Benchmarking Standard Library and User Defined Models of Renewable Generation

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***Abstract*—The representation of renewable generators in dynamic simulations is growing in importance with their increasing penetration. Industry task forces have pushed for and developed generic models, also known as standard library models (SLMs). Often, these models originate from manufacturers of devices such as wind turbines. These can be proprietary, or commonly referred to as user-defined models (UDMs). There have been known to be discrepancies in SLMs and UDMs due to lack of transparency, difficulty in debugging adverse interactions with other models, implementation across different software platforms, and modeling future systems. The paper shows that it is possible to tune SLMs to reach a steady state post-disturbance response within 1% of the UDMs. There are instances where bugs, deficiencies, or complex control schemes in the UDM result in an inability to match the SLM to the UDM exactly. In these cases, the deficiencies and response differences are identified and explained.**

***Index Terms*—transient stability, renewable energy, dynamic models, user defined models, benchmarking**

I. INTRODUCTION

With the increasing penetration of renewable energy, the modeling of these sources in bulk power system studies is also evolving as new technologies are introduced. Of most prevalence recently are the dynamic models representing solar photovoltaics (PV) and wind generation, and storage. Typically, these models originate from the manufacturers of these devices such as wind turbines. However, the models tend to be proprietary to the vendor [1]–[3] in that their implementation is kept confidential and they are released as a “black box” to the modeling community.

In North America, the Western Electricity Coordinating Council (WECC) Renewable Energy Modeling Task Force (REMTF) has been a major force working towards the development of generic models for use in power system simulations. The 2010 North American Electric Reliability Corporation (NERC), Integration of Variable Generation Task Force (IVGTF) Task 1-1 report [2] outlines the need for such generic models for variable generation such as wind and PV. It explains that the term “generic” refers to a model that is standard, public and not specific to any vendor, so that it can be parameterized in order to reasonably emulate the dynamic behavior of a wide range of equipment. These models are meant to be reduced-order, positive sequence and suitable for transmission planning studies of a large network.

Generic models help ensure consistency across different software platforms that are used by different entities. Reference [3] comprehensively describes not only the myriad issues arising from the widely prevalent proprietary or user-defined models (UDM) for renewables but also the work that has gone into standardizing them [4]–[6]. Challenges include the lack of transparency and hence difficulty in debugging adverse interactions with other models, implementation across different software platforms, and modeling future systems.

In addition to real world studies, renewable generation representation is also important in test systems that are widely used for research and education. There are have been major developments towards large-scale, realistic but synthetic test systems [7]–[9], which also consist of dynamic models for conventional generation [10]. Work is ongoing to model renewable generation dynamics in these networks. The question is, though, how to represent these devices i.e. which models and parameters to use that are representative of renewable generation operation and dynamic response in the real world.

With this in view, this paper aims to represent, as closely as possible, some of the widely-prevalent UDMs from actual bulk power system models using SLMs and highlight the issues encountered in obtaining similar responses due to model discrepancies. The paper leverages the the second generation [5] renewable SLM models that are referred to as REGC, REPC etc., which can be used in combinations to represent Solar Inverters as well as Type 3 or 4 Wind Machines. To enable an in-depth discussion in the space available, the paper focuses on a solar inverter implementation of these models with UDMs used of the same type. The UDMs were set up and tuned to give appropriate responses under a series of grid disturbance tests to provide a benchmark response. The SLMs were then tuned to closely match the UDM response to create SLM parameter sets that can be used to create a realistic representation of renewable machines when integrated into a system network model. The manufacturers chosen to represent each machine type as the UDM baseline were selected due to their prolific presence in the power system, particularly in the Electric Reliability Council of Texas (ERCOT) region.

The paper is organized as follows. Section II describes the test system used for all simulations and its key parameters. Section III lists all the scenarios i.e. transient contingencies applied to test the performance of the renewable dynamic models. The results of simulating these across UDMs and SLMs

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are elaborated on in Section IV, with Section V summarizing the main takeaways and directions for future work.

