Validation of solar power plant dynamic model using commissioning test measurements

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***Abstract* — Dynamic RMS model validation against commissioning test measurements of any newly installed or upgraded generating system is required in the National Electricity Market (NEM) of Australia. Many variable renewable energy plants, particularly PV solar, have been commissioned recently in Australia and much experience has been gained through the model validation process.**

Typical compliance tests include assessments of the power plant voltage control (fixed reactive power / voltage / voltage-droop / power factor), active power dispatch control and frequency control. The tests used for demonstrating compliance of the solar farm (or wind park) against the technical performance requirements set out in the Generator Performance Standards (GPS) can be used for model validation purpose.

This paper describes the process of validating the dynamic RMS models by comparing the simulated responses against actual plant responses and AEMO's model accuracy requirements. A few challenges from the model validation process, including impacts of reduced number of inverters, frequency disturbance simulation method, solar irradiance and low PPC meter sampling rate, are discussed. Some example model overlay plots are presented for illustration.

Keywords-photovoltaic, solar farm, dynamic RMS model, validation

I. INTRODUCTION

The National Electricity Market (NEM) interconnects five states along the South and East Coast of Australia – Queensland, New South Wales (including the Australian Capital Territory), Victoria, South Australia and Tasmania. The NEM incorporates around 40,000 km of transmission lines and cables [1]. It has a total electricity generating capacity, including rooftop solar PV, of almost 54 GW (as at December 2017) [1].

Due to the abundance of renewable resources, Australia has attracted a significant interest in solar and wind energy generation. At the time of writing, the NEM had:

- Wind generation increased by 26.0% in 2018, and this is equivalent to 3,009 GWh [2]
- Utility-scale solar generation increased by 198.3% in 2018, and this is equivalent to 1,463 GWh [2]
- Thirty utility-scale metered renewable generators were commissioned in 2018, including twenty one utility-scale solar power stations [2]
- There are 2.2 GW of committed solar projects and 24.6 GW of proposed solar projects [3].

To connect a plant into the NEM, the proponent must liaise with the connecting Network Service Provider (NSP) and the Australian Energy Market Operator (AEMO). The connection process can be divided into four main stages, i.e. Pre-feasibility, Enquiry, Application and Completion. These include negotiation of performance standards to be met by the generator based on the National Electricity Rules (NER).

Once the plant is registered in the Completion (Final) stage, the plant owner is allowed to commence commissioning. On top of the typical commissioning activities, the plant owner is also required to confirm the plant's compliance with the agreed technical performance requirements set out in the GPS and to provide accurate dynamic Root Mean Square (RMS) models that resemble the plant's physical responses. A successful commissioning will lead to:

- Approval for unrestricted commercial operation of the plant
- Validated dynamic RMS models and parameters

According to the connection process map published by AEMO [4], the indicated timeframe for the final stage could vary from 2 months to 2 years. Based on the authors' solar farm commissioning experience, some factors that could affect the timeframe are:

- The assessment requirements from the NSP and AEMO during the pre-commissioning and commissioning process, which could vary depending on the location of the connecting plant;
- The robustness and functionality of the encrypted plant dynamic models provided by the original equipment manufacturer (OEM);
- The solar farm design and whether it includes additional dynamic reactive power support devices (such as a STATCOM or synchronous condenser); and

- The availability of energy source during the commissioning tests.

The authors have been involved in solar farm electrical system design and performance standard compliance tests in Australia. More than 1GW of solar farms have been successfully designed and commissioned during 2017-2019. The objective of this paper is to present some experience in solar farm commissioning and the dynamic RMS model validation area.

The structure of this paper is as follows:

- Section II provides some background information of the pre-commissioning and commissioning process in the NEM, including a high-level description of typical dynamic RMS models used in representation of a solar farm.
- Section III describes the different types of commissioning tests involved in validating the dynamic RMS models.
- Section IV compares the model dynamic responses against measurements from commissioning tests, describes the simulation overlay process and highlights the model accuracy requirements specified by AEMO.
- Section V and VI discuss the challenges faced during the dynamic RMS model validation process.

II. BACKGROUND

A. Pre-commissioning and commissioning process in the NEM

Several key activities occurring before and during plant commissioning are presented as follows:

1. **Commissioning program:** AEMO requires the submission of a commissioning test program (otherwise referred to as the test plan) three months before commissioning. The program should specify the type of dynamic response tests to be performed and the test schedule. A load profile must also accompany the test plan that schedules the amount of active and reactive power to be generated for each test for every day of the test campaign. This can be given in intervals as small as 5 minutes.

2. **Pre-test simulations:** Pre-test simulation studies are performed in RMS software platforms using the design (R1) models and parameters. The purpose of the pre-test simulations is to ensure that the extent of changes applied to reactive power and voltage at the point of connection will not adversely impact the network to which the plant is connected.

