Real-time Model Development of the IEEE Benchmark Distribution Feeder Test System for Microgrid Stability and Controls

Hamed Nademi, James Choi[*], Prottay Adhikari[*], Luigi Vanfretti[*], Shehab Ahmed[**], and Kourosh Sedghisigarchi[***]
California State University, San Marcos, CA 92096 USA
[*]Rensselaer Polytechnic Institute, Troy, NY 12180 USA
[**]King Abdullah University of Science and Technology, Saudi Arabia
[***]California State University, Northridge, CA 91330 USA

***Abstract*—The importance of power system real-time modeling and simulation is now evident due to its ability to support developers during design, prototyping and verification processes. Studying challenges faced during substantial integration of distributed energy resources (DERs) and distribution loads imposes diverse dynamic characteristics onto microgrids that need to be fully addressed from stability standpoint. This paper discusses the development of a real-time model of a microgrid distribution test case introduced in a prevalent IEEE PES technical report entitled IEEE PES-TR66. The model is developed using MATLAB/Simulink and RT-LAB tools employing switching equivalent circuits for power electronic components to build up DERs, solar PV and battery energy storage as well as distribution loads, such as variable-speed drives. Comparative performance analysis of the obtained results is provided for the developed benchmark test system during steady-state and transients. This real-time use case model is helpful to analyze microgrid stability and verify control designs to understand dynamics of a distribution feeder with multiple connected DERs for real-time hardware-in-the-loop (HIL) and controller HIL studies.**

Keywords—control design, motor load failure, power converters, real-time analysis, stability monitoring.

I. INTRODUCTION

Distributed Energy Resources (DERs) including wind, solar PV, battery energy storage (BES), geothermal, and backup diesel generators are being widely integrated throughout power grids. The connection of renewable energy resources to existing systems typically requires advanced simulation platforms and a common basis for analysis to achieve results with high fidelity and reduced risk [1]. Power systems modeling and simulation tools continue to evolve in order to deliver upon the required fidelity during large scale substantial integration of DERs to ensure that different grid and microgrid architectures are safely operating in compliance with smart grid operational requirements. Thus, the way of connecting renewable energies to the existing systems is too shortsighted. Instead, electric power supply systems must be further modernized to allow a larger scale integration of new resources. With its high scalability, photovoltaics and wind are the strongest driver of this change, affecting all areas of supply and utilization along the electric energy value chain.

In emerging renewable-based generation plants, the demand for an effective and frequent load isolation/reconnection to meet power variations and stability requirements has significantly increased [2], [3]. To achieve this goal, a seamless energy transition with the utility grid needs the implementation of schemes providing sufficient observability and stability monitoring on a real-time basis.

Unlike conventional grids with high inertia, power electronics-based future grids constitute of a huge number of non-synchronous incompatible players [3]. Consequently, the key question to be answered is: how does this change stability analysis and requirements? Particularly, for new energy and power systems with low inertia, this issue is more of a system-level problem; system design hand-in-hand with equipment/subsystem designs and it is pivotal to study those issues using a benchmark system for real-time testing. Notably, integrating millions of power electronics devices into distribution power networks could lead to harmonics or oscillations that could lead to instability issues, as articulated in recent studies [4]-[6].

This work describes the development of a real-time microgrid test system based on an IEEE use case specified in the IEEE PES-TR66 report [7] and shown in Fig. 1. The report is entitled “Microgrid Stability Definitions, Analysis, and Modeling” and aims to address the gap of educating and establishing standards for researchers interested in this subject. We aim to categorizes the potential modeling needs so that a real-time (RT) model can be executed through RT simulators such as OPAL-RT [8]. The microgrid model is developed using MATLAB utilizing switching equivalent circuits for power electronic components interfacing the generation systems comprising BES and PV as well as the industrial distribution loads such as variable-speed drives (VSD) and motors. A detailed configuration of the BES system and its design parameters is discussed in this paper.