II. Test System

In order to create a consistent testing platform to be used, a power flow model was created to represent a typical grid connected renewable energy project. The values in Table I used for the Main Power Transformer (MPT), collector system, and padmount transformers represent typical values found in grid connected renewable energy projects. The values used for the renewable machine active power, reactive power, and MVA rating vary based on the manufacturer selected to serve as the baseline for each machine type. While benchmarking each machine type, the power flow models were identical with exceptions given to certain model parameters needed specifically in the UDM. However, even in instances where parameters in the power flow model are not identical between the UDM and SLM, machine capabilities and project equipment (MPT, collector system, and padmount transformer) are identical.

A. Transmission System

The transmission system, which resembles a single machine infinite bus (SMIB) setup, is represented by a generator (slack) bus connected at the point of interconnection (POI), corresponding to the high-side of the MPT. The slack bus dynamic model is represented by a “playback model” which allows voltage and frequency signals to be applied where the model is connected. The MVA Base for the machine located at the POI bus was set to 10,000 MVA in order to simulate a strong transmission system. The values entered into the playback model and any MVA adjustments for each scenario are detailed further in the paper.

B. Renewable Machine Test Model

An equivalent power flow model was developed to be used for all renewable machines. This power flow model contains all project equipment up to the model POI including the renewable machine, padmount transformer, collector system element, and the MPT. Each model element has parameters representative of typical values as observed in grid connected renewable generation projects.

The following assumptions were used:

1) Pre-event POI voltage is set to 1.000 pu (345 kV)
2) Each power flow model consists of approximately 200 MW of installed renewables
3) Machine thermal ratings were ignored, and ratings are only used when necessary for impedance calculations.

Due to the confidential nature of machine protection settings, a set of NERC PRC-024-2 [11] compliant protection settings were included in each of the dynamic models. This was done to give a typical representation of how machines are protected in the field as manufacturers are required to design and deliver their renewable machines with compliance.

TABLE I
PARAMETERS

Machine Parameters	Machine parameters including Active Power, Reactive Power, and MVA Rating vary by machine type and capability of the machines used as reference for each type
WTG Pad Mounted Transformer Parameters	Rating: 2.95 MVA Primary Voltage: 34.5 kV (Wye – Gnd) Secondary Voltage: Variable per machine type (Delta) Impedance (S= 121 MVA, V = 34.5 kV) • R = 0.002330 pu • X = 0.099970 pu
Collector System Parameters	• R = 0.000616 pu • X = 0.000647 pu • B = 0.008640 pu
Main Power Transformer	Voltage: 345/34.5 kV (Wye – Gnd /Delta) Load Tap Changer (OLTC): 345 kV, ±16x 0.625% Tap Minimum/Maximum: 90%/110% Impedance: H-X = R = 0.008680 X = 0.069460; S = 204.75 MVA

C. SLM Models

The below SLMs were used to represent the solar inverter:

- REGCAU1: Renewable Energy Generator/Converter
  - inputs: real (Ipcmd) and reactive (Iqcmd) current command
  - outputs: real (Ip) and reactive (Iq) current injection into the grid model
- REECAU1: Renewable Energy Electrical Control model
  - inputs: power reference, both active (Pref) and reactive (Qref) that can be externally controlled, and feedback of the reactive power generated (Qgen)
  - outputs: Ipcmd and Iqcmd
- REPCTAU1: Renewable Energy Plant Control model
  - inputs: either voltage reference (Vref) and measured/regulated voltage (Vreg), or Qref and measured (Qgen), all at the plant level
  - outputs: reactive power command that connects to Qref of REEC

Tuned parameter values for these models based on the simulation results are provided in the Appendix.

III. Scenarios

This section describes the scenarios or contingencies that were applied in order to test the performance of the models