3. **Hold point testing:** When commissioning a new plant for the first time (or plant alteration), a number of Hold Points are generally required whereby the generating system overall output is constrained to a number of pre-defined megawatt (MW) levels. At each Hold Point, a report and the test data are required to be submitted to AEMO and NSP for review and approval, before progressing further with the commissioning activities. This process allows for staged release of capacity subject to:
    - Demonstration that the operation of the plant does not pose security risk to the system;
    - Successful demonstration of applicable GPS clauses; and
    - Comparison of simulated model responses against measured responses for all tests specified in the commissioning program.

B. Solar inverter model

As photovoltaic (PV) solar panels output Direct Current (DC), solar farms which connects to the electricity grid need to convert the electricity generated by the PV panels into Alternating Current (AC). The DC/AC conversion is performed by grid-tie solar inverters. The most commonly installed solar inverters for utility-scale solar farms in the NEM are central inverters. The commonly used inverter size varies from 1.5 MW to 3 MW, however market trends will continue to follow OEM developments in this regard.

For dynamic simulations, a detailed collector system model is not required because the dynamic response can be represented using a lumped equivalent model with reasonable accuracy. This has the benefit of increasing the simulation speed and easily allowing adjustments to the inverter control system.

Typically, dynamic RMS inverter model consists of the following components:

- Active and reactive current controller
- Fault ride through (FRT) grid support
- Inverter protection
- Phase Locked Loop (PLL)

The inverter interface to grid model is commonly represented by a current source model as shown in Figure 1. The inverter model receives active and reactive current commands (or power commands) from plant level controller. It then calculates the active and reactive current reference from the commands and measured voltage.

In a large voltage disturbance event (or fault event), the FRT grid support feature of the inverter takes over from the plant level control and modifies the active and reactive current reference in response to the large voltage excursion. This FRT feature allows the inverter to remain connected to grid during the short periods of voltage excursion.

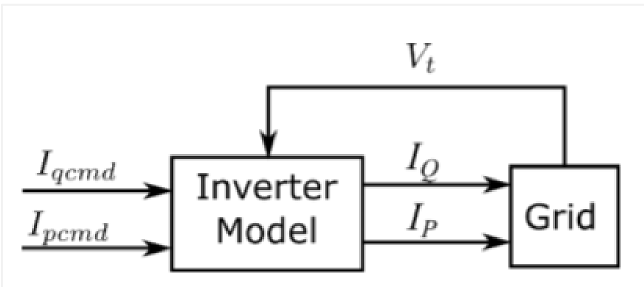

Figure 1: A generic inverter generator model [5]

The inverter model also consists of PLL which is used to define reference phase of the terminal voltage. Together with the measured voltage magnitude, the voltage angle between the inverter and the grid is used to control the active and reactive current injection into the grid. The phase information is crucial for the inverter control to respond correctly, especially when there is a fault event in the grid.

Voltage and frequency protections are also included in an inverter model. In case of over/under voltage or frequency conditions, the inverter will be tripped and disconnected from the grid. Normally the OEM's inverter model will allow different time delays for different voltage and frequency protection threshold levels.

C. *Power plant controller model*

A utility-scale solar farm is normally equipped with plant level controller(s), which is known as Power Plant Controller (PPC). PPC consists of two basic components: monitoring and control.

For generator connection into the NEM, the technical performance requirements are listed in the Schedule 5 of NER. The technical requirements are mainly specified at the Point of Connection (POC) of the generating plants. For monitoring, PPC takes the measurements of voltage, active power, reactive power and frequency at the POC which are provided by an integrated or an external dedicated measurement unit.

For control, the PPC must have at least the following functions to meet the NER technical requirements:

- Active power ramp regulation
- Frequency regulation
- Reactive power control
- Power factor control
- Voltage control
- Voltage droop control

While only some of the above control functions will be selected upon agreement with AEMO and NSP, the NER requires each function be tuned and proven to meet the technical requirements via simulations and on-site testing.

Some solar farms in the NEM have been required to regulate the voltage at a remote bus with a droop via the PPC, which measures reactive power at the POC. The purpose of this requirement is to avoid interaction with other voltage-controlled devices (e.g. transformer tap controller). As a result of this requirement, some of the OEMs had to modify their PPC control.

D. *Lumped equivalent collector network model*

The purpose of a lumped equivalent model of the solar farm collector system is to provide a simplified aggregate model that accurately represents the grid side response of the solar farm. A paper by National Renewable Energy Laboratory [6] describes a constant power aggregation method for equivalencing wind farm collector systems. This methodology is also applicable to a solar farm. The analysis assumes that the provided inverter dynamic model is a per unit model and its response would be valid when being used in a lumped representation. The lumped equivalent network model is typically used in the R2 model simulation.

