21, rue d'Artois, F-75008 PARIS
http://www.cigre.org

CIGRE US National Committee
2019 Grid of the Future Symposium

Advanced High-Fidelity Lumped EMT Grid Modeling & Comparison

S. DEBNATH
Oak Ridge National Laboratory
USA

Q. XIA, M. SAEEDIFARD
Georgia Institute of Technology
USA

M. ARIFUJJAMAN
Southern California Edison
USA

SUMMARY

There is increased interest in performing electromagnetic transient (EMT) studies of large power grids for stability purposes. The large power grids may not represent the entire grid, but portions of interest. For example, studies are being performed to identify the impact of extreme events on solar power plants in California that requires the EMT model of the grid in California, but not the complete western interconnection (WI) grid model to which the grid in California is connected. The EMT models of grids are necessary to perform integration studies of large power electronics systems like utility-scale photovoltaic (PV) systems, high-voltage direct current (HVdc) systems, flexible alternating current transmission systems (FACTs), and others. Traditionally, models of grids available to utilities are the transient stability (TS) models. Hence, it assumes significance to identify methods of developing high-fidelity EMT models for portions of the grid (of interest) from the information available in the existing TS models of the entire grid. In this paper, a conversion mechanism along with upgradation based on data-driven methods is applied to develop EMT models of grids. The conversion mechanism utilizes information from TS models of grids to generate EMT models of grids. These models can be extracted for the required portion of the grid. While these models adequately represent the local voltage behaviour of the grid, they are inadequate in representing the frequency behaviour of the grid. The data-driven methods are applied to identify frequency dynamics of the grid, and the EMT models are upgraded with the data-driven methods. The resulting upgraded EMT models of grids can perform the studies mentioned above. These models are tested under contingencies of interest to validate the developed models.

debnaths@ornl.gov

KEYWORDS
Electromagnetic transient (EMT), transient stability (TS), TS to EMT conversion, lumped ac grid modelling.

INTRODUCTION

Increased penetration of power electronics is observed in the grid through generation like photovoltaic (PV) generation, energy storage systems (ESSs), and variable-speed wind generation; power flow controllers like high-voltage direct current (HVdc) systems and flexible alternating current transmission systems (FACTS); and, other emerging power electronics like solid-state power substations (SSPSs), solid-state transformers (SSTs), and others. The higher penetration of power electronics leads to requirements to perform electromagnetic transient (EMT) simulation studies for larger portions of the grid. Conventionally, only the local area connecting to a specific equipment in the grid, namely HVdc systems or FACTS, were modeled in EMT simulation studies to understand the stability of the equipment and the impact of extreme events (like lightning) on the equipment. With higher penetration of power electronics, there are changing requirements of performing EMT simulation studies of larger regions. These requirements arise from limitations in traditional transient stability (TS) simulation models to provide accurate representation of dynamics in the system during unbalanced transients in the system [1] [2] [3]. They have led to creation of multiple North American Electric Reliability Corporation (NERC)-led task forces or working groups: Inverter-based Resource Performance Task Force (IRPTF) and System Planning Impacts from Distributed Energy Resources working group (SPIDER-WG), CIGRE B4.82 and C4.56 working groups, and others. One of the requirements identified by the NERC IRPTF is EMT modeling and simulation of areas with PV resources during contingency event studies [1] [2] [3]. The working groups in CIGRE, including B4.82 and C4.56, are identifying the role of EMT simulations to study the stability of large-scale systems.

One of the gaps identified is the absence of utility grid models in EMT simulation tools. Towards the same, in this paper, a method to develop EMT simulation models of large grids that may not represent the entire grid is presented. The method is based on conversion of TS simulation models of the portion of grid of interest to EMT simulation models. The TS simulation models of grids are typically the planning and operational models utilized by utilities. The converted EMT simulation models represent the voltage behavior adequately with high-fidelity representation, but limited dynamics of frequency are incorporated in the models. The frequency dynamics are incorporated in to the EMT simulation models using data-driven techniques to result in the upgraded EMT simulation model of the grid. The upgraded EMT simulation model of the grid can be utilized to evaluate the performance of utility-scale PV systems, multiple HVdc systems (point-to-point and multi-terminal), FACTS, multiple ESSs, and other power electronic equipment connected to the grid. They can also be utilized to evaluate the impact of extreme events in bulk power systems on multiple power electronic equipment.