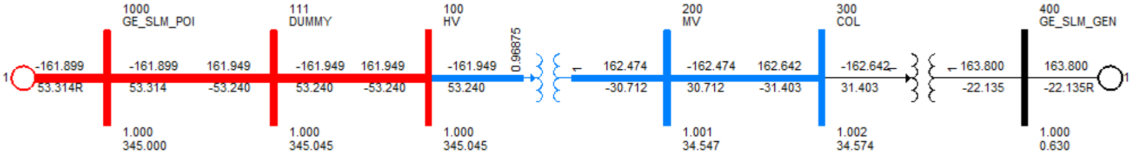

Fig. 1. Oneline of the test system

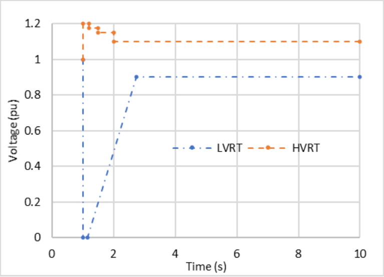

Fig. 2. High and Low Voltage Ride Through test signals

TABLE II
FREQUENCY RIDE THROUGH TEST SIGNALS

LFRT		HFRT	
Time (s)	Frequency (Hz)	Time (s)	Frequency (Hz)
1.000	60.0	1.000	60.0
1.001	57.5	1.001	61.8
3.001	57.5	:	:
3.002	58.0	:	:
31.001	58.0	31.001	61.8
31.002	58.4	31.002	61.6
541.001	58.4	541.001	61.6
541.002	59.4	541.002	60.6

for benchmarking. At the beginning of each simulation, a flat run i.e. a no-disturbance simulation of 1.0 second is performed in order to show proper initialization of the models.

1) Lagging Voltage Ride Through Test (LaVRT): The power flow model is set up such that the renewable project is providing maximum active power at a lagging power factor (pf) of 0.95 pu at the POI. This is done by setting Qgen = Qmax = Qmin to lock the reactive power at a specific value. If the renewable machine cannot provide a lagging pf of 0.95 at the POI based on manufacturer specified reactive power capability, the maximum permissible lagging value was used based on machine ratings and the UDM internal Q-V curves.

Once the load flow model is initialized in the lagging direction, the high and low voltage ride through tests are performed at the POI with the playback model. The high voltage ride through (HVRT) profile chosen for testing is the NERC HVRT profile as detailed in NERC PRC-024-2. The low voltage ride through (LVRT) profile chosen for testing is the ERCOT mandated LVRT profile used when testing the response of renewable projects prior to interconnection [12]. The values entered into the playback model for the LVRT and HVRT tests are shown in Figure 2.

2) Leading Voltage Ride Through Test (LeVRT): The setup is similar to the LaVRT except that the renewable project operates at 0.95 pu leading. Then the high and low voltage ride through tests are performed at the POI using the playback model, with the values shown in Figure 2.

3) Frequency Ride Through Test (FRTT): The power flow model is set up such that the renewable project is providing maximum active power and a reactive power value within its manufacturer determined reactive power limits. This is done by solving the model with a nominal (1.0 pu) grid voltage, the project on load tap changer (OLTC) operating, and allowing Qgen to settle between Qmax and Qmin; where Qmax and Qmin are based on machine ratings and the UDM internal Q-V curves. Once the power flow model is initialized, the high and low frequency ride through tests are performed at the POI with the playback model. The profiles chosen for testing are the NERC high frequency ride through (HFRT) and low frequency ride through (LFRT) profiles for ERCOT, as detailed in PRC-024-2. Table II shows the values entered into the playback model for the LFRT and HFRT tests.

4) Weak Grid Fault Ride Through Test (WGFRTT): The power flow setup is similar to the one for the FRTT scenario. To simulate a weak grid condition, the MVA Base of the machine located at the POI bus was reduced to give a grid Short Circuit Ratio (SCR) of approximately 5. The fault test is performed at the POI with the playback model. The fault profile was chosen to represent a three-phase fault at the POI, where the voltage at the POI bus is forced to 0 pu for 6 cycles (0.1s) before instantaneously recovering to nominal upon fault clearance. The values entered into the playback model for the Fault Ride Through Tests are shown in Table III.

TABLE III
FAULT RIDE THROUGH TEST

Time (s)	Voltage (pu)
1.000	1.000
1.001	0.000
1.100	0.000
1.101	1.000
10.00	1.000

5) Strong Grid Fault Ride Through Test (SGFRTT): To simulate a strong grid condition, the MVA Base of the machine located at the POI bus was left at 10,000 MVA. The same fault as in the previous scenario is then applied.