III. VALIDATION METHODOLOGY

A. *Types of model validation test*

The NEM-connected generating plant owner is required to validate the design (R1) models using the measurements from commissioning tests. The purpose is to ensure that the models represent the installed system. Once approved by AEMO, the "R1" models will be classified as "R2" models.

The same measurement from the commissioning tests can be used to assess compliance of the generating plant against the technical performance requirements set out in the GPS. In general, there is a synergy between the tests required for GPS compliance assessment and R2 model validation.

Below is a list of the typical solar farm commissioning tests that are used for R2 model validation:

- Reactive power (or power factor) reference step test
- Voltage reference step test
- Active power reference step test
- Frequency control test
- External voltage disturbance test (e.g. capacitor switching test)
- Dynamic and steady state reactive power capability assessment

B. *Monitoring*

AEMO requires that several locations [7] are monitored during commissioning tests. These locations are:

1. POC or HV terminals of the step-up transformer
2. MV collector bus to which the feeders of the generating units are connected
3. The generating unit(s) which are electrically closest and furthest with respect to the MV grid
4. PPC
5. Each type of reactive support device that may be present

Given that multiple meters are likely to be required to monitor these locations, it is required that the meters are synchronised, and all recorded data has a timestamp which is recorded to a consistent time base (and format). The PV inverter responses can be very fast, therefore high speed monitoring is required to capture the dynamic response adequately (i.e. sampling rates over 10 kHz are recommended).

It is also important that the monitoring system used for gathering data for model validation is independent of the control system. This is to ensure that the RMS models can be accurately verified and validated by an independent source and not from its internal data logger.

C. *Model accuracy requirements*

AEMO has published Power System Model Guidelines (PSMG) [8] under the NER clause S5.5.7(a)(3). The PSMG [8] describes the model performance measures used to determine the model accuracy in terms of transient and settled responses. Accuracy bands are to be applied to the simulated RMS responses in the time domain. In general, the following performance measures are applied to the model validation:

1. **Transient response.** The measured transient response must be within the ±10% accuracy band calculated from the simulated response for 95% of the samples within transient window. For all plant control internal-quantities and terminal quantities for aggregated model, the accuracy requirement can be relaxed to 90%. This applies to the reference step tests and external disturbance tests (illustrated in Figure 2).

There are two definitions of transient windows defined in the PSMG [8], for controlled change and uncontrolled change. The definitions are presented in Figure 3 and Figure 4.

2. **Settled response.** The accuracy bands applied to the settled response is normally ±10% of the total change in quantity. The total quantity change is taken to be the final value of the model response minus the initial value of the model response (i.e. immediately prior to application of step or disturbance).