The model shows a common 400V busbar connected to the point of common coupling (PCC) fed from the grid connected transformer and supplying different types of loads that sum up to 60 kW, with each load type having an equal capacity, i.e., 20 kW. The direct on-line (DOL) motor load is represented by a fan load (induction motor), and the VSD motor load with space vector modulation is represented by a pump load. DOL motors are widely used to start small motors. In practice, a DOL starter is employed if the motor’s high inrush current doesn’t result in an excessive voltage drop on the supply feeder, otherwise, a soft-started will be used to suppress the high voltage drop.

II. CONFIGURATION OF THE DEVELOPED REAL-TIME TEST SYSTEM FOR STABILITY MONITORING

It should be emphasized that the original IEEE model includes a ZIP load. This has been replaced by a variable load in this study for better evaluation of dynamic phenomena, especially in terms of motor starting and power surges. Fig. 2 shows an upgraded operational microgrid model that was developed for real-time simulation in this paper. Table I presents capacity ratings of the main generation sources and loads.

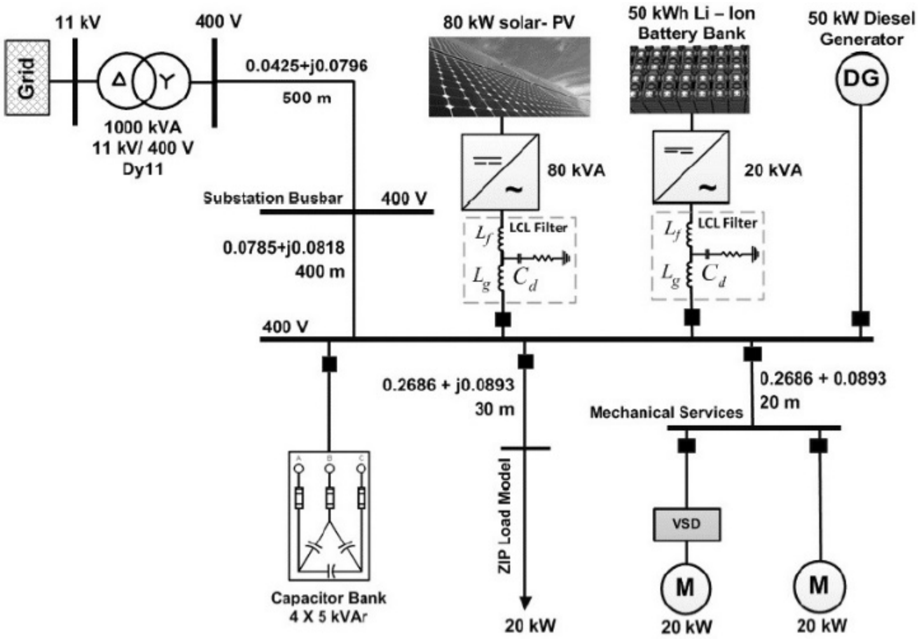

Fig. 1. IEEE Microgrid test system for dynamic and stability studies [7].

