just a 3-phase to ground, but also unbalanced transmission faults (e.g., a single-line to ground fault, and a phase-to-phase fault).

realistic model and all the parameters are within the reasonable range of values. The model, and simulations, here are performed in the Siemens PTI PSS®E software program, Version 35.5.

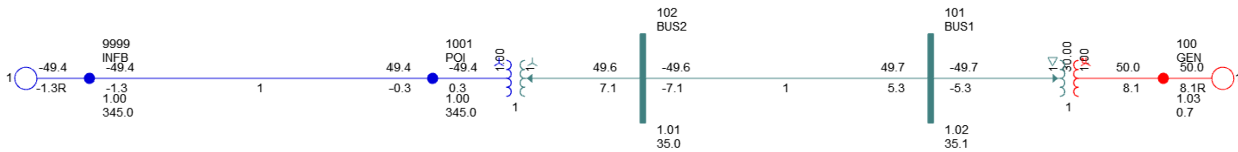


Figure 3. Example aggregated IBR plant model.

## Step 1 – Model Sanity Check

The first step of a model quality test would typically be a quick review of all of the provided data to sanity check the values of model parameters, both the steady-state and dynamic models.

The power flow model data for the aggregated generator (Figure 3), the aggregated generator step-up transformer (Figure 4), the single equivalent feeder (Figure 5) and the explicit model of the substation power transformer (Figure 6) are all shown respectively in Figures 3 to 6. A close perusal of these figures shows that all the steady-state model data seem reasonable, namely:

1. The generator MW, Pmax, Pmin, MVA, Qmax and Qmin all seem reasonable. That is, Pmax is 50 MW and Pmin is 0 MW, which is reasonable for a PV plant, since at its minimum it would produce no power (0 MW) and its maximum MW should not, typically, exceed the MVA rating. Also, the Qmax/Qmin[3] values defined a ± 0.95 pf capability at the inverter level, which is typical and reasonable for inverters. Finally, the R Source and X Source values are provided as 0 and 0.15 pu, which again are quite reasonable[4].
2. The generator step up transformer data also looks reasonable. The transformer leakage reactance is 0.06 pu on its aggregated MVA rating of 52.5 MVA. This is quite reasonable.

[3] In some cases, a more detailed Qmax/Qmin definition might be done by using Machine Capability Curve feature available in most commercial software tools to define Qmax/Qmin as a function of load (MW) on the inverter. This has not been done here in this simple example, since we are assuming a constant Qmax/Qmin over the entire operating range of the inverter, which is possible for some designs. Of course, even in such a case (i.e., constant Qmax/Qmin capability over the entire operating range of the inverter) for PV plants, the effects of ambient temperature on the PV cells will affect MW, and thus MVar, capability of the inverters. Such temperature effects need to be taken into consideration in planning studies, but cannot be explicitly modeled since ambient temperature is not an input to power flow (or dynamic) models.

[4] **Note:** in this case the so-called generic REGC_B model is being used to model the full-converter interface of the PV plant. For this model a source impedance is needed, since the model develops the network interface model as a voltage source (i.e., voltage behind source impedance). Thus, the values of R + jX Source defined this source impedance in the model. Other models, and user-defined models, may use (or not) the source impedance in a different way. Thus, it is important to consult the model's user's manual to understand how the value should be parameterized and also consult with the equipment vendor. Also, note that these values of source impedance are not necessarily to be used directly in short-circuit analyses. For short-circuit analyses in tools like ASPEN or CAPE other models are needed and such discussions are outside of the scope of this document.

The transformer X/R ratio is 10, which is reasonable for small medium to low voltage transformers. Also, the winding configuration seems reasonable and typical for such plants.

3. The aggregated feeder impedance model of 0.005 + j0.01 pu on 100 MVA base (system MVA base), and cable charging of B = j0.02 pu, also seems quite reasonable for this size of a PV plant where the collector system would typically be relatively short spans on underground 34.5 kV cable.

4. Finally, a perusal of the main substation power transformer data shows that the transformer leakage impedance is 0.0025 + j0.1 pu on its nameplate rating of 33 MVA, which is quite reasonable for this size of a transformer (i.e., X/R ratio of 40 and leakage reactance of 10%). In this example we assume that the transformer does not have an on-load tap-changer, which is the most typical case with renewable power plants. However, there are many plants that do have on-load tap-changers, and if so that too should be modeled. Finally, for this example it is assume that the fix-tap position on the HV winding is 1.0, however, again this is not necessarily always the case, and so it should be ensured that the actual field setting of the fix tap position is modeled.

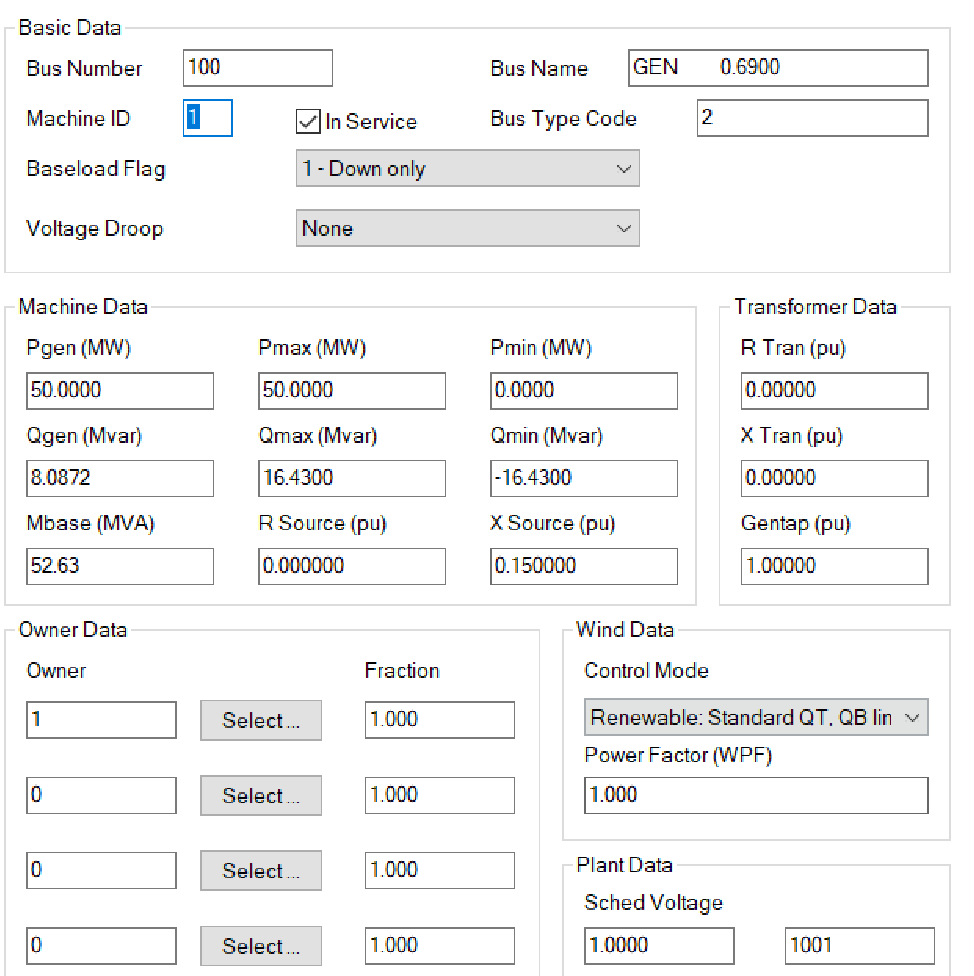


Figure 4. Example IBR plant model power flow aggregated generator data.

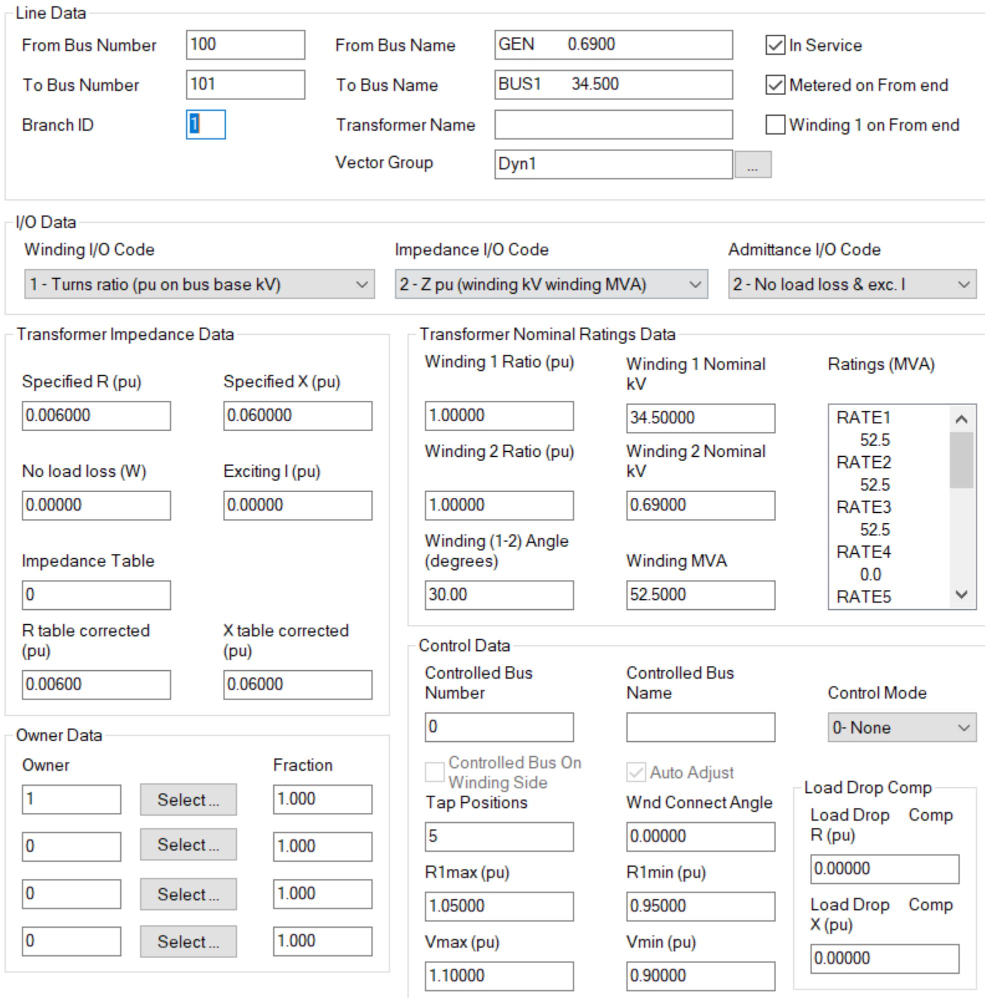


Figure 5. Example IBR plant model power flow aggregated generator step-up transformer data.