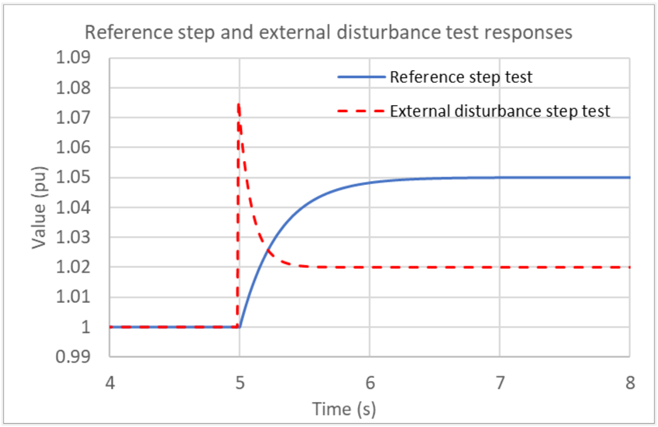

Figure 2: Example of reference step and external disturbance test responses

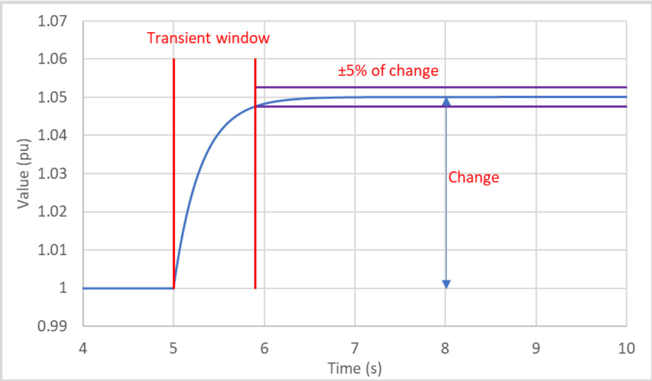

Figure 3: Transient window definition for controlled change

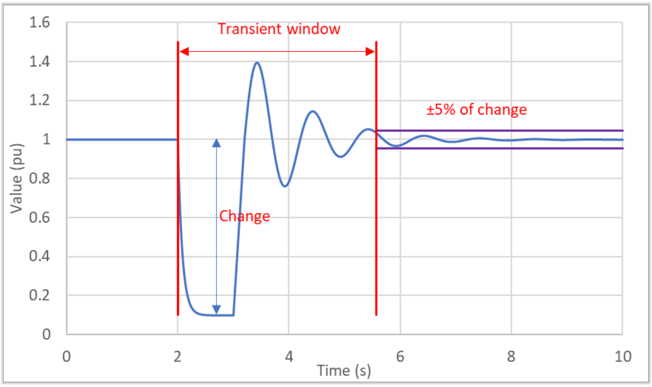

Figure 4: Transient window definition for uncontrolled change

D. *Simulation overlay process*

As mentioned earlier, a lumped model is typically used for R2 model validation. If an external reactive plant is used to produce a voltage disturbance, a full network model will be used in the simulation. The general model alignment steps are listed as follows:

1. Update generator active and reactive power output at the PV inverter terminal
2. Confirm the transformer tap position (if applicable)
3. Check load flow bus voltages against measurement
4. Simulate the corresponding test disturbance
5. Check steady state results and make fine adjustment of system fault level if needed
6. Check model alignment with measurement against tolerance band
7. Report findings and consult with model source code author if needed

IV. MODEL RESPONSE OVERLAY WITH TEST MEASUREMENT

This section presents some overlays between RMS model responses and commissioning test measurements. In each figure, the 10% accuracy bands are superimposed to assess and demonstrate the model compliance with AEMO's PSMG accuracy requirements [8]:

A. *Reactive power reference step test*

Figure 5 presents the HV terminal reactive power response to the negative step. A negative 20 Mvar step is applied to the reactive power reference of the PPC.

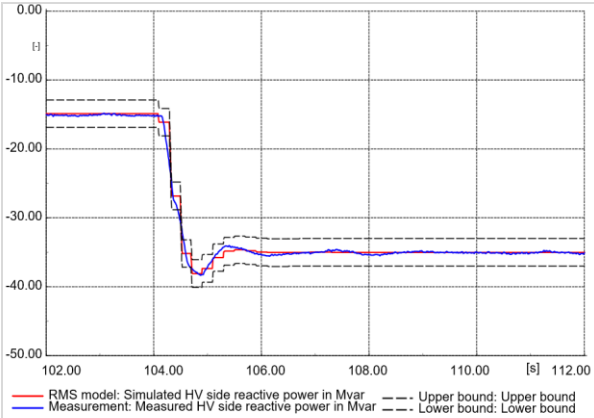

Figure 5: Overlay of Q response to a negative 20 Mvar step

B. *Voltage reference step test*

Figure 6 presents the HV terminal voltage response to a positive 2.5% step is applied to the voltage reference of the PPC.

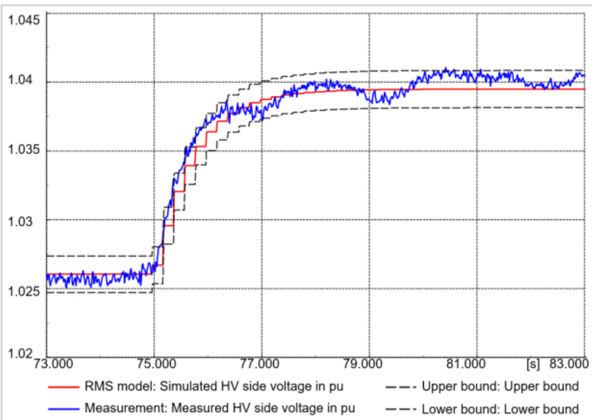

Figure 6: Overlay of V response to a positive 2.5% voltage step

C. Active power reference step test

Figure 7 presents the active power response to a positive ramp in the PPC active power setpoint. A positive step is applied to the active power setpoint of the PPC which is rate limited.

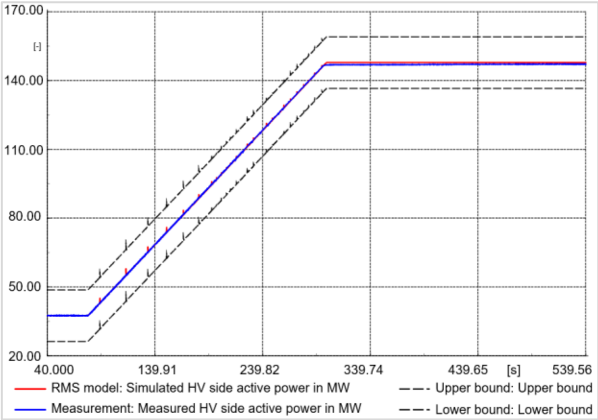

Figure 7: Overlay of P ramping up response

D. Frequency control test

Figure 8 presents the active power response to positive 1 Hz step. A positive 1 Hz step is applied to the frequency reference of the PPC.