METHOD TO DEVELOP EMT SIMULATION MODELS OF GRIDS

The stability of the control system in a power electronic equipment is typically evaluated by assuming its connection to ac voltage sources to represent stiff grids or to ac voltage sources in series with impedances to represent weak grids. However, this representation of ac grids is insufficient to adequately represent the operating conditions experienced by the power electronic equipment in the real-world. A better method to evaluate the power electronic equipment is by connecting its model (that includes the control system) with a grid model that provides an exact representation of the grid. As power electronic equipment require high-fidelity models, the grid models need to be in EMT simulation tool. Traditional grid models are available in TS simulation tools. This limitation is further exacerbated with the increased presence of power electronics. The representative grid models (like the ac voltage source in series with an impedance), in this case, do not adequately capture the non-linear dynamic behavior of multiple power electronics and the control interactions are not adequately captured. In these cases, the control system of the power electronic equipment needs to be evaluated under various operating conditions where there are disturbances observed in the voltage and frequency of the grid. They also require models that adequately represent the high-frequency characteristics of the connected grid due to the high bandwidth of the control systems.

One of the methods to develop the EMT model (high-fidelity) of the grid is through conversion from TS models. This conversion provides adequate representation of the voltage dynamics. In this paper, the representative EMT models of the grid in the Pittsburg, CA, and Victorville, CA, regions are developed. E-Tran tool has been utilized to convert the utility models of the local areas (Pittsburg and Victorville, CA) from a western electricity coordinating council (WECC) grid model in PSS®E in to PSCAD. A sensitivity analysis is performed based on the defined contingency events in the grid to identify the size of the local area dynamic model required to adequately represent the voltage behavior.

The converted local area dynamic model in PSCAD consists of the models of actual components in the local area, namely, Pittsburg and Victorville, CA. It also consists of equivalent circuit models representing the dynamics of the rest of the WECC grid. Some of the issues observed while converting the models from PSS®E to PSCAD using E-Tran include the following:

1. Some of the exciter models are not well represented in PSCAD like REXSYS. Once these exciters are initialized, some of the states in the exciter diverge in the simulations. This problem can be resolved by removing the generators that do not significantly alter the voltage dynamics in the system.
2. The absence of governor models in PSCAD does not lead to stable simulation, unlike in PSS®E. This problem can be resolved by removing generators that do not significantly alter the voltage dynamics in the system.
3. Negative resistances and impedances in the equivalent circuit models result in the simulation states diverging when simulated for long periods. This problem can be resolved by considering positive resistances and impedances as one of the options in the E-Tran tool. The changes suggested do not alter the voltage dynamics.
4. HVdc models from PSS®E (like cdc6t dynamic models) are converted in to stiff ac voltage source with fixed frequency and limited dynamic behavior represented. This problem can be resolved by adding an internal control mechanism in to the HVdc models in PSCAD that enable incorporating dynamic behavior of the HVdc systems.

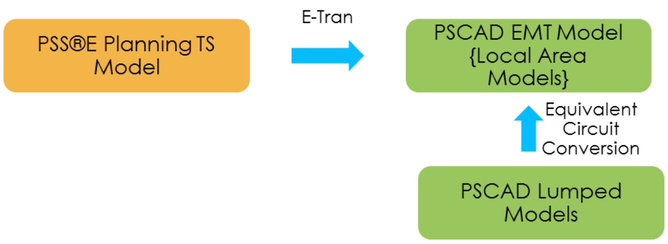


Figure 1: Integrated dynamic model development procedure.

The procedure explained above develops EMT models of the local grid without the dynamics of the frequency incorporated. To adequately represent the frequency behavior of the grid, a lumped representative dynamic model of the grid could be developed like the data-driven model developed in [4] [5]. The lumped representative dynamic models are then integrated into the developed local area dynamic model of the grid. The equivalent circuit models in local area dynamic model include ac stiff voltage sources with internal impedances. The voltages at the terminals of these sources are defined along with the initial active and reactive powers. While integrating the lumped dynamic model into local area dynamic model, the frequency behavior of all the sources in the equivalent circuit models need to be varied. This requires converting the ac stiff voltage sources with internal impedances and the voltages defined at the terminals into the controllable voltage sources with external defined impedances. The controllable voltage source can take an external frequency as an input, with the external frequency being the output of the lumped dynamic model. The conversion method is based on identifying the voltage of the ac stiff voltage sources from the terminal voltages defined and the initial active/reactive power provided. The conversion method also needs to convert the per-unitized impedances to the actual impedances. Once the conversion of all the voltage sources in the equivalent circuit model is completed, the lumped dynamic model can be integrated into the local area dynamic models. Through this procedure, ac grid models of Pittsburg and Victorville, CA, are developed. These models are, hereafter, termed as integrated dynamic models. This process is summarized in Fig. 1.