6) Automatic Voltage Response Test (AVRT): The AVR profile was created to simulate a ±2% deviation from nominal grid voltage. This value was chosen to represent a typical small change in grid voltage to demonstrate the response of the project's power plant controller without engaging the renewable machine's voltage ride through modes. The playback values for the AVR tests are shown in Table IV.

TABLE IV
AVR TESTS

AVR Step Down		AVR Step Up	
Time (s)	Voltage (pu)	Time (s)	Voltage (pu)
1.000	1.000	1.000	1.000
1.001	0.980	1.001	1.020
10.00	0.980	10.00	1.020

7) Primary Frequency Response Test (PFRT): Similar to the AVR tests, the PFR profile was created to simulate a ±0.2 Hz deviation from nominal grid frequency. The playback frequency values for the PFR tests are shown in Table V.

IV. SIMULATION RESULTS

This section describes the results of simulating the scenarios, using both the SLMs and UDMs. Note that one of the goals here is also to highlight the discrepancies observed

TABLE V
PFR TESTS

PFR Step Down		PFR Step Up	
Time (s)	Frequency (Hz)	Time (s)	Frequency (Hz)
1.000	60.0	1.000	60.0
1.001	59.8	1.001	60.2
10.00	59.8	10.00	60.2

between the UDM and SLM responses, so that they may be addressed by further research or by the modelers/manufacturers. A response as close as possible between the SLM and UDM models was obtained by tuning the model parameters, and in general results matched within 1% of each other, which is also the criteria used here to determine a “good match”.

As a starting point, the SLM parameters were set up using a combination of recommended parameters from the manufacturer UDM documentation and comparing the UDM control block diagrams against the SLM control block diagrams to identify parameters/control loops that could be considered common between the two types of models. This enables a base level consistency of modeling across the SLM and UDMs and improves the likelihood of getting similar responses.

Comparing the SLM and UDM responses during the HVRT portion of Scenarios 1 and 2 shows a sufficiently matched response for the active power (Figure 3), reactive power (Figure 4), voltage and frequency. The behavior of each of these variables in the SLM are tuned to match the UDM behavior in both shape and magnitude throughout the entire test. Both the SLM and UDM also reach identical steady state values at the end of the simulation.

The VRT controls of the SLM are found within the REECAU1 model. The portion of its block diagram relevant to this discussion is shown in Figure 5. The VRT control loop provides a reactive current offset to the existing reactive current command that originates from the power plant controller (REPCTAU1). The main parameters to be tuned within this control loop are, Vdip, Vup, Kqv, dbd1 and dbd2. Vdip and Vup are the respective lower and upper voltage thresholds for entering and exiting VRT mode. The Vdip value also freezes the reactive current command from the REPCTAU1 for LVRT but not for HVRT. The proportional gain, Kqv, along with the voltage difference between the existing inverter terminal voltage and the voltage reference is used to provide the reactive current response during the VRT event. These values are tuned based on a review of the UDM VRT control mode to match up as close as possible the entry/exit into VRT mode and the associated reactive power response during the voltage event.

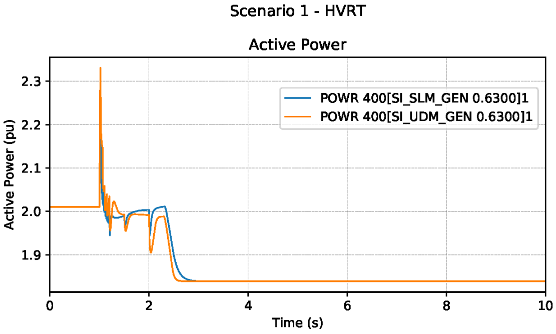

Fig. 3. Active power during lagging pf high voltage ride through test

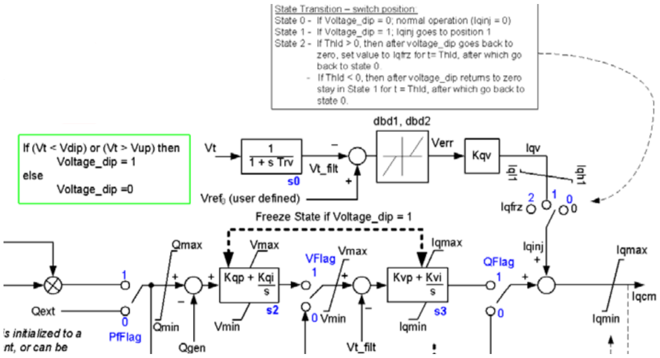

Fig. 5. VRT control portion of the REECAU1 model [13]