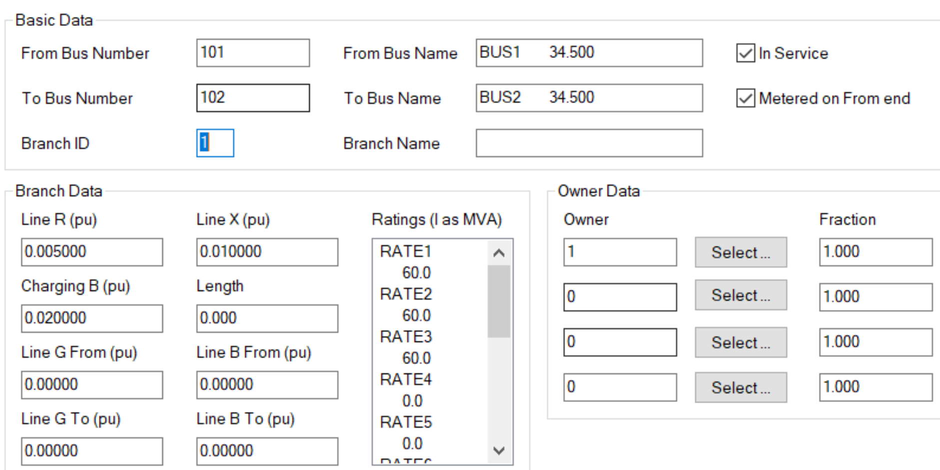


Figure 6. Example IBR plant model power flow equivalent feeder model data.

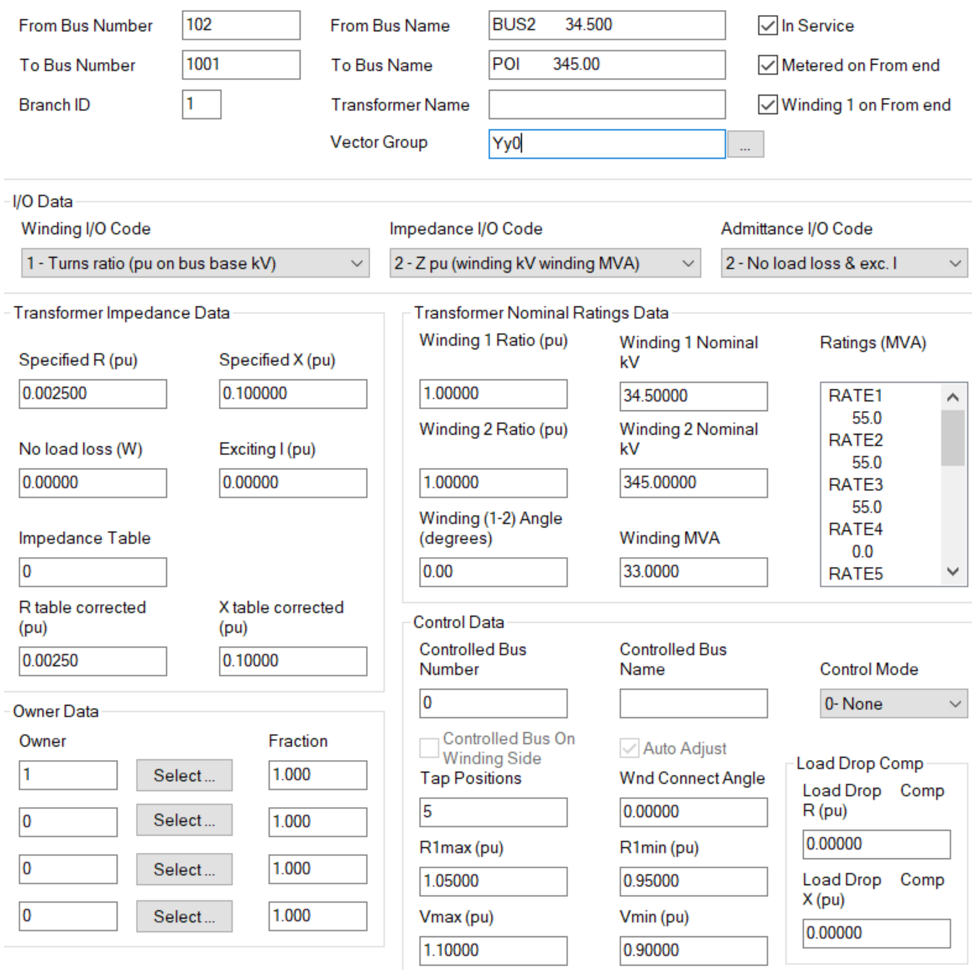


Figure 7. Example IBR plant model power flow substation power transformer data.

The next level of model data checking would be to perform a quick sanity check of the dynamic model parameters. In this regard, such a sanity check of the dynamic model parameters is only truly possible, by the user, if the model is of a generic type (i.e., standard library model that is publicly available with good block-diagrams and documentation). It is typically difficult, if not in some cases impossible, to do such a sanity check on user-written black-box models since the user will invariably not know what most of the parameters actually represent. In such cases, one must rely on the OEM to have checked the parameters.

It is important to emphasize the point of proper parameterization of the models, whether user-written or generic standard library models. The vast majority of model quality test failures (e.g., model fails to initialize properly, or responds in an overly oscillatory manner, etc.) are due to improper parameterizations. Thus, it is imperative to properly check to ensure that the models have been properly parameterized to reflect the chosen control strategy, with reasonable gains and time constants in the various control loops.[5]

In our example here, we are using the generic models and so we can potentially check the parameters to see if they are within the typical expected ranges. Appendix F in reference [5] gives a set of tables that defined the typical range of each of the parameters of the most commonly used generic renewable energy system (RES) models. Doing this we see that the parameters provided here are reasonable. An important note is that such a parameter sanity check is not to be taken as an absolute must comply, but rather some level of judgement must be applied. For example, for the gain *Ki* in the *REPC_A* model the typical range of values in Appendix F of [5] is given as 0 to 10. The value in the model here is 10. Had the value been say 15, that does not mean it is wrong. Gains can actually vary over quite a wide range. The key is that the controls must be stable and yield the expected response and performance. So the idea is simply to ensure that the value is reasonable, and to then once we are comfortable with the quality of the model to move forward and performed our detailed analyses (e.g., stability studies) to ensure that the performance of the plant is stable and acceptable for all credible, and some extreme, contingency scenarios per the regional planning standards.

Finally, in the case of the generic RES models all of the major software tools have an additional flag that can be set in the power flow model for the generator. As can be seen in Figure 3, the baseload flag has been set to '1 – Down Only'. This is quite reasonable, since it means that the plant is always running at its maximum power tracking point and thus has no MW in reserve and can only reduce is power down for high-frequency events. That is, it will not respond to underfrequency events. If a scenario is to be modeled where the plant is assumed to be curtailed, such that it is not at its maximum power tracking point and thus capable of also providing a response to an underfrequency event, then the baseload flag should be changed to '0 – Normal'. This feature does not necessarily work with user-written models. For vendors specific user-written models the vendor, and the model's user's manual, have to be consulted to identify how to manage the plants frequency response capability.

## Step 2 – Model Quality Test Simulations

The second step of a model quality test is then to identify if the model of the power plant will meet the four requirements that were laid out at the beginning of this section, i.e.,:

- ensure that the model initializes properly in the software and for a no-disturbance run the model's output remains in steady-state and does not change noticeably nor diverge,
- ensure that the model responds in an orderly and expected fashion to voltage and frequency events,

[5] As for the model quality test discussion, adequate parameterization of a model for validity of the model's response compared to the actual IBR unit or IBR plant is out of scope. Nevertheless, model validation is an important step before a model is used in studies that guide decisions in the power system planning or interconnection process.

- ensure that the model responds in an orderly, and well damped fashion to transmission level faults, and
- ensure that the model behaves well numerically for a reasonable range of system strength at the interconnection point.

With this in mind, the most logical simulation test to perform to assess these basic features would be:

- Test 1: A non-disturbance simulation to assess initialization.
- Test 2: A plant voltage reference step test up and back down (e.g., 2% up and back down) to test voltage response of the plant.
- Test 3: A forced step down and back up (e.g., by 2%) of the infinite bus voltage as another way to test voltage response of the plant.
- Test 4a: A plant active power (MW) reference step up and back down to test active power response (e.g., by 20%).
- Test 4b: A plant active power (MW) reference step up and back down to test active power response, with the plant initially in a curtailed mode (i.e., baseload flag = 0 – Normal).
- Test 5a: A forced step up and down in the network frequency (e.g., 250 mHz), through the infinite bus, to test the active power frequency response of the plant.
- Test 5b: A forced step up and down in the network frequency, through the infinite bus, to test the active power frequency response of the plant, with the plant initially in a curtailed mode (i.e., baseload flag = 0 – Normal).
- Test 6: A simulation of a normally clearly (e.g., 5 cycle duration) 3-phase to ground fault at the POI of the plant.
- Test 7: A simulation of a back-up clearing event. That is, first a normally clearly (e.g., 5 cycle duration) 3-phase to ground fault at the POI, followed by an emulated single-line to ground (SLG) fault that lingers on and is cleared after an additional e.g., 10 cycles[6]. The idea here is for example, one breaker might become stuck and have to be cleared by zone 2 relays.
- Test 8: A series of successive simulations where the reactance of the radial line connecting the plants POI to the infinite bus is increased in steps to "emulate" increasing effective Thevenin impedance looking into the grid, and thus a gradually weakening grid condition.

[6] In a positive-sequence (fundamental-frequency) program one cannot truly simulate a SLG fault. The SLG fault is emulated by making the fault impedance = calculated negative sequence fault impedance + zero sequence fault impedance as calculated in a short-circuit simulation program such as ASPEN one-liner. This "emulates" the effective fault impedance, and the response seen is really only the positive-sequence response. For EMT models unbalanced faults can certainly be simulated.

For the sake of completeness a brief explanation will be given here of the intent behind each test. The intention behind Test 1 and 6 should be quite clear, and needs no explanation. Test 2 will help to verify that the model properly responds to a voltage step tests. Test 3 is another way of checking the volt/var response of the plant is reasonable, but forcing the voltage at the POI to actually drop by a small amount and then come back up. This is done through what is typically called a 'play-back' function, i.e., all commercial software platforms (positive-sequence and EMT) have such a feature, where a programs voltage and frequency wave-form can be played into a node/bus of a model. That is the approach taken for this test, and also for Test 5a & 5b (for the forced network frequency step). Again, the intent is simply to gauge if the model behaves reasonably for an actual, admittedly pre-programed, voltage and frequency step on the grid. Finally, we have Tests 7 & 8. The intent of Test 7 is to look at what might be a typical type of fault simulated in planning studies, and can also happened in real-life, where a fault being as a normally cleared fault, however, due to a mis-operation of a stuck-breaker on one of the phases, the fault turns into a SLG fault and is eventually cleared through back-up clearing (Zone 2).