The developed method can be utilized to develop EMT models of transmission grids in various studies like in the stability studies performed by North American Electric Reliability Corporation’s (NERC’s) Inverter-Based Resource Performance Task Force (IRPTF) [1] [2] [3] [6].

RESULTS

Contingency Identification

The contingency analysis of the WECC system aims to identify critical events where the developed models can be evaluated. The most common types of contingencies include transmission line fault, loss of transmission line, and loss of generator, changing or setting of generator, opening or closing of transformer, and movement of generator, load. In this paper, two types of the aforementioned contingencies, loss of generator and transmission line faults, are applied to the two locations.

The typical deadband in governors is in the range of 0.036 Hz in many generators [7]. Thus, the contingencies which cause the frequency variation outside the range will be considered as critical. In terms of voltage, the voltage magnitude that has 10% to 15% voltage deviation of bus voltage magnitude will be considered as critical based on [1] [2]. The blue cut fire in 2017 caused interruption disturbance of 1,200 MW capacity of PV plant [1]. The contingencies related to the largest generation loss in [1] are the line-to-line fault occurring near the LUGO substation. Thus, the line-to-line fault at LUGO is considered as one of the contingencies. In addition, the canyon-2 fire in 2018 caused a line-to-line fault at SERRONA which also has a wide-area impact [2]. Thus, the transmission line faults are also applied at SERRANO. The fault impedances are same as given in the blue cut fire report [1], where $R_f = 0.000174$ pu and $X_f = 0.003813$ pu (impedances on 500 kV base).

Frequency violation is defined when $f_{u\_pitt}, f_{d\_pitt} \notin [59.964, 60.036\ ]$ Hz or $f_{u\_vic}, f_{d\_vic} \notin [59.964, 60.036\ ]$ Hz. The f_u is the peak frequency and f_d is the lowest frequency after the contingency is applied. Frequency dip is defined as Δf and is calculated by equation (1).

$$\Delta f = f_0 - \max(f_1, f_2) \tag{1}$$

where f_0 is the frequency before the fault happens, and f_1, f_2 are defined as $(f_u - f_0)$ and $(f_l - f_0)$, respectively. The voltage magnitude deviation is calculated by equation (2).

$$\max\left\{ {(V_{n\_pitt} - V_{l\_pitt})}/{V_{n\_pitt}}, {(V_{n\_vic} - V_{l\_vic})}/{V_{n\_vic}} \right\} \tag{2}$$

where V_{n_pitt} is the normal operating voltage at Pittsburg and V_{l_pitt} is the lowest voltage upon fault at Pittsburg. Similar definitions are provided for the voltages at Victorville.

All contingencies which have violation are listed below.

Table 1.4-1: Contingencies analysis results summation.