Considering the VRT control loop within the SLM is an offset to the previous time step reactive power output, it is sometimes difficult to match some UDMs’ VRT response since UDMs use a different method for VRT control, closer to local voltage PI control in order to provide maximum/minimum reactive power injection during a low/high voltage event in order to maximize the ride through capability of the generator. Thus, in order to replicate this type of response, the Vdip and Vup values are sometimes bypassed by setting them to 0 and 2 respectively and using the REPCTAU1 model to represent the VRT control of the generator.

For the LVRT portion of Scenarios 1 and 2, there are slight differences in the responses of the SLM and UDM while the general shape and trend of the responses are very similar,

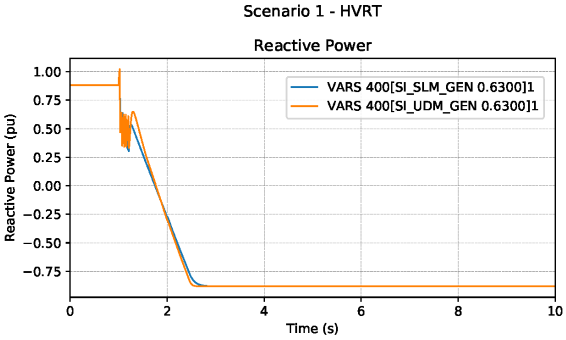

Fig. 4. Reactive power during lagging pf high voltage ride through test

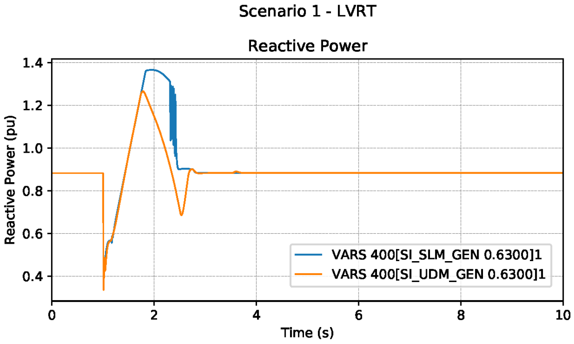

Fig. 6. Reactive power during lagging pf low voltage ride through test

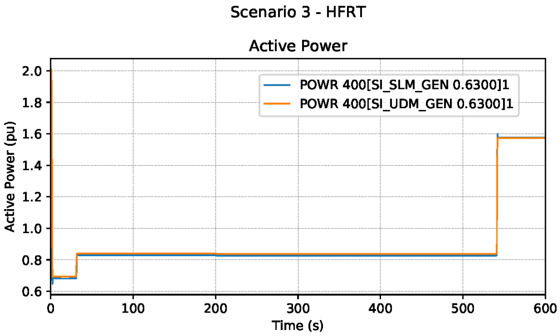

Fig. 7. Active power during high frequency ride through test

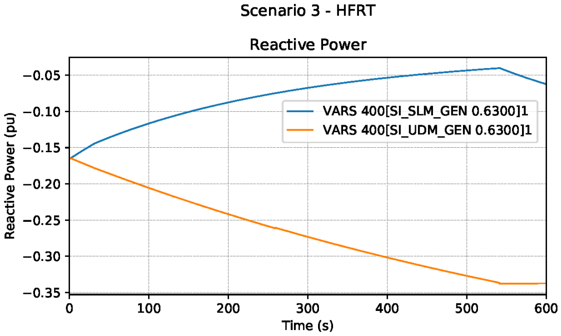

Fig. 8. Reactive power during high frequency ride through test

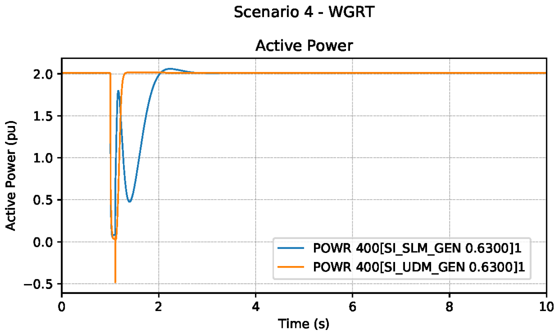

Fig. 9. Active power during weak grid fault ride through test

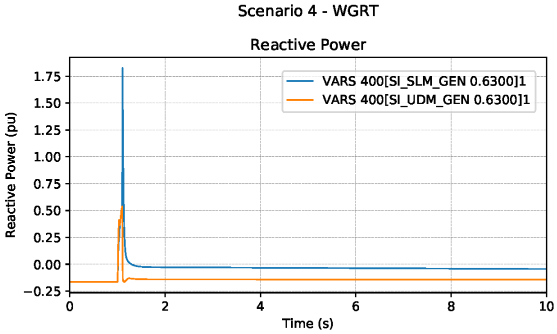

Fig. 10. Reactive power during weak grid fault ride through test

as seen in Figure 6. This is due to the implementation of hysteresis control in the UDM, which is missing in the SLM. The hysteresis in the UDM is intended to reduce oscillations in the model, however it cannot be disabled. Hysteresis control allows for the model to enter and exit voltage ride through mode at different voltage thresholds. This helps the model reduce oscillations when switching between control modes and the effect of this can be seen in the reactive power response in Figure 6 as the SLM has slight oscillations and the UDM does not. This should be a topic of discussion with SLM development groups to further enhance the SLMs with more options for VRT control.