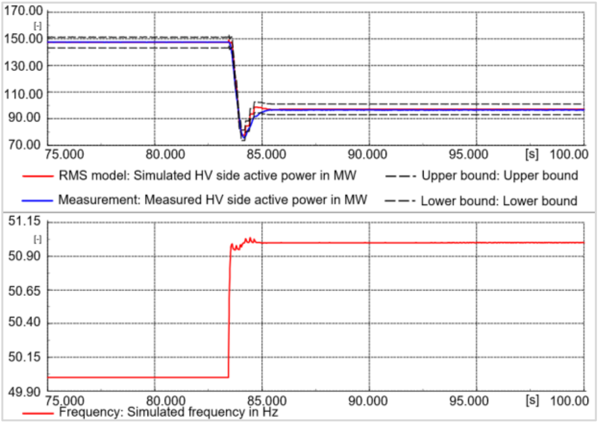

Figure 8: Overlay of P response to positive 1 Hz step

E. External voltage disturbance test

Figure 9 presents the voltage response to capacitor switching out. This example test involves switching out a capacitor filter within the solar farm.

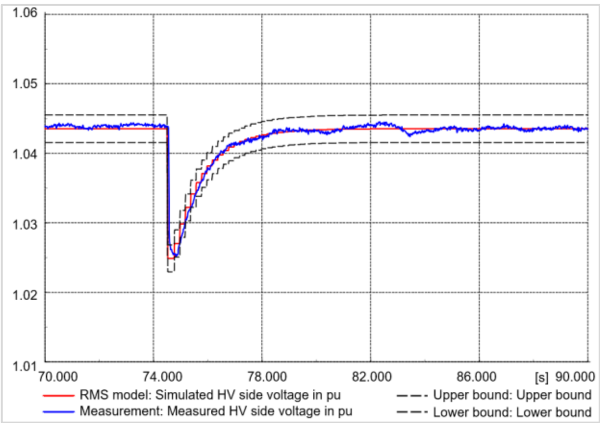

Figure 9: Overlay of V response to capacitor switching out

V. MODEL VALIDATION CHALLENGES

Some challenges encountered by the authors during the model validation process are described as follows.

A. Reduced number of inverters

Sometimes only a portion of the solar farm (e.g. several feeders) is ready for commissioning. With a reduced number of inverters, the apparent power rating of the aggregated PV generator model needs to be adjusted accordingly. Typically, the inverter and PPC model control gain parameters are specified on the apparent power MVA base of generator. With reduced MVA base, the gain is different of the measured system and hence the error signal generated is different which is applied to the controller. Therefore, the control gain parameters in the model (e.g. proportional and integral gains) also needs to be adjusted to accommodate for the reduced number of inverters.

For example, in a solar farm which consists of 40 inverters rated at 2.5 MVA each, the apparent power rating of the aggregated generator model is 100 MVA. In the first stage of commissioning, 17 inverters are commissioned. So, the apparent power rating of the aggregated generator model will be adjusted to 42.5 MVA. The solar farm in this example is set to operate in power factor control via PPC. In the full inverter model, the power factor proportional-integral (PI) controller gain parameters are set to 0.1 (KP) and 1.0 (KI) respectively. Figure 10 compares model response alignment against test measurement, with different machine base MVA and PPC gain parameters. The following observations are made from Figure 10:

- With a machine base of 100 MVA and the original gain parameters (KP = 0.1 and KI = 1.0), the model response (plots in green colour) exhibits a fast transient response and an overshoot. This response does not align with the measured response (plots in blue colour).
- With a reduced machine base of 42.5 MVA and the original gain parameters (KP = 0.1 and KI = 1.0), the model transient response (plots in pink colour) improves and the response is more damped. But the response does not align with the measured response.
- With a reduced machine base of 42.5 MVA and the gain parameters multiplied by the ratio of 42.5 to 100 (KP = 0.0425 and KI = 0.425), the model response (plots in red colour) aligns well with the measured response.

This performance variation is important for utilities to consider for solar farms with some inverters out-of-service.

B. Frequency disturbance simulation method

Regardless of whether the solar farm is participating in the frequency control ancillary services (FCAS) in the NEM, AEMO require the frequency control function of the solar farm to be tested and verified during commissioning. Typically, the PPC is set to provide a frequency control service for the solar farm.