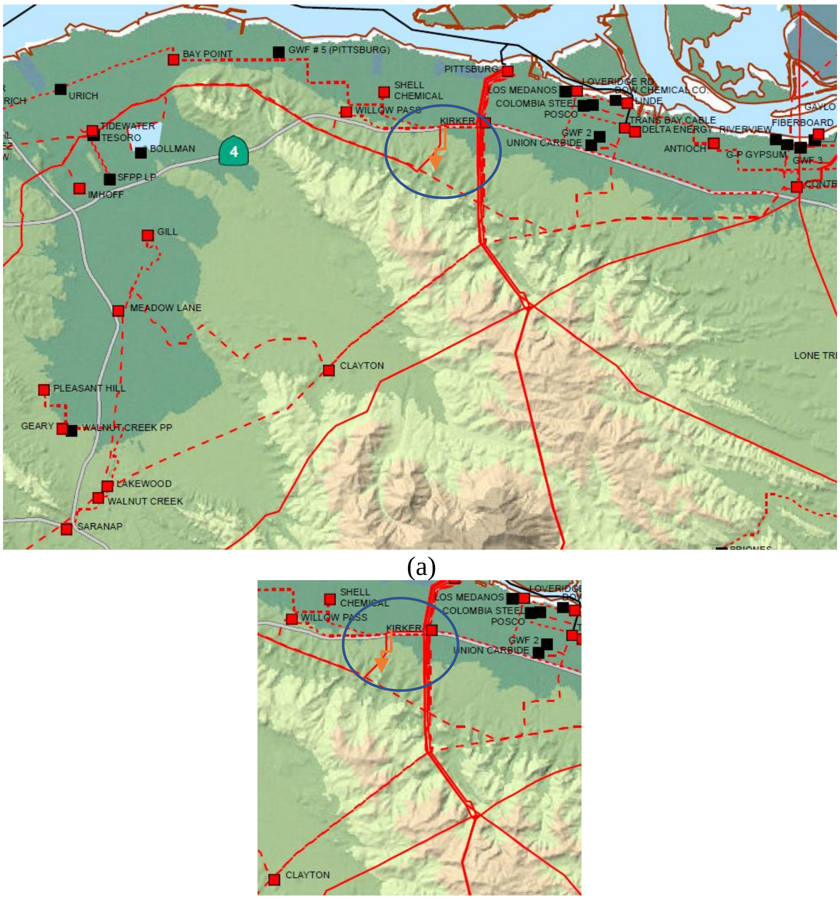
Contingencies Type	**Lost Generation (MW)**	**Location of Interest**	**Voltage Magnitude Deviation**	**Frequency Deviation**
L-L faults near LUGO	None	Victorville	14.96%	N/A
L-L faults near SERRANO	None	Victorville	12.53%	N/A
L-L faults near GATES	None	Pittsburg	12.5%	N/A
Generator loss near SFO	1470.172	Victorville	N/A	0.08
Palo Verde generator loss	2756	Victorville	N/A	0.16
HAYNES3 generator loss	804.4	Pittsburg	N/A	0.06

Evaluation of Developed Models

Based on the identified contingencies near Pittsburg and Victorville, CA, the integrated dynamic models of the ac grids are evaluated. The reference models for evaluating the voltage violations are based on considering a much larger portion of the ac grid in the local area dynamic models. The corresponding regions for Pittsburg, CA, are shown in Fig. 2 to provide an idea of the size of the models considered. The contingencies are based on the blue-cut fire that resulted in a line-to-line fault near Lugo, CA, and a similar fault near Kirker, CA (that represents the SERRANO fault mentioned above).

The results from the simulation of line-to-line fault contingencies in the two models developed are shown in Figs. 3 and 4 for Pittsburg, CA, and Victorville, CA, respectively. A comparison of the frequencies observed through the simulation of the developed and reference models in Figs. 3(a) and 4(a) indicate minor differences, with the fast changes well represented. Similarly, the voltages shown in Figs. 3(b) and 4(b) also indicate very close resemblance of the results generated from the developed model with the results from the reference model. The zoomed-in version of the voltage during the fault are shown in Figs.

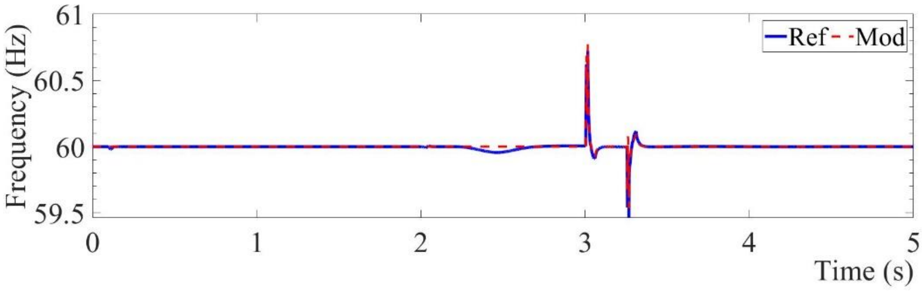
3(c) and 4(c), which shows that the high frequency dynamics in the voltages are adequately represented by the developed model of the ac grid. The results indicate that the development models (labelled as ‘Mod’ in the figures) provide adequate representation of voltage and frequency variations, when compared with respect to the reference models (labelled as ‘Ref’ in the figures).