For both the HFRT and LFRT parts of Scenario 3, the active power and frequency responses of the SLM and UDM are very similar in both shape and magnitude and reach a steady state value within 1% of each other. The reactive power response differs as seen in Figure 8 since both models utilize different controls during frequency deviations. These discrepancies arise since the only control taking place is active power control due to frequency deviations so the reactive power and voltage responses are solely the result of responding to small deviations in the reference. Since both the UDM and SLM utilize droop control, any small difference in reference deviation will provide a different error to be passed through the reactive power control loop. Small differences in the reference and error are exacerbated through droop control as both models will not be driven to the same setpoint. This can potentially be mitigated by adding in a small deadband, i.e. 0.001 pu, or a very small droop value in order to keep the model from responding during small voltage excursions. However, care must be taken as some UDMs do not have deadbands, similar to this model, that can be adjusted to alleviate this discrepancy.

The responses for Scenarios 4 and 5 i.e. the fault ride through tests are quite similar, such that the differences seen between the UDM and SLM are also consistent. The voltage, frequency, and active power reach a steady state value within 1% of each other and only the reactive power response differs between the SLM and UDM as both models utilize different methods for reactive power recovery. While both models return to the same pre-event active power output, the UDM returns to near the same pre-event apparent power rating while the SLM does not have this same apparent power reference. This leaves the SLM to settle at a different reactive power steady state value (Figure 10).

The SLM active power response in Figure 9 also shows a secondary dip while the UDM ramps steadily back to nominal. The cause of this dip is the interplay between the generator model time constants and frequency control proportional gains. More specifically, the active power mismatch arises from the the PI gain Kpg and Kig within the REPCTAU1 model. In order to obtain a fast response for PFR, the resulting gain values cause the voltage dip upon recovery from the fault. When the PFR control in the SLM is turned off for the same fault, the responses are almost identical with no secondary dip. Further evaluation of these gain parameters is ongoing to check for a better fit to match both the fault and PFR scenarios. The SLM was tuned such that the secondary dip was minimized while still allowing the model to remain stable through all scenarios.