The tests listed above were performed on the example positive-sequence (fundamental-frequency) PV plant model provided here, as listed in Table 1.

Finally, note that here for ease of explanation and illustration of the typical process we have used a generic (public) model. However, the process and steps described here are equally applicable to any user-written model, including EMT models.

Table 1. Example Model Quality Test Simulations

| Test No. | Description |
|---|---|
| 1 | 20 second no-disturbance run |
| 2 | Vref step (i) up 2% at 5 seconds, (ii) down 2% at 25 seconds, (iii) down another 2% at 45 seconds, (iv) back up 2% at 65 seconds. |
| 3 | Using playback force the INFB voltage (i) up 2% at 5 seconds, (ii) down 2% at 25 seconds, (iii) down another 2% at 45 seconds, (iv) back up 2% at 65 seconds. |
| 4a | Pref step (i) up by 0.2 pu at 5 seconds, (ii) down by 0.2 pu at 25 seconds, (iii) down another 0.2 pu at 45 seconds, (iv) back up 0.2 pu at 65 seconds. |
| 4b | Pref step (i) up by 0.2 pu at 5 seconds, (ii) down by 0.2 pu at 25 seconds, (iii) down another 0.2 pu at 45 seconds, (iv) back up 0.2 pu at 65 seconds. ***The plant is curtailed – baseload flag = 0.*** |
| 5a | Using playback force the INFB frequency (i) up 250 mHz at 5 seconds, (ii) down 250 mHz at 25 seconds, (iii) down another 250 mHz at 45 seconds, (iv) back up 250 mHz at 65 seconds. |
| 5b | Using playback force the INFB frequency (i) up 250 mHz at 5 seconds, (ii) down 250 mHz at 25 seconds, (iii) down another 250 mHz at 45 seconds, (iv) back up 250 mHz at 65 seconds. ***The plant is curtailed – baseload flag = 0.*** |
| 6 | A 3-phase fault to ground simulated at the POI (bus 1001) for 5 cycles and then removed. |
| 7 | A 3-phase fault to ground simulated the POI for 5 cycles, followed by a 10 cycle "emulated" SLG fault (i.e., higher impedance fault). |
| 8 | A series of simulations where the impedance between the POI and the infinite bus is increased in steps at 5 seconds, 10 seconds, 15 seconds and 20 seconds to emulated successively decreasing system strength. |

The results of the above simulations, for the example case here, are shown in Figure 7 through Figure 16. Briefly, the following observations can be made:

1. Test1 shows that the model runs clean and flat for a no-disturbance run, as required.
2. Test 2 shows the expected response in reactive power at the point-of-interconnection (POI) for voltage reference step tests. Note that for the Vref step up the plant hits its maximum reactive limit. This is a function of both the size of the voltage step and the effective SCR at the POI. Thus, it is not necessarily an indicator of plant performance. The plant performance will need to be assessed in the context of a full transmission system model under various credible contingency scenarios to tests the range of potential, and actual and credible, system strength at the POI.
3. Test 3 shows a similar result to Test 2, as would be expected. The main difference being that in this case actual small voltage dips are emulated through playback at the POI. Notice, however, that the voltage at the POI jumps up (for example for the forced step up in voltage) but then gradually comes down a little as the plant suddenly reduced reactive power to reduce the voltage. This is because the forced (playback) voltage is being done at the infinite bus (bus 9999, Figure 2) and there is some impedance between the infinite bus and the POI bus (bus 1001, Figure 2).
4. Tests 4a and 4b also show the expected results. In both tests the plant is at a partial load level of 25 MW. In Test 4 the plant only responds to an active power reference step (Pref) to reduce power because it is always running at its maximum power tracking point and thus has no head room to respond to an underfrequency event (i.e., baseload flag = 1 – Down Only). In Test 4b, the baseload flag is set to 0 to allow it to move both up and down in power. Thus, the plant responds to both an increase and decrease step in Pref.
5. Tests 5a and 5b also show the expected results. Again , in both tests the plant is at a partial load level of 25 MW. In Test 5a the plant only responds only to an over-frequency event because it is always running at its maximum power tracking point and thus has no head room to respond to an underfrequency event (i.e., baseload flag = 1 – Down Only). In Test 5b, the baseload flag is set to 0 to emulate curtailing the plant. Thus, the plant responds to both an under- and over-frequency step.
6. Tests 6 and 7 simulate a normally cleared and delayed clearing of a fault at the POI. In both cases the plants response is reasonable and damped.
7. Finally, in Test 8 we see that the model is numerically stable down to an SCR of about 2. Below that the model is numerically unstable. This seems reasonable. IMPORTANT NOTE: this is not a guarantee that the plant will behave in a stable fashion down to an effective SCR of 2. Such an evaluation would require a much more in-depth study with a detailed 3-phase vendor specific model and a reasonable representation of the nearby transmission system. If the plant is going to be credibly operating in such weakened conditions, then separate detailed studies may be needed to verify that it will operate in a reasonable astable fashion.

Thus, at this point one may conclude that the models are of acceptable quality and can be taken to the next step to be used in planning or interconnection studies, as appropriate.

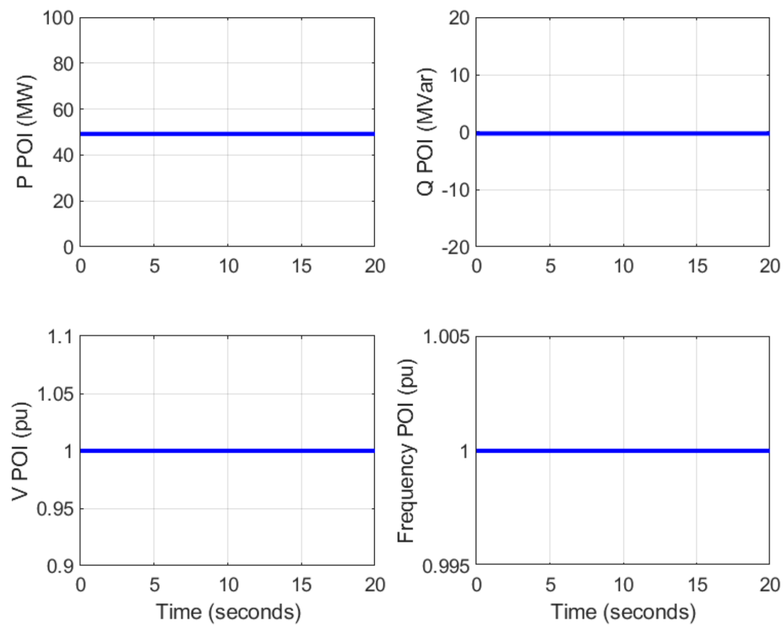


Figure 8. Test 1 – no-disturbance simulation

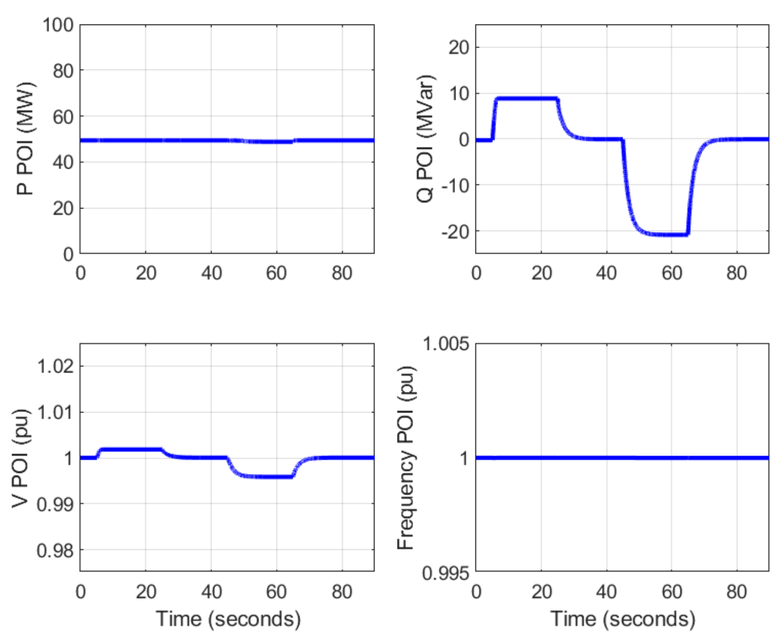


Figure 9. Test 2 – Vref step up and down test

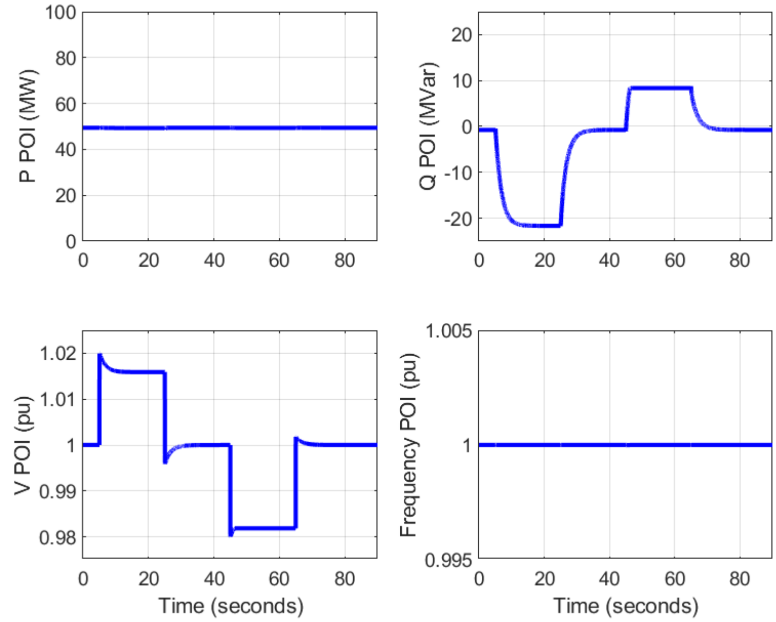


Figure 10. Test 3 – force step up and down in the voltage of the infinite bus

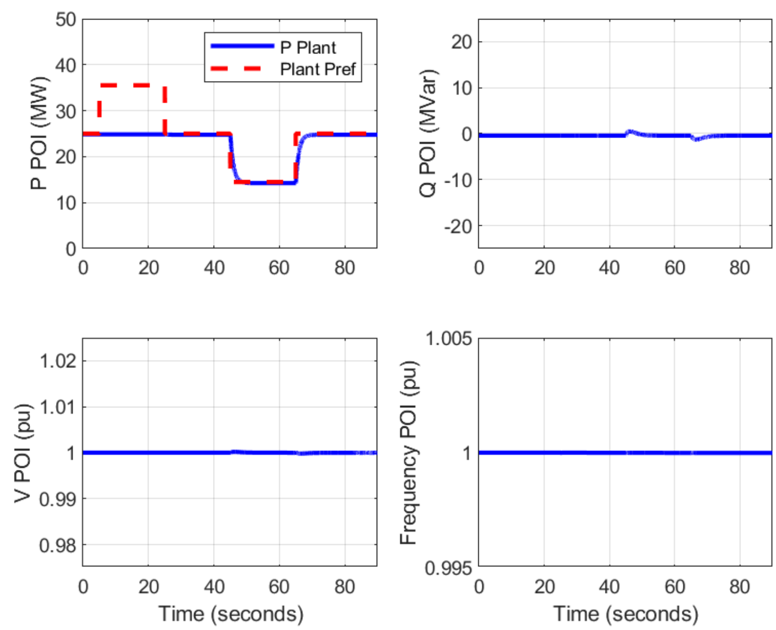


Figure 11. Test 4a – active power reference (Pref) step up and down on the power plant controller (PPC).