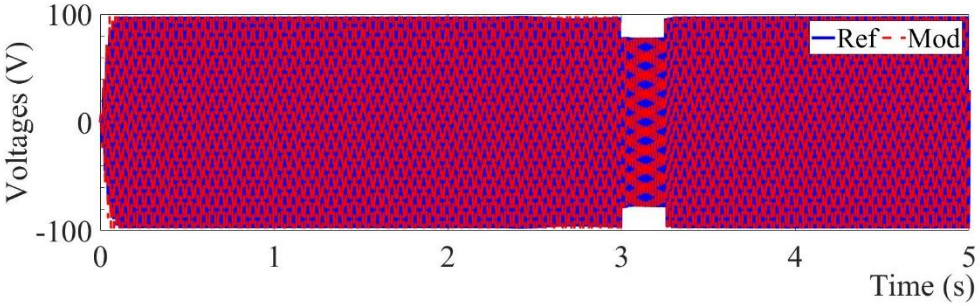
(a)

(b)

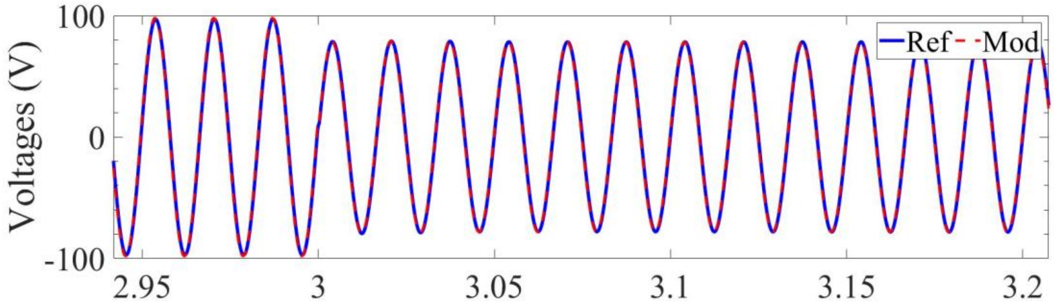
Figure 2: Local area considered at Pittsburg, CA: (a) Reference local area model, (b) Actual local area model [8]. The orange arrow indicates the location of fault considered with the fault location identified by the blue circle.



(a)

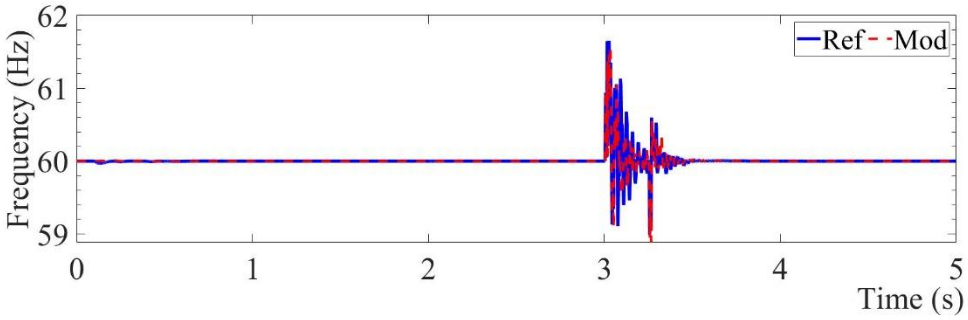


(b)

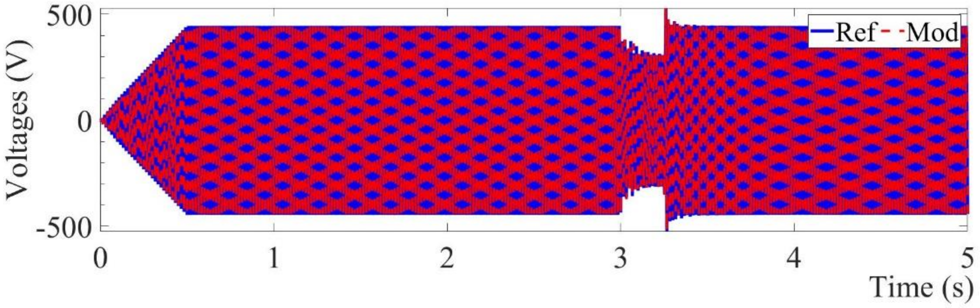


(c)