The frequency control test is normally performed by injecting a simulated frequency deviation step at the PPC, i.e. forcing the frequency measured by the PPC to a new value. PPC will then send the corresponding active power commands to inverters. The on-site test setup is shown in

Figure 11. As the frequency deviation is simulated into the PPC only, the inverters measure the real grid frequency and not the frequency deviation event.

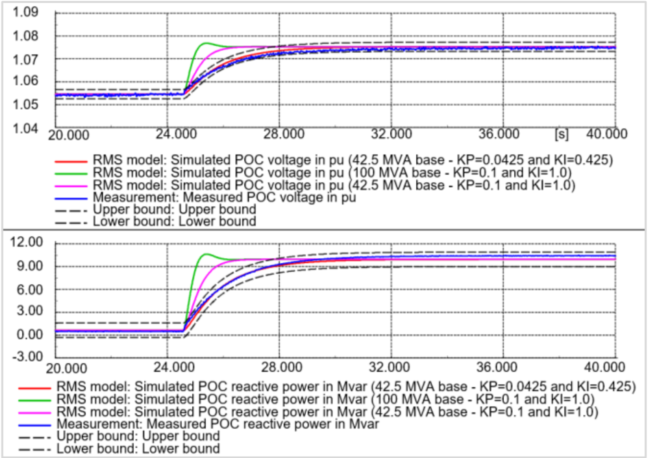

Figure 10: Overlay of voltage and reactive power response to a positive step in power factor setpoint, with different machine base MVA and PPC gain parameters

For the dynamic model validation, the frequency control test is normally simulated using a "play-back" method. A frequency profile is injected via the grid equivalent generator. As the frequency profile is injected into the grid, both inverter and PPC models will detect the frequency deviation. The model simulation setup is shown in Figure 12. This method differs from the on-site test where only the PPC detects the frequency deviation. Depending on how the PLL is modelled in the inverter, the fast frequency deviation step might cause a rapid change in the angle between the inverter PLL and POC. As a result, the inverter PLL could lose its accuracy and produce some undesired inverter response to frequency deviation, e.g. active power reduces during under-frequency event.

Another method that can be used to simulate a frequency disturbance is to use network load switching event. For example, a load output can be ramped up over a time period to re-create an underfrequency event. A classical generator can be used to represent the grid with a carefully considered inertia.

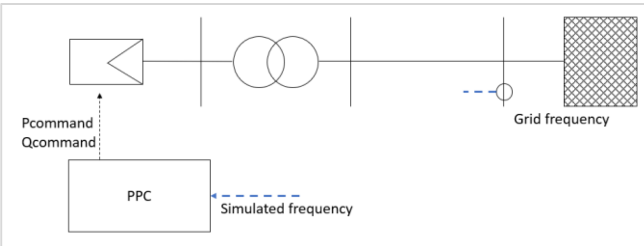

Figure 11: Setup for on-site frequency control test

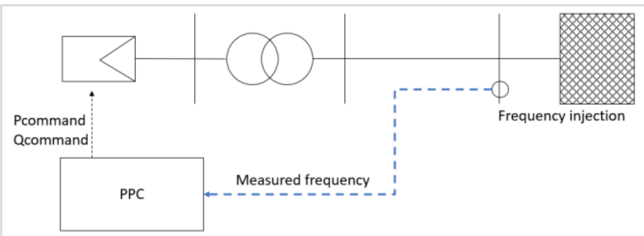

Figure 12: Setup for model simulation of frequency control test

C. Variation in solar irradiance

Solar irradiance, often called the solar resource is the energy source for PV technology type generator. The amount of solar irradiance varies depending on the changing atmospheric conditions and sun position, both during the day and throughout the year.

Cloud shading is the main atmospheric condition that influence the solar irradiance. Shading due to fast moving clouds can affect solar irradiance significantly, and thus PV generation. Fast fluctuations of PV generation output could cause flicker problems in the grid. Figure 13 presents an example of variation in solar irradiance due to cloud shading.

As a result of the solar irradiance variation, the active power output of solar farm could fluctuate. Figure 14 presents the overlay of active power response to a negative 1 Hz step in frequency reference of PPC. As shown in the figure, there are multiple negative steps in the active power output. Most of these negative steps are not caused by the frequency step, but by the solar irradiance variation. This explains why the negative steps are not shown in the simulated model response. Therefore, it is recommended to record solar irradiance during commissioning test in case they are needed to explain the misalignment between simulated and measured responses. Within reasonable timeline and cost, the test can be repeated during a period with steady solar irradiance to isolate the plant controller response and the external factors affecting the plant performance.