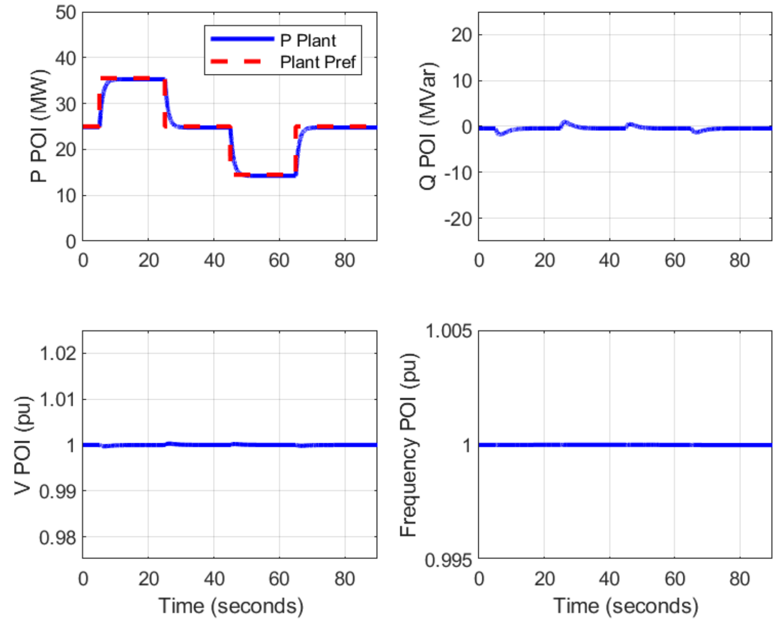


Figure 12. Test 4b – active power reference (Pref) step up and down on the power plant controller (PPC), while the plant is curtailed (i.e., baseload flag = 0).

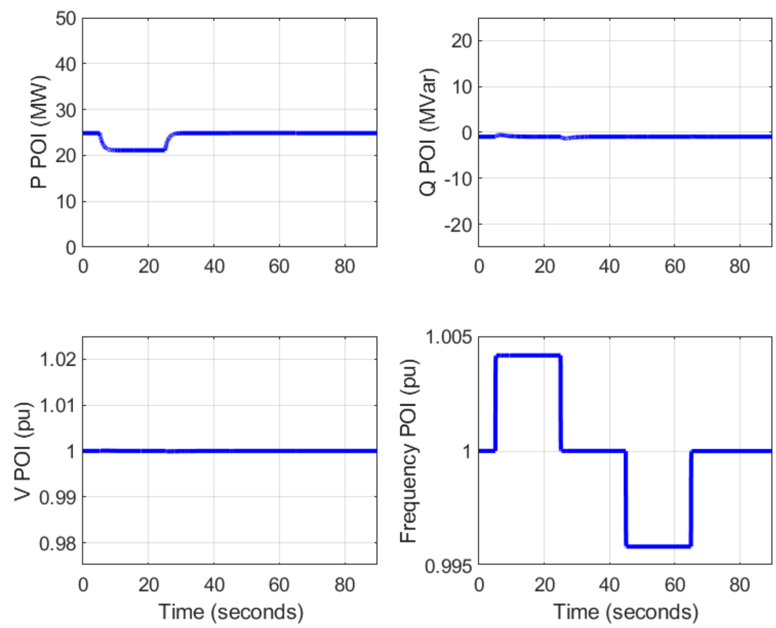


Figure 13. Test 5a – forced frequency step up and down by 250 mHz through playback at the infinite bus.

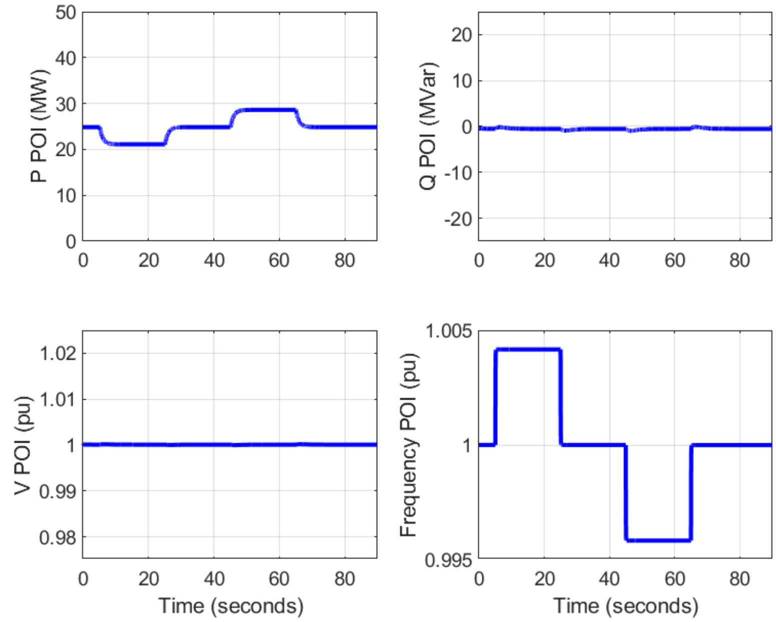


Figure 14. Test 5b – forced frequency step up and down by 250 mHz through playback at the infinite bus, while the plant is curtailed (i.e., baseload flag = 0).

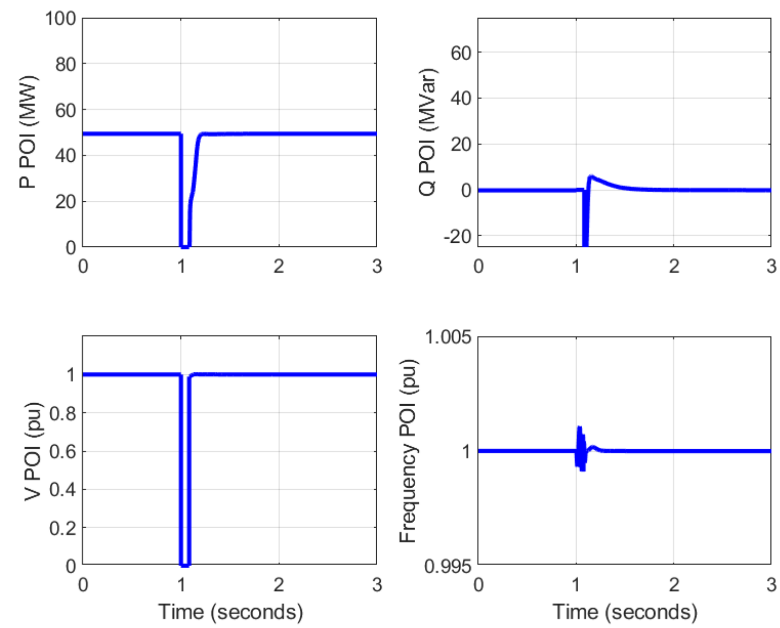


Figure 15. Test 6 – 3-phase to ground fault at the point-of-interconnection, normally cleared in 5 cycles.

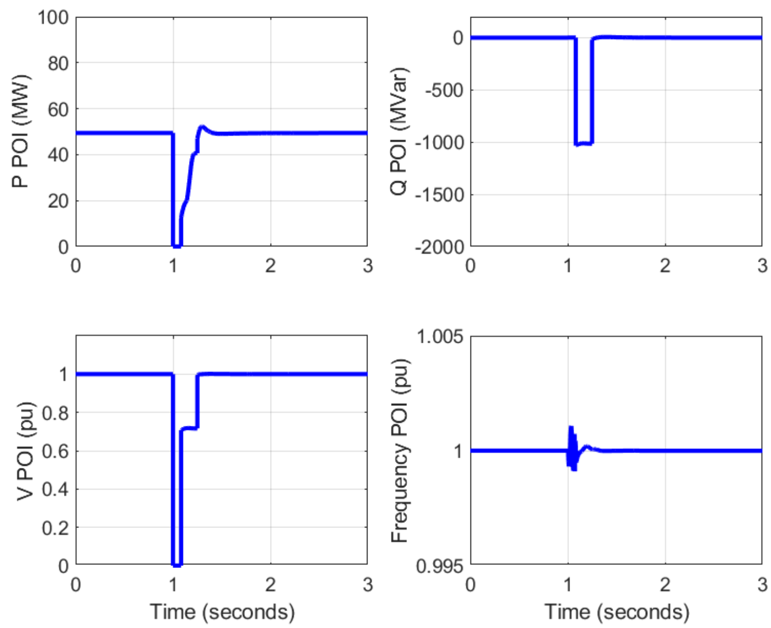


Figure 16. Test 7 – 3-phase to ground fault at the point-of-interconnection, normally cleared in 5 cycles, followed immediately by a SLG fault for another 10 cycles, cleared by Zone 2 relays.