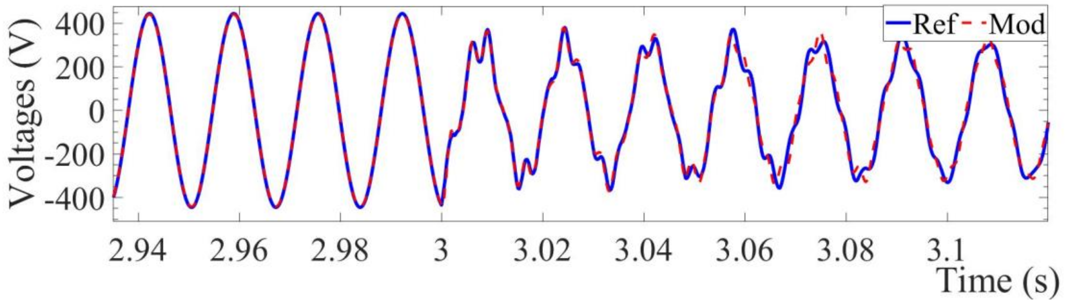
Figure 3: States measured at Pittsburg, CA, during fault near Kirker: (a) Frequency, (b) Voltage, and (c) Zoom-in voltage. “Ref” refers to the reference model and “Mod” refers to the developed model simulation results.



(a)



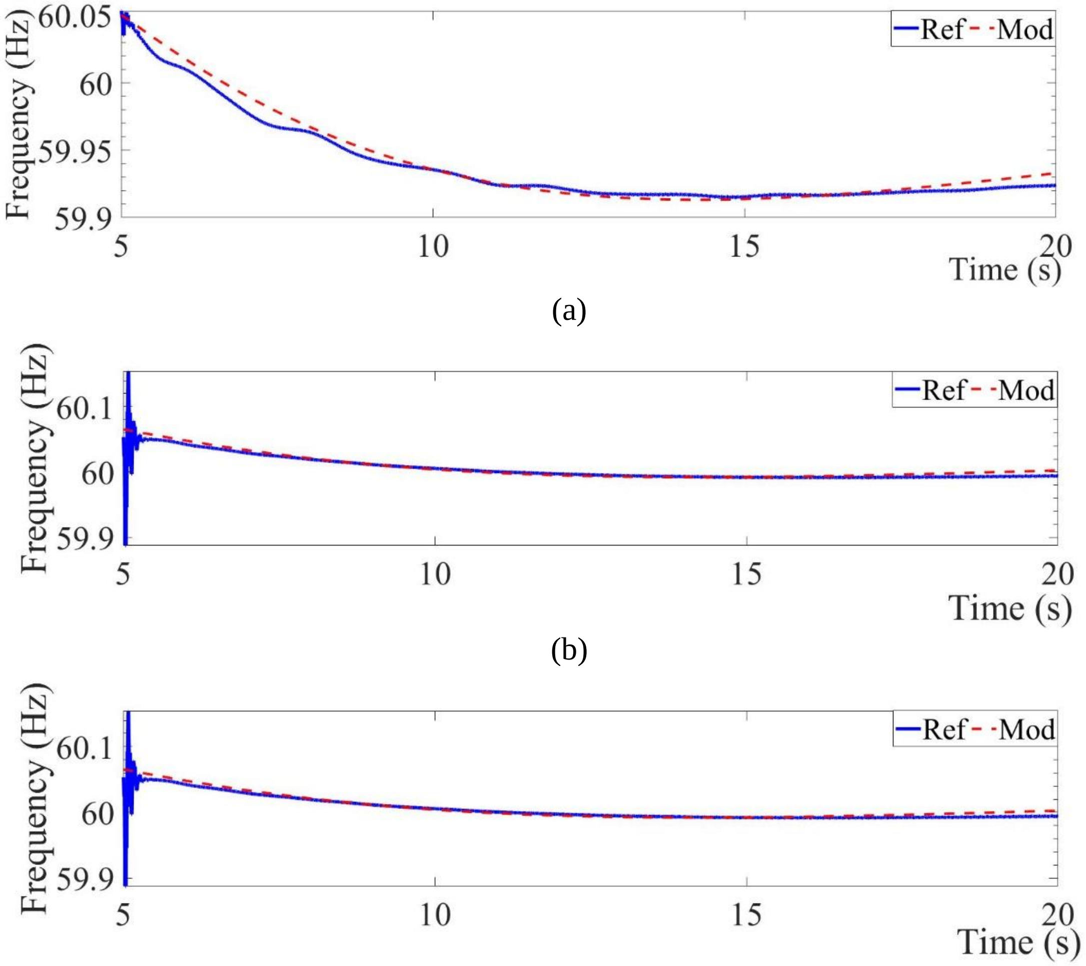
(b)