In addition, the solar irradiance across the utility-scale solar power plant can vary considerably due to the size of the plant. This poses some challenges to represent the variation in solar irradiance when an aggregated model is utilised for the model validation purposes. Typically, the average irradiance is measured from a number of pyranometers located across the site and this does not necessarily represent the effective solar irradiance of the whole site and this may not align with the linearised DC power input of the inverter in the RMS model.

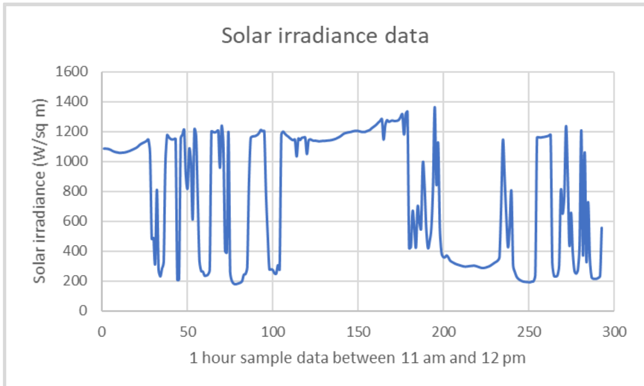

Figure 13: Variation in solar irradiance due to cloud shading

D. Low sampling rate of PPC monitoring meter

The selection and settings of the PPC monitoring meter, in particular the sampling rate, could impact the solar farm dynamic performance. Typical sampling rates observed can be as low as 200ms or up to 1s. This is considered slow in grid connected applications when compared to the PPC cycle time, which is normally in the order of 100ms. With the lower sampling rate, the PPC takes longer time to receive the next measurement and this results in a greater error at the input of the PI controller. This will lead to faster and under-damped (overshoot) plant response as compared to the simulated response. The response is illustrated using the output of a sample and hold block, which is presented in Figure 15. According to the Nyquist sampling theorem, the sampling rate needs to be two times the frequency of interest. So, the sampling time for a 100ms PPC should be 50ms or less.

Figure 16 shows that, with the sampling rate of 1s, the measured response is faster and produces an overshoot compared to simulated response. When the sampling rate is reduced to 10ms, the measured response aligns well with the simulated response as shown in Figure 17.

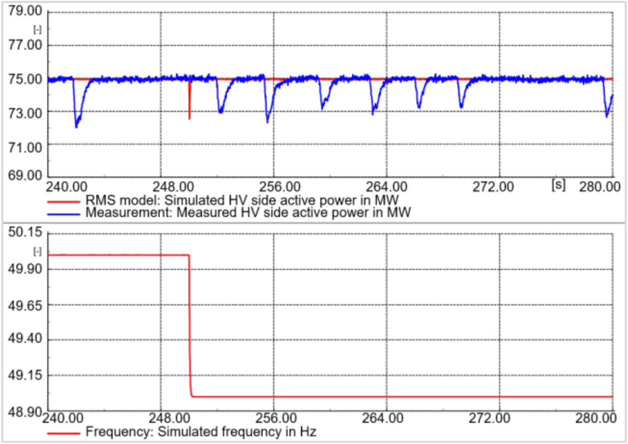

Figure 14: Active power response influenced by solar irradiance

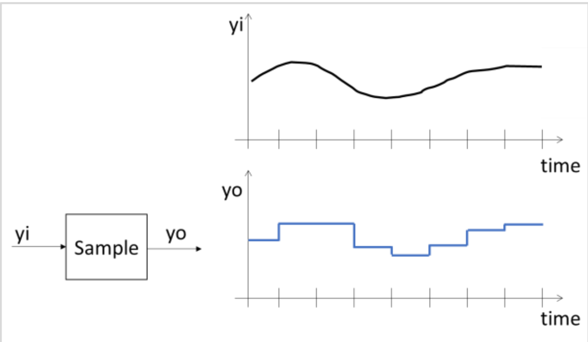

Figure 15: Output of sample and hold block

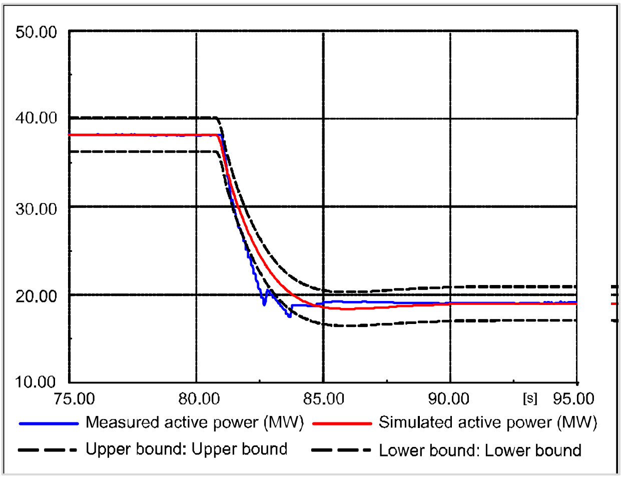

Figure 16: Overlay of simulated response with measured response (sampling rate of 1 s and PPC cycle of 100 ms)