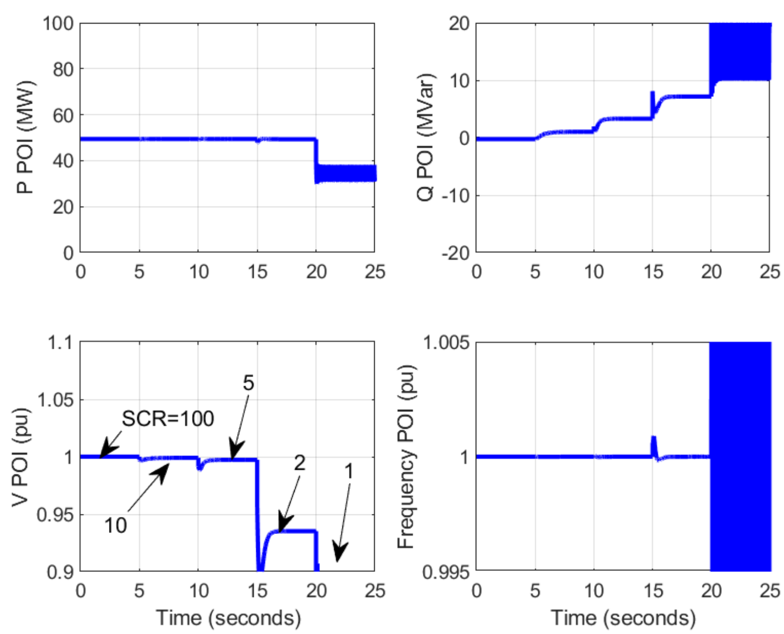


Figure 17. Test 8 – Decreasing in steps the effective Thevenin impedance looking into the network (i.e., between the POI and infinite bus) to emulate decreasing short-circuit ration (SCR) at the POI.

# 4 WHAT MODEL QUALITY TESTING IS NOT

It seems pertinent here to describe briefly what model quality testing is not intended to do and some of the issues that may arise during model quality testing if it is not done in the appropriate context.

Consider that a power plant model will at some point, also have to be validated. The process of model validation is quite an extensive one and outside of the context of this report to be discussed in detail. However, a very brief account will be given. The process of model validation for a power plant may be summarized briefly into the following three steps, which are presently under discussion in the IEEE P2800.2 Working Group:[7]

1. Type testing the individual IBR units or supplemental IBR device. In this step, tests are performed on an individual IBR unit (e.g., individual type 3 or 4 wind turbine generator, or individual PV inverter, etc.) or a supplemental IBR device (e.g., plant controller, reactive compensation device, protection relay) in either a factory setting or the field. The tests are typically performed by the respective OEM. Various aspects of the IBR unit functionality such as low/high voltage ride-through, real and reactive power response, etc. are tested through numerous tests and the measured response of the tests are compared to simulation models of the individual IBR unit to validate the individual IBR unit model. See for example reference [6]. An example plot from that reference is shown below (Figure 17) to illustrate the point.

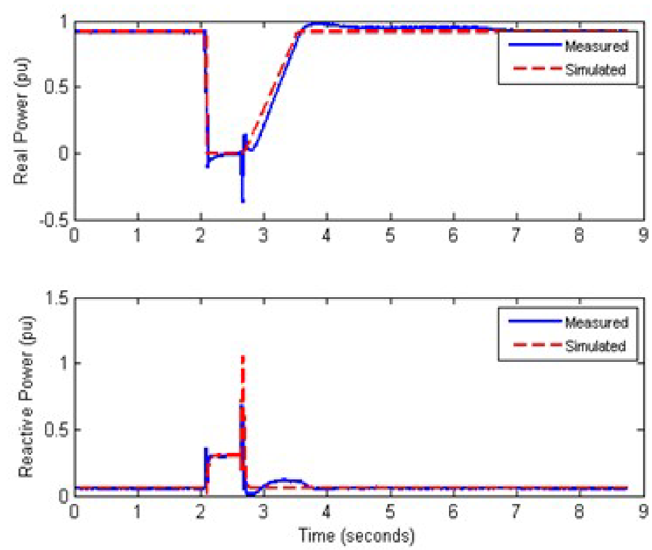


Figure 18. Measured versus simulated response of a PV inverter for an LVRT test. Simulated response is the dashed-red lines. (Vendor 4). (Reproduced with permission © IEEE 2017 from reference [6])

[7] For information about the IEEE P2800.2 Working Group for Test and Verification of BPS-Connected Inverter-Based Resources, see https://sagroups.ieee.org/2800-2/ .

2. Once the individual IBR unit models, and as applicable the supplemental IBR device models, have been validated, typically by the respective OEM, they are used to develop the aggregated model of the entire IBR plant. Let us for now consider the simplest case, which is a plant with only one type of IBR unit (e.g., one type of PV inverter from a single OEM). Then, an aggregate model is developed as shown below in Figure 18. The IBR unit and generator step-up transformer are aggregated models (i.e., MVA base = number of units × MVA base of individual unit), the equivalent feeder model is developed typically using the NREL approach [7], or other appropriate approaches [8].

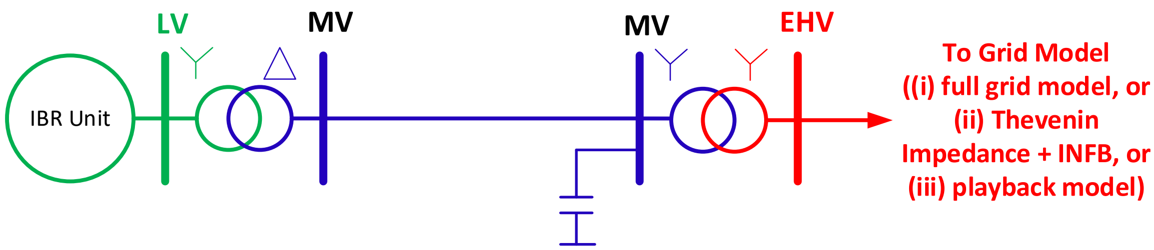


Figure 19. Aggregated IBR plant model.

1. The aggregate IBR plant model must then be verified to match the actual equipment and the control systems configuration—if still in the design phase, this could be done during the design evaluation verification step; if the plant has been constructed in the field, this could be done during the as-built evaluation verification step. At this point, the IBR plant model is considered "verified," but not yet "validated" because no comparison has been done between measurements and simulation for the entire plant model.
2. A series of tests are subsequently performed in the field on the entire plant, such as voltage reference step tests on the PPC and frequency reference step tests, to validate the entire plant level model in terms of the total plant volt/var response and frequency response. See references [6] and [9] for detailed examples.
3. With proper monitoring devices in place, over the operational life of the IBR plant, actual field performance and response of the plant can be observed, through on-line disturbance monitoring, and such data used to periodically revalidate the entire plant level model for both small and large-disturbances. Clearly, such revalidation is subject to the extent that significant events occur.

As and aside, we simply acknowledge that the interpretation of the phrase valid plant model is somewhat subjective. There are in broad terms two approaches to model validation at present. The North American approach, where the plant model is validated typically during commissioning tests (typically with voltage disturbances being small and in the range of a few percent, and emulated frequency disturbances being actually what might be considered as large, i.e., around 100 to 300 mHz), and then revalidated periodically through disturbance monitoring and/or additional field tests. The approach being adopted in some European regions where the plant model is compared to measured small disturbance response from field tests during commissioning (similar to the North-American approach), and then over a so-called mandatory trial-period compared to the actual field performance response of the plant for captured small and large[8] system disturbances. Only once both these actions are taken, then the model is declared as valid in the European approach. A through discussion on this subject, and the pros and cons of the two approaches is outside of the scope of this document.

Above said it should be thus clearly understood that the objectives of model validation and model quality testing are complementary but quite different. In fact, most typically model quality testing will be done only after model validation and is done by transmission planners, while model validation is most commonly done by the IBR plant owner/operator and IBR unit OEM. For example, after IBR unit type testing and model validation by the OEM, the model may be handed off to transmission planners or developers for their use in performing system or interconnection studies. Thus at this point, the model might be subjected to model quality testing as described in the previous section to ensure the model is of sufficient quality to move onto the next step. Similarly, after the complete plant model is developed, parameterized, verified, and validated, and then submitted to the transmission planners, again model quality testing as described in this report should be performed to ensure the models behave well and are of sufficient quality to incorporate into the planning or interconnection study cases.[9]

Also, model quality testing is not to be confused, or co-mingled, with plant performance testing and verification with prescribed technical requirements (e.g., conformity assessment for IEEE 2800 [10]) of a plant. That is, for example, once a validated model is received from an entity, the planners will want to perform a model quality test. After performing the model quality test, the next step might be to take that model into their planning or interconnection study cases to test and verify the conformity of the plant's performance to their regional performance standards (e.g., IEEE Std 2800™-2022). Although IBR plant models of good quality and validity could be used for pre-commissioning plant-level performance verification during conformity assessment by responsible entities, these two activities are quite separate and should be done separately. If one tried to do too many things at once, there is the potential for confusing results causing unnecessary delays in adopting a model.

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[8] In many cases, depending on the system, large disturbances may not occur during the mandatory trial period and so in the end all comparisons may be to what is deemed as small disturbances. Note: in the context of this discussion small disturbances would be in the range of say 1 to 5% change in voltage, while large disturbances would be in the range of say 20 to 90% change in voltage, i.e., a close in multi-phase fault. For frequency disturbances, this depends very much on the system. For example, in the Eastern Interconnection anything greater than say 100 mHz is an extremely large frequency disturbance, while in a small islanded system a large disturbance might be a 500 mHz change in frequency.

[9] A discussion of who would be responsible for carrying out the model quality tests (MQT) is outside the scope of this report and could depend on the context for what the model is used, e.g.:

- For IBR plant design, the MQT may be performed by the IBR plant developer or their consultant.
- For IBR plant design evaluation, the MQT may be performed by the transmission planner, their consultant, or a third party
- For interconnection studies, the MQT may be performed by the transmission planner.

As an example, consider the test case from section 3 (Figure 2). Let us repeat Test 3, but this time starting with a power flow solution where the plant is initialized such that the aggregated PV generator is at its maximum reactive output (Qmax). The results we get is shown in Figure 19. Such model quality tests are often done in large batches, looking at numerous models being submitted from multiple plants. Thus, the engineer reviewing the results may be quickly reviewing plots looking for patterns of behavior. Under such conditions, the immediate reaction to seeing Figure 19 might be to say, “why is the plant not increasing reactive power when the voltage steps down at 45 seconds?”. Thus, the model might be rejected and put aside to be further investigated. Clearly, once a closer look is taken it should become evident that since the initial condition of the power flow is such that the aggregated PV inverter is at its Qmax, then at 5 seconds when the voltage is forced up, the plant correctly responds to decrease Q and try to pull the voltage down. However, once the voltage is brought back up to its initial condition, the reactive output of the aggregated PV inverter returns to its Qmax. Now when voltage is forced down at 45 seconds, the inverters have no room to increase Q and so there is no change in Q, and no attempt to raise voltage. The point here is that model quality testing should be simple and focused on setting up a neutral condition to try to quickly and simply ensure that the model is of sufficient quality, in order to avoid unnecessary delays in the model being moved to the next step of design evaluation or system studies. This is only one simple example, but many other similar confusions can occur if the quality testing is not kept simple and focused.