(c)

Figure 4: States measured at Victorville, CA, during fault near LUGO: (a) Frequency, (b) Voltage, and (c) Zoom-in voltage. "Ref" refers to the reference model and "Mod" refers to the developed model simulation results.

The results from the generator loss conditions mentioned in Table 1 are shown in Fig. 5. As shown in Fig. 5, the simulation results of the frequency dynamics from developed models closely resemble the results from the reference model. The reference model used here is based on the actual WECC grid model as described in PSS®E.



(c)

Figure 5: Frequency measured during: (a) Palo Verde generator loss, (b) generator loss near SFO, and (c) HAYNES3 generator loss. "Ref" refers to the reference model and "Mod" refers to the developed model simulation results.

CONCLUSIONS

A conversion method to develop the EMT models of grids from the TS models is described in this paper. The models are converted using E-Tran tool. There are challenges observed with the conversion tool, which are described in this paper. Mitigation methods are proposed to address them. Moreover, the converted models provided adequate representation of only the voltage dynamics. To provide adequate representation of frequency dynamics, data-driven models are incorporated into the converted models to develop the integrated models. The integrated models can be used to perform stability studies of control systems of single power electronic equipment or multiple power electronics-based systems in a region. They can also be utilized for analysis of extreme events using EMT simulations. The integrated models provide adequate representation of both voltage and frequency dynamics under defined contingencies on which they were tested.

ACKNOWLEDGEMENT

This paper is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number 34019.

The authors acknowledge Dr. Jiuping Pan from ABB and Dr. Sudipta Chakraborty from Opal-RT for their valuable inputs in this work. Authors would also to thank Dr. Jian Fu and Dr. Hariharan Krishnaswami for overseeing the project developments and providing guidance.

BIBLIOGRAPHY

[1] North American Electric Reliability Corporation. *1200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report.* 2016. [Online]. Available: https://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf
[2] North American Electric Reliability Corporation. *900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report.* [Online]. Available: https://www.nerc.com/pa/rrm/ea/October%209%202017%20Canyon%202%20Fire%20Disturbance%20Report/900%20MW%20Solar%20Photovoltaic%20Resource%20Interruption%20Disturbance%20Report.pdf
[3] North American Electric Reliability Corporation. *April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report.* [Online]. Available: https://www.nerc.com/pa/rrm/ea/April_May_2018_Fault_Induced_Solar_PV_Resource_Int/April_May_2018_Solar_PV_Disturbance_Report.pdf
[4] S. Debnath and J. Sun, "Fidelity Requirements with Fast Transients from VSC-HVdc," IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, 2018, pp. 6007-6014.
[5] YV Makarov, MA Elizondo, JG O'Brien, Q Huang, H Kirkham, Z Huang, M Chinthavali, S Debnath, N Mohan, W Hess, D Duebner, D Orser, H Brown, D Osborn, J Feltes, DK Chandrashekhara, W Zhu, "Models and methods for assessing the value of HVDC and MVDC technologies in modern power grids," Technical Report, PNNL-26640, Project GM 0074, Grid Modernization Laboratory Consortium, U.S. Department of Energy, July 2017.
[6] North American Electric Reliability Corporation. *Key Takeaways – Inverter Manufacturer and Relay Manufacturer Coordination Meeting*, April 2019.
[7] *Frequency Response and Frequency Bias Setting*, NERC Reliability Standard BAL-003-1, May 2009. [Online]. Available: https://www.nerc.com/pa/Stand/Reliability%20Standards/BAL-003-1.pdf

[8] California Energy Commission, https://www.energy.ca.gov/maps/infrastructure/3P_Enlg.pdf