The reactive power and voltage responses during the AVR Step Up and Step Down Tests are very similar in both phase and magnitude. The frequency and active power responses

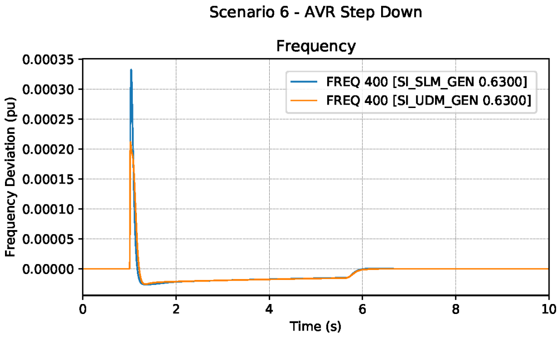

Fig. 11. Frequency during AVR step down test

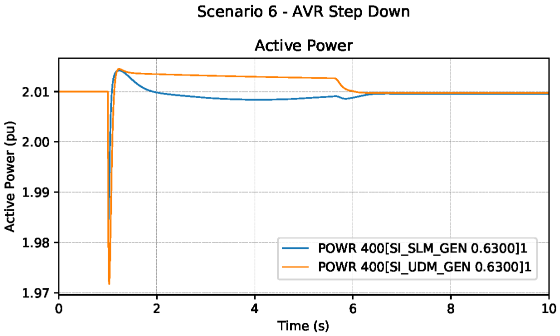

Fig. 12. Active power during AVR step down test

during the AVR Step Up test have some deviation. The instantaneous voltage step up used in the test produces a measured frequency spike. The SLM and UDM respond slightly different to this frequency deviation. When the frequency control in the SLM is disabled, all variables respond much more similarly throughout the simulation. Finally, the PFR Step Up and Step Down tests show a good match. The active power, reactive power, voltage, and frequency responses have similar shapes and magnitudes and reach steady state values within 1% of each other.

V. SUMMARY

Overall, the paper has shown that it is possible to tune SLMs to reach a steady state post-disturbance response typically within 1% of the UDMs while matching the general response shape during the transient events under most test scenarios. There are instances where bugs, deficiencies, or complex control schemes in the UDM result in an inability to match the SLM to the UDM exactly. In these cases, the deficiencies and response differences were identified and explained.

Future work will apply these SLMs benchmarked with UDMs prevalent in the ERCOT region using the SMIB approach, to larger systems such as the synthetic grids based on the footprint of Texas [14] for further benchmark testing. This is to verify whether the system level dynamic response of the network using SLMs corresponds well with the actual grid response that could be represented by a combination of both UDMs and SLMs, under several transient conditions. The goal will be to identify and address any further discrepancies and further close the gap between SLMs and UDMs.

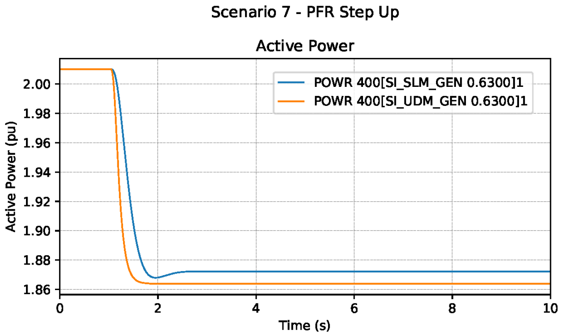

Fig. 13. Active power during PFR step up test

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APPENDIX

TABLE VI
DYNAMIC MODEL PARAMETERS

400 'USRMDL' 1 'REGCAU1' 101 1 1 14 3 4 1 0.02 10.0 0.6 0.0 1.0 2.0 0.6 0.0 -2.0 0.02 0.0 9999.0 -9999.0 1.0

400 'USRMDL' 1 'REECAU1' 102 0 6 45 6 9 0 0 0 0 0 0 0.8 1.19 0.0 0 0.0 1.4 1.0 -1.0 0.0 0.0 0.0 0.0 0.0 0.402 -0.402 1.2 -1.2 1.0 10.0 1.0 10.0 0.0 0.02 1.0 -1.0 1.0 -1.0 1.0 0.025 0.1 1.0 1.1 1.0 0.0 0.0 0.0 0.0 0.10 1.0 1.1 1.0 0.0 0.0 0.0 0.0

400 'USRMDL' 1 'REPCAU1' 107 0 7 27 7 9 100 100 111 '1 ' 0 1 0 0.0 1.0 5.0 0.0 0.1 0.0 0.0 0.0 0.0 0.1 -0.1 0.0 0.0 0.402 -0.402 0.01 3.33 0.0 -0.00028 0.00028 10000.0 -10000.0 1.0 0.0 0.1 20.0 20.0

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