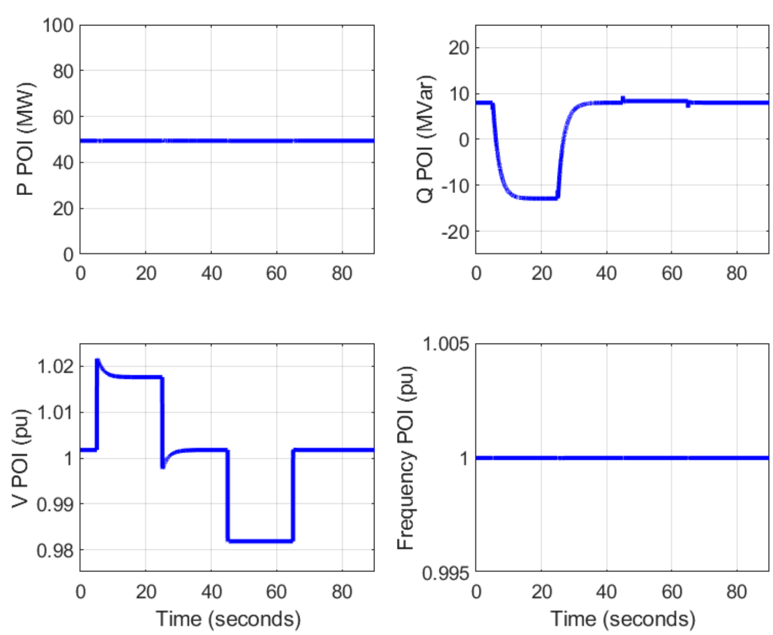


Figure 20. Test 3 – force step up and down in the voltage of the infinite bus, while the plant is initially at Qmax.

On occasion a utility, consultant, or other entity performing simulation studies may need to use a model of a power plant across multiple software platforms for various reasons. This may including going across different positive-sequence (fundamental-frequency) simulation platforms, or across two different simulation environments (e.g., positive-sequence versus EMT). Thus, the model quality testing may need to be done on all the various software platforms. Here an extra step of caution should be taken. Initially, there may be an expectation that the model quality tests across two (or more) software platforms should yield identical results. This is not necessarily always true. There are many practical considerations to be had, namely:

1. Different software platforms will have significantly different means of solving the network equations at the network interface of a dynamic model. Thus, any simulations (e.g., faults, large voltage changes, etc.) that are heavily influenced by the network solution and network convergence may result in different simulation results across multiple simulation platforms for the exact same model, where generic, user-written or real-code based control models.
2. Going across simulation domains (i.e., comparing positive-sequence simulations and EMT simulations) much care must be taken to realize the various aspects that may yield significant differences in results, namely:
    a. Only positive sequence simulations results should be compared[10].
    b. Only balanced events should be simulated.
    c. Consideration should be given to the fact that higher frequency phenomena in the EMT domain may need to be filtered out of the simulation results as they cannot be simulated in positive-sequence.
    d. The much shorter integration steps in EMT, as compared to the significantly larger integration steps in positive-sequence tools can also yield significant differences.
    e. The importance of ensuring that the network (i.e., collector system, transformers, grid equivalent model, etc.) components are also consistently modeled across the platforms to be reasonably similar. The network components models in EMT can be quite more complex and so may result in some differences in simulation results across simulation domains.

To simply illustrate some of these issues, consider the two simulations in Figure 20 and Figure 21. In these two simulations the exact same illustrative PV plant model (Appendix A) is simulated in Siemens PTI PSS®E and GE PSLF™. The models and model parameters are identical, and as can be seen the initial power flow solutions are also identical. In Figure 20 the same 3-phase to ground fault is simulated at the POI of the plant. The results look almost identical, except for the frequency at the POI. Now for our assumed model here the plant frequency relays trip if frequency goes below 57 Hz for more than 200 ms. Thus, for both simulation

[10] This is because if one runs an unbalance event in an EMT tool, this will not be conducive to a direct comparison to a simulation in a positive-sequence fundamental-frequency simulation tool.

platforms the model does not trip, since the frequency at the terminals of the aggregated PV inverter does not stay below 57 Hz for too long. However, if the actual frequency protection was set to trip the inverters if frequency dipped below 57 Hz more or less instantaneously, then in GE PSLF$^{TM}$ (and possibly even the other tool) the plant would trip. This, however, is a false trip because the actual frequency does not change. This observed change in the simulation tool is a function of how frequency is calculated in positive-sequence tools (see: https://www.wecc.org/Reliability/WECC_White_Paper_Frequency_062618_Clean_Final.pdf). Thus, care must be taken to review such results to ensure any trips are realistic and if not, then the frequency relays should be either placed in an alarm only mode or disabled.

In the second example, Figure 21, notice how there is a slight difference in the Q response of the plant at the POI despite the fact that the models, and model parameters, are identical and played-back voltage is also as identical as possible. None-the-less, there is a slight and noticeable difference in the Q response because the voltages at the POI are slightly different between the two software programs just because of the way the playback functions were implemented. Thus, one must either (i) accept the different results, or (ii) continue to iteratively tweak the playback voltage functions to the extent possible to make the voltage at the POI in both programs match as closely as possible. These are intricacies and realities of different software tools. Note also, as has been seen many times in the past, for both generic and user-written models, these small differences in voltage and network solution can sometimes give rise to significant differences in model behavior across software platforms even when the models and their parameters are identical. This is because if a protection or limiter action takes effect around a given voltage threshold, it might be set off in one software platform and not the other since the network solutions in each tool may come to a converged solution ever so slightly on opposite sides of the threshold, given numerical precision bounds applicable in each software. For example, consider Figure 22. In this example we repeated the simulation of a sudden high-voltage step, but in both tools, stepped the voltage at the POI to a transient overvoltage of 1.26 pu[11]. Now one can see that in one tool the voltage at the terminals of the inverter model goes ever so slightly above 1.2 pu, which causes the PV inverter to trip based on it high-voltage protection settings . While in the other software tool the network solution at the POI is such that the terminal voltage of the inverter does not quite reach 1.2 pu (reaches 1.1966 pu) and thus the PV inverter does not trip. The models, all data and the playback functions are identical. The difference is due to the network solution being different in the third decimal place. This is quite reasonable. So one must accept this difference or simply tweak in the playback voltage in one of the tools to force the voltage at the terminals of the inverter to converge to the exact same value to the extent possible to see the same result.

In summary, these examples here may seem trivial, however when model quality tests are done in large volumes often engineers are trying to require hundreds of results in quick order and so may not have the luxury of looking into such minutia and thus small issues such as exemplified

[11] Honestly, such transient overvoltage scenarios (even to 1.15 pu) are in our opinion somewhat inappropriate in positive-sequence programs since the network is a lumped constant impedance matrix. However, many utilities presently perform such simulations thus we are discussing them here.

here may throw perfectly good models into the "bad-quality" bucket to come back to later and spend more time to try to figure out the issues. This then causes delays in the whole process and can quickly cause bottlenecks in the queue of system or interconnection studies process. Thus, some initial forethought in the model quality testing process to avoid such issues may in the long run save considerable time.

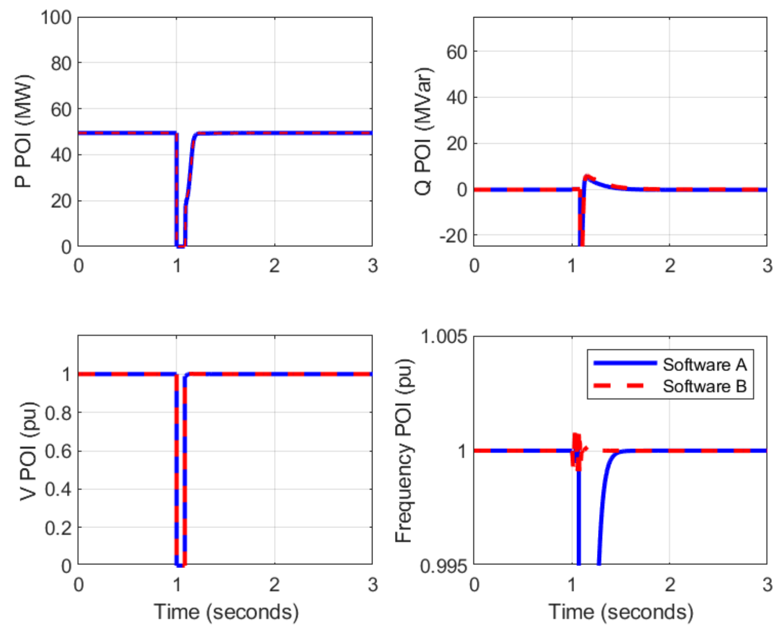


Figure 21. Normally cleared 3-phase fault at the POI.

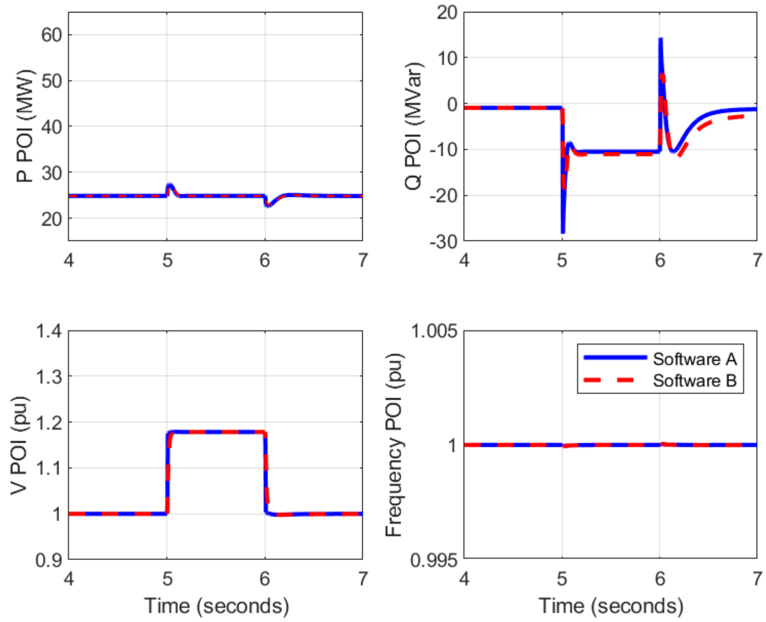


Figure 22. Playback of a large over-voltage step (sudden increase of voltage at the POI to 1.18 pu for 1 second) at the POI.