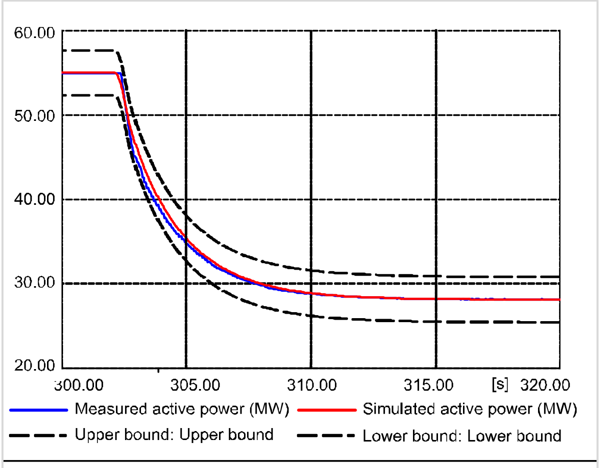

Figure 17: Overlay of simulated response with measured response (sampling rate of 10 ms and PPC cycle of 100 ms)

E. Difficulty in validation of FRT control

Some of the model dynamic responses are difficult to be validated via on-site tests, i.e. fault-ride-through performance. As required by Schedule 4.15 of the NER, the plant owner must institute and maintain a compliance program. As part of the compliance program, a high speed monitoring system is to be permanently installed for continuous data collection. Any disturbance recording can be used to for compliance demonstration and model validation purpose.

VI. Discussions

The generating system model validation requirements used in the NEM today are largely developed from the commissioning experience of synchronous machines, which have the following features:

- Most generating systems are unique, e.g. different combinations of transformer, generator, excitation control system, power system stabilizer, governor, etc.
- Transfer functions (frequency response) of the control system which are based on physical equations can be measured on-site to verify the structure and settings of the controller
- The generating system responses are not particularly fast

These attributes contrast significantly with those of the variable renewable energy systems, e.g.

- Solar farm control system designs are standardized and modular. PPC and inverters are likely from the same OEM as sophisticated communication and controls are required for proper coordination.
- Inverter performances are synthesised based on the OEM's proprietary algorithms which are typically treated as confidential information
- The generating system responses can be very fast as there is not rotating parts

In light of these differences between inverter and synchronous machine technologies, reconsideration of the model validation objectives and methodology is needed:

- For the same type of inverter, it will be better to perform type-testing at the OEM factory, with site-specific control parameter downloaded to the inverters. This can significantly shorten the model validation process on-site when the commissioning timeframe is tight.
- Is the conventional RMS simulation software sufficient to model the sophisticated power-electronic inverters and controls, and accurate enough to resemble the responses? Because of this, there has been a growth trend to use EMT software for dynamic simulation.
- As the penetration of VRE increases in grids previously dominated by retiring synchronous machines, solar farms of the future may need to either reinforce system strength with the inclusion of a synchronous condenser or provide ancillary demand services such as a battery energy storage system. The inclusion of additional supporting plant may impact on the control strategy and hence may impact on the type and number of tests that can be performed.
- Due to the variation of solar irradiance and each PV panel and inverter within a solar farm may behave slightly differently, is it reasonable to assume plant measurement to align closely with simulation responses which are based on ideal conditions? Should power system stability studies based on realistic scenarios which considers the modelling uncertainties, or ideal model behaviour that can only exist in some perfect conditions only?

VII. CONCLUSIONS

This paper presents some commissioning tests used for validating the RMS dynamic models of solar farm inverter and PPC. It also provides some example of simulated model responses overlaid with commissioning test measurements to demonstrate compliance with AEMO's power system model accuracy requirements.

This paper further discusses some challenges encountered during model validation process due to reduced number of inverters during commissioning, frequency disturbance simulation method, impact of moving clouds and sampling rate of PPC monitoring meter.

In order to streamline the model validation process, it is good practice to ensure that:

- Model parameters are consistent to the actual plant configuration and necessary conversion factor to be applied;
- Complete test log with GPS timestamp is kept including records of setpoint, weather / plant operating conditions and constraints imposed by the network operators;
- Measurement equipment are calibrated. Test data is consistent and signals uniform in every measurement file.

The authors consider the model validation process valuable as it enables better understanding of the plant performance and capability. As the utility-scale solar PV technology is still relatively new, site testing results are important feedback to the OEMs for further research and development.

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