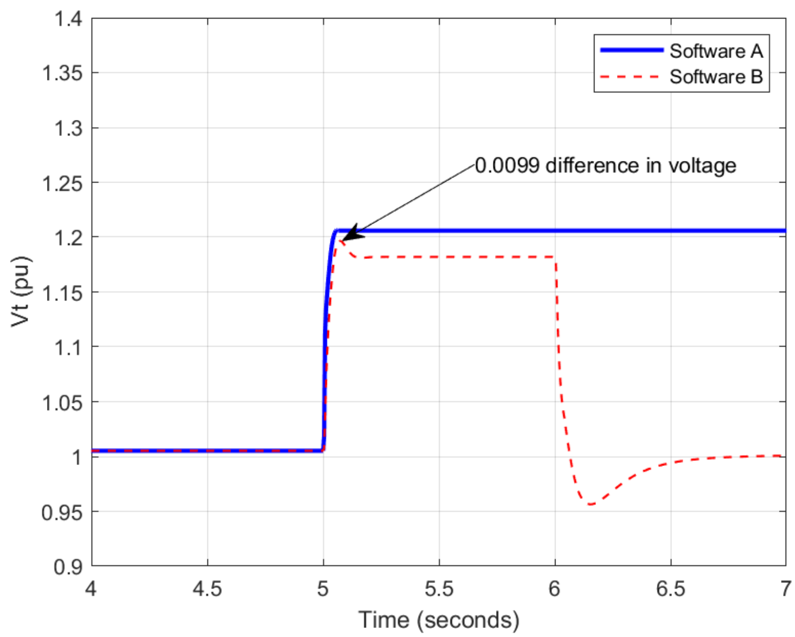


Figure 23. Playback of a large over-voltage step (sudden increase of voltage at the POI to 1.26 pu for 1 second) at the POI.

# 5 SUMMARY AND RECOMMENDATIONS

With the ever expanding portfolios of renewable energy systems worldwide, the is a steady influx of inverter-based resources coming into power systems. The vast majority of these renewable resources are wind and solar-photovoltaic (PV) power plants. All such resources are connected to the bulk power system through power-electronic converters and thus referred to commonly as inverter-based resources (IBRs). In the context of this continued large influx of IBRs into the bulk electric power systems around the world, many utilities, and independent system operators (ISOs), have struggled with the quality of the dynamic simulation models that are often submitted by power plant owner/operators for the purposes of planning studies performed by utilities. Whether these models are of a generic (standard library models in simulation tools) or vendors specific user-written black-box type, they still may be subject to such concerns of model quality. Moreover, the same is true whether the models are used in commercially available positive-sequence phasor-domain software tools, or electromagnetic transient simulation (EMT) tools. Many utilities, and ISOs, have thus developed their own so-called model quality tests to screen models that are submitted to them to try to catch such potential issues upfront and to thus work with the power plant owner/operators to try to resolve such issues prior to incorporating the models into their planning process.

In this report an example aggregated IBR plant model was developed and the procedures for model quality testing (MQT) demonstrated, at least one such approach and using the example case. Through this demonstration, and additional discussion and examples, it has been illustrated that:

1. MQT is a process that is distinct from model validation or performance requirements assessment of a plant through design evaluation and simulation.
2. MQT should be performed at different steps of the development of an IBR platn, and likely by different entities.
3. The running of the MQT scenarios is typically automated to the extent possible, however, some engineering judgement is required to understand the results.
4. MQT should be done for models of IBR units, supplemental IBR devices, and IBR plants, and should be performed on all types of models (i.e., generic and user-defined) and modeling tools (i.e., positive-sequence fundamental-frequency models and EMT models).

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# A EXAMPLE CASE DYNAMICS AND POWER FLOW DATA

The dynamic model data for the example case used in this report is as follows:

```
/* Generic Test Case - Does not pertain to any vendor or specific plant              */
/*                                                                                   */
/* DEVELOPED BY: P. Pourbeik, PEACE(R)                                               */
/*                                                                                   */
/* VERSION: 1.0              */
/*             */
/* DATE: 1/26/23                                                        */
/*              */
/* LAST REVISED BY:                 */
/*             */
/* LAST REVISED DATE:                */
/*             */
/* COMMENTS ON LAST REVISION:                                                        */
/*             */
/* DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES               */
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/*      USE OF THIS SOFTWARE OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR  */
/*      ITEM DISCLOSED IN THIS SOFTWARE AND ASSOCIATED DOCUMENTATION.                    */
/* ORGANIZATION THAT PREPARED THIS DOCUMENT/SOFTWARE:                                    */
/* Power and Energy, Analysis, Consulting and Education, PLLC (PEACE)                   */
/*                                                                                      */


/9999 'USRMDL'  1   'PLBVFU1'    1   1   3   4   3   6
/1    1     'VF'
/        1 1 0.01 0.01
9999 'GENCLS' 1     100.0000       0.0000    /

/ Generic PV Plant
/
/ Generator/Converter Model
/
100 'USRMDL' '1' 'REGCBU1' 101 1 2 7 5 8
 0 0
 0.01 0.008 999 -999 10 0.008 1.1
/
/ Electrical Control Model
/
100 'USRMDL' '1' 'REECDU1' 102 0 6 77 7 20
 0 0 0 0 0 0
 0.9000 1.1000 0.0080 -0.100 0.1000  4.0000 1.0000 -1.0000 0.0000 0.0000
 0.0000 0.0000 0.0200 0.3287 -0.3287 1.1000 0.9000 0.0000 1.0000 0.000
 1.0000 0.0000 0.0100 0.5000 -0.500  1.0000 0.0000 1.1000 0.0100
 0.1000 1.0000 0.2000 1.0000 0.3000  1.0000 0.4000 1.0000 0.5000 1.0000
 0.6000 1.0000 0.7000 1.0000 0.8000  1.0000 0.9000 1.0000 1.5000 1.0000
 0.1000 1.0000 0.2000 1.0000 0.3000  1.0000 0.4000 1.0000 0.5000 1.0000
 0.6000 1.0000 0.7000 1.0000 0.8000  1.0000 0.9000 1.0000 1.5000 1.0000
 0.0000 0.0000 0.0100 0.0000 0.0000  0.0500 1.200 0.0500
/
/ Plant Controller Model
```

```
/
100 'REPCA1', 1, 1001 1001 9999 '1' 0 1 1
 0.00800 2.0000 10.000 0.0000 0.1500 0.8500 0.0000 0.0000 0.0400 1.0000
 -1.0000 0.0000 0.0000 0.32870 -0.32870 0.000 1.000 0.0200 -0.0006 0.0006
 99.000 -99.000 1.0000 0.0000 0.0200 20.0000 20.0000
/
/*********************************************************************************
/ HIGH/LOW VOLTAGE PROTECTION
/              BUS where voltage is monitored 1
/                   Bus where generator is located 1
/                        ID of generator 1
10  'VTGDCAT'  100  100  1  0.890 99.00 5.00 0.01 /
11  'VTGDCAT'  100  100  1  0.500 99.00 0.30 0.01 /
12  'VTGDCAT'  100  100  1  0.050 99.00 0.15 0.01 /
13  'VTGDCAT'  100  100  1  0.000 1.100 1.00 0.01 /
14  'VTGDCAT'  100  100  1  0.000 1.200 0.02 0.01 /
/*********************************************************************************
/ HIGH/LOW FREQUENCY PROTECTION
/              BUS where voltage is monitored 1
/                   Bus where generator is located 1
/                       ID of generator 1
16  'FRQDCAT'  100  100 1  57.00 63.0 0.200 0.01 /
/*********************************************************************************
/
```

The power flow data is as follows:

```
@!IC, SBASE,REV,XFRRAT,NXFRAT,BASFRQ
0,   100.00, 34,     0,     1, 60.00     / PSS(R)E 34 RAW created by rawd34  THU, FEB 23 2023
10:41
TEST CASE

GENERAL, THRSHZ=0.0001, PQBRAK=0.1, BLOWUP=5.0
GAUSS, ITMX=100, ACCP=1.6, ACCQ=1.6, ACCM=1.0, TOL=0.0001
NEWTON, ITMXN=20, ACCN=1.0, TOLN=0.1, VCTOLQ=0.1, VCTOLV=0.00001, DVLIM=0.99, NDVFCT=0.99
ADJUST, ADJTHR=0.005, ACCTAP=1.0, TAPLIM=0.05, SWVBND=100.0, MXTPSS=99, MXSWIM=10
TYSL, ITMXTY=20, ACCTY=1.0, TOLTY=0.00001
SOLVER, FNSL, ACTAPS=0, AREAIN=0, PHSHFT=0, DCTAPS=1, SWSHNT=1, FLATST=0, VARLIM=99, NONDIV=0
RATING, 1, "RATE1 ", "RATING SET 1                     "
RATING, 2, "RATE2 ", "RATING SET 2                     "
RATING, 3, "RATE3 ", "RATING SET 3                     "
RATING, 4, "RATE4 ", "RATING SET 4                     "
RATING, 5, "RATE5 ", "RATING SET 5                     "
RATING, 6, "RATE6 ", "RATING SET 6                     "
RATING, 7, "RATE7 ", "RATING SET 7                     "
RATING, 8, "RATE8 ", "RATING SET 8                     "
RATING, 9, "RATE9 ", "RATING SET 9                     "
RATING,10, "RATE10", "RATING SET 10                    "
RATING,11, "RATE11", "RATING SET 11                    "
RATING,12, "RATE12", "RATING SET 12                    "
0 / END OF SYSTEM-WIDE DATA, BEGIN BUS DATA
@!   I,'NAME        ', BASKV, IDE,AREA,ZONE,OWNER, VM,        VA,    NVHI,   NVLO,   EVHI,   EVLO
   100,'GEN         ',   0.6900,2,   1,   1,   1,1.03052, -
17.6121,1.10000,0.90000,1.10000,0.90000
   101,'BUS1        ',  34.5000,1,   1,   1,   1,1.01739,
9.3150,1.10000,0.90000,1.10000,0.90000
   102,'BUS2        ',  34.5000,1,   1,   1,   1,1.01432,
9.0569,1.10000,0.90000,1.10000,0.90000
  1001,'POI         ', 345.0000,1,   1,   1,   1,1.00000,
0.5664,1.10000,0.90000,1.10000,0.90000
  9999,'INFB        ', 345.0000,3,   1,   1,   1,0.99990,
0.0000,1.10000,0.90000,1.10000,0.90000
0 / END OF BUS DATA, BEGIN LOAD DATA
@!   I,'ID',STAT,AREA,ZONE,      PL,        QL,        IP,        IQ,        YP,        YQ,
OWNER,SCALE,INTRPT,  DGENP,     DGENQ, DGENF
0 / END OF LOAD DATA, BEGIN FIXED SHUNT DATA
@!   I,'ID',STATUS,   GL,        BL
```

```
0 / END OF FIXED SHUNT DATA, BEGIN GENERATOR DATA
@!   I,'ID',      PG,        QG,        QT,         QB,      VS,    IREG,     MBASE,     ZR,
ZX,         RT,         XT,     GTAP,STAT, RMPCT,       PT,         PB,    O1,    F1,  O2,    F2,
O3,    F3,  O4,    F4,WMOD, WPF,NREG
   100,'1 ',    50.000,     8.085,    16.430,   -16.430,1.00000,  1001,    52.630, 0.00000E+0,
1.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0,    50.000,     0.000,   1,1.0000,   0,
1.0,   0,   1.0,   0,   1.0,1, 1.0000
  9999,'1 ',   -49.418,    -1.256,  9999.000, -9999.000,0.99990,  9999,100000.000, 0.00000E+0,
1.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0,  9999.000, -9999.000,   1,1.0000
0 / END OF GENERATOR DATA, BEGIN BRANCH DATA
@!   I,     J,'CKT',     R,           X,          B,                    'N A M E'                 ,
RATE1,    RATE2,    RATE3,    RATE4,    RATE5,    RATE6,    RATE7,    RATE8,    RATE9,   RATE10,
RATE11,   RATE12,    GI,       BI,       GJ,       BJ,STAT,MET,  LEN,  O1,  F1,    O2,  F2,
O3,  F3,    O4,  F4
   101,   102,'1 ', 5.00000E-3, 1.00000E-2,   0.02000,'                                        ',
60.00,    60.00,    60.00,     0.00,     0.00,     0.00,     0.00,     0.00,     0.00,     0.00,
0.00,     0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  1001,  9999,'1 ', 0.00000E+0, 2.00000E-2,   0.02000,'                                        ',
1000.00,  1000.00,  1000.00,     0.00,     0.00,     0.00,     0.00,     0.00,     0.00,
0.00,     0.00,     0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
0 / END OF BRANCH DATA, BEGIN SYSTEM SWITCHING DEVICE DATA
@!   I,     J,'CKT',          X,   RATE1,   RATE2,   RATE3,   RATE4,   RATE5,   RATE6,   RATE7,
RATE8,   RATE9,  RATE10,  RATE11,  RATE12,  STAT,NSTAT,  MET,STYPE,'NAME'
0 / END OF SYSTEM SWITCHING DEVICE DATA, BEGIN TRANSFORMER DATA
@!   I,     J,     K,'CKT',CW,CZ,CM,     MAG1,        MAG2,NMETR,               'N A M E',
STAT,O1,  F1,    O2,  F2,    O3,  F3,    O4,  F4,     'VECGRP', ZCOD
@!   R1-2,       X1-2,   SBASE1-2,     R2-3,       X2-3,   SBASE2-3,     R3-1,       X3-1,
SBASE3-1, VMSTAR,   ANSTAR
@!WINDV1,  NOMV1,    ANG1,  RATE1-1,  RATE1-2,  RATE1-3,  RATE1-4,  RATE1-5,  RATE1-6,  RATE1-7,
RATE1-8,  RATE1-9, RATE1-10, RATE1-11, RATE1-12,COD1,CONT1,   RMA1,    RMI1,    VMA1,    VMI1,
NTP1,TAB1,  CR1,     CX1,   CNXA1,NOD1
@!WINDV2,  NOMV2,    ANG2,  RATE2-1,  RATE2-2,  RATE2-3,  RATE2-4,  RATE2-5,  RATE2-6,  RATE2-7,
RATE2-8,  RATE2-9, RATE2-10, RATE2-11, RATE2-12,COD2,CONT2,   RMA2,    RMI2,    VMA2,    VMI2,
NTP2,TAB2,  CR2,     CX2,   CNXA2,NOD2
@!WINDV3,  NOMV3,    ANG3,  RATE3-1,  RATE3-2,  RATE3-3,  RATE3-4,  RATE3-5,  RATE3-6,  RATE3-7,
RATE3-8,  RATE3-9, RATE3-10, RATE3-11, RATE3-12,COD3,CONT3,   RMA3,    RMI3,    VMA3,    VMI3,
NTP3,TAB3,  CR3,     CX3,   CNXA3,NOD3
   101,   100,     0,'1 ', 1, 2, 2, 0.00000E+00, 0.00000E+00,1,'
',1,   1,1.0000,   0,1.0000,   0,1.0000,   0,1.0000,'Dyn1        '
 6.00000E-3, 6.00000E-2,    52.50
1.00000,  34.500,  30.000,     52.50,     52.50,     52.50,     0.00,     0.00,     0.00,     0.00,
0.00,     0.00,     0.00,     0.00,     0.00, 0,      0, 1.05000, 0.95000, 1.10000, 0.90000,   5,
0, 0.00000, 0.00000,   0.000,   0
1.00000,   0.690
   102,  1001,     0,'1 ', 1, 2, 2, 0.00000E+00, 0.00000E+00,2,'
',1,   1,1.0000,   0,1.0000,   0,1.0000,   0,1.0000,'Yy0         '
 2.50000E-3, 1.00000E-1,    33.00
1.00000,  34.500,   0.000,     55.00,     55.00,     55.00,     0.00,     0.00,     0.00,     0.00,
0.00,     0.00,     0.00,     0.00,     0.00, 0,      0, 1.05000, 0.95000, 1.10000, 0.90000,   5,
0, 0.00000, 0.00000,   0.000,   0
1.00000, 345.000
0 / END OF TRANSFORMER DATA, BEGIN AREA DATA
@! I,   ISW,     PDES,      PTOL,    'ARNAME'
   1,     0,     0.000,     5.000,'AREA    1   '
0 / END OF AREA DATA, BEGIN TWO-TERMINAL DC DATA
@!  'NAME',   MDC,      RDC,      SETVL,     VSCHD,      VCMOD,      RCOMP,    DELTI,METER
DCVMIN,CCCITMX, CCCACC
@! IPR,NBR,ANMXR,ANMNR,   RCR,    XCR,  EBASR,  TRR,    TAPR,   TMXR,   TMNR,   STPR,    ICR,
IFR,   ITR,'IDR', XCAPR,NDR
@! IPI,NBI,ANMXI,ANMNI,   RCI,    XCI,  EBASI,  TRI,    TAPI,   TMXI,   TMNI,   STPI,    ICI,
IFI,   ITI,'IDI', XCAPI,NDI
0 / END OF TWO-TERMINAL DC DATA, BEGIN VSC DC LINE DATA
@!  'NAME',   MDC,     RDC,   O1,  F1,    O2,  F2,    O3,  F3,    O4,  F4
@!IBUS,TYPE,MODE,     DCSET,   ACSET,     ALOSS,     BLOSS,   MINLOSS,     SMAX,      IMAX,
PWF,        MAXQ,       MINQ, VSREG,  RMPCT,NREG
0 / END OF VSC DC LINE DATA, BEGIN IMPEDANCE CORRECTION DATA
@!I,   T1,    Re(F1),  Im(F1),    T2,    Re(F2),  Im(F2),    T3,    Re(F3),  Im(F3),    T4,
Re(F4),  Im(F4),    T5,    Re(F5),  Im(F5),    T6,    Re(F6),  Im(F6)
@!     T7,    Re(F7),  Im(F7),    T8,    Re(F8),  Im(F8),    T9,    Re(F9),  Im(F9),    T10,
Re(F10), Im(F10),    T11,  Re(F11), Im(F11),    T12,  Re(F12), Im(F12)
@!      ...
```

```
0 / END OF IMPEDANCE CORRECTION DATA, BEGIN MULTI-TERMINAL DC DATA
@!  'NAME',    NCONV,NDCBS,NDCLN,  MDC, VCONV,     VCMOD, VCONVN
@!  IB, N,ANGMX,ANGMN,    RC,      XC,    EBAS,   TR,    TAP,    TPMX,   TPMN,   TSTP,     SETVL,
DCPF,    MARG,CNVCOD
@!IDC, IB,AREA,ZONE,   'DCNAME',  IDC2,   RGRND,OWNER
@!IDC,JDC,'DCCKT',MET,   RDC,        LDC
0 / END OF MULTI-TERMINAL DC DATA, BEGIN MULTI-SECTION LINE DATA
@!   I,     J,'ID',MET,DUM1,  DUM2,  DUM3,  DUM4,  DUM5,  DUM6,  DUM7,  DUM8,  DUM9
0 / END OF MULTI-SECTION LINE DATA, BEGIN ZONE DATA
@! I,   'ZONAME'
   1,'ZONE-001    '
0 / END OF ZONE DATA, BEGIN INTER-AREA TRANSFER DATA
@!ARFROM,ARTO,'TRID', PTRAN
0 / END OF INTER-AREA TRANSFER DATA, BEGIN OWNER DATA
@! I,   'OWNAME'
   1,'OWNER1      '
0 / END OF OWNER DATA, BEGIN FACTS DEVICE DATA
@!  'NAME',         I,     J,MODE,   PDES,      QDES,  VSET,      SHMX,      TRMX,   VTMN,
VTMX,   VSMX,      IMX,     LINX,   RMPCT,OWNER,    SET1,      SET2,VSREF, FCREG,   'MNAME'
,NREG
0 / END OF FACTS DEVICE DATA, BEGIN SWITCHED SHUNT DATA
@!  I,MODSW,ADJM,ST, VSWHI,  VSWLO, SWREG,  RMPCT,   'RMIDNT',      BINIT,N1,     B1, N2,     B2,
N3,     B3, N4,     B4, N5,     B5, N6,     B6, N7,     B7, N8,     B8, NREG
0 / END OF SWITCHED SHUNT DATA, BEGIN GNE DATA
@!  'NAME',        'MODEL',     NTERM,BUS1...BUSNTERM,NREAL,NINTG,NCHAR
@!ST,OWNER,NMETR
@! REAL1...REAL(MIN(10,NREAL))
@! INTG1...INTG(MIN(10,NINTG))
@! CHAR1...CHAR(MIN(10,NCHAR))
0 / END OF GNE DATA, BEGIN INDUCTION MACHINE DATA
@!   I,'ID',ST,SC,DC,AREA,ZONE,OWNER,TC,BC,  MBASE, RATEKV,PC,  PSET,      H,       A,       B,
D,       E,     RA,        XA,        XM,        R1,        X1,        R2,        X2,        X3,
E1,    SE1,   E2,    SE2,   IA1,   IA2, XAMULT
0 / END OF INDUCTION MACHINE DATA, BEGIN SUBSTATION DATA
0 / END OF SUBSTATION DATA
```

**Program:**

Bulk System Integration of Renewables and Distributed Energy Resources

3002027506



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