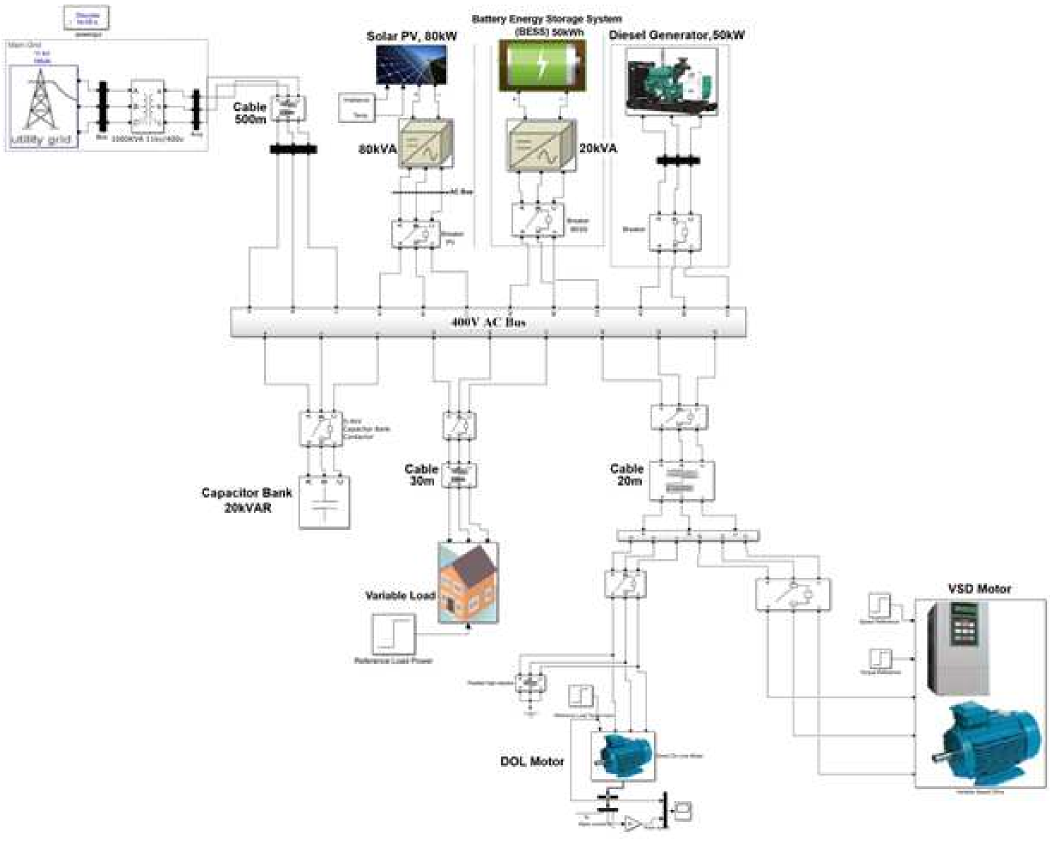

Fig. 2. Implemented IEEE Microgrid test system in RT-Lab used for real-time and HIL stability monitoring evaluation.

TABLE I

RATING VALUES AND SPECIFICATIONS OF THE MICROGRID USE CASE

Parameter	Value	Parameter	Value
PV Inverter Power	80kVA	Battery Inverter Power	20kVA
Diesel Generator Power	50kW	LI-ion Battery Capacity	50kWh
Variable Load Capacity	15kW-25kW	VSD / DOL Motor Rating	20kW
Busbar Voltage	400V	Utility Transformer Ratio	11kV / 400V

A. *Battery Energy Storage Architectures and Controls*

There are many different technologies that can be used for energy storage in power grids, including batteries, fuel cells and flywheels. A bidirectional DC-DC converter interconnected with the battery module offers flexibility to the system and makes it easier to control flow of energy to and from the battery. The most commonly available inverters for PV and BES are based on two blocks [9], [10]: a DC-DC converter and a DC-AC converter.

The developed DC-DC bidirectional converter is illustrated in Fig. 3. The bus inductors are chosen based on switching frequency and current ripples to fluctuate within tolerable limits [11]. The developed model is flexible enough to adopt key parameters for RT experiments considering application requirements. The main circuit parameters used in the converter model are listed in Table II.

TABLE II

CIRCUIT PARAMETERS FOR THE DESIGNED DC-DC BIDIRECTIONAL BATTERY STORAGE CONVERTER

Parameter	Value	Parameter	Value
Converter Inductance, L_1	40mH	Bus Capacitances and Resistances, C_1, C_2, R_{C1}, R_{C2}	2mF, 0.013 Ω
Bus Inductances, L_2, L_3	400μH	Switching Frequency	4kHz

RT-LAB has a built-in Lithium-ion battery model whose characteristics are shown in Fig. 4 and are based on the datasheet available in [12] for the Corvus AT6500 with rated capacity of 90Ah. The battery pack voltage will vary between 924V and 1050V if the state-of-charge (SOC) is kept above 60%.

There are two main control loops implemented for the battery module of interest in this study as briefly explained in the consecutive section.

B. *Current Control and Voltage Control Strategies*

There are two main control loops implemented for the battery module of interest in this study as briefly explained in the consecutive sections.

There are two control layers associated with the battery and DC-DC power converter. The current control loop generates the duty cycle for each of the IGBT switches by comparing a current reference signal and the measured current considering both battery charging and discharging modes. Therefore, Table III details four operational modes for the bidirectional converter depending on the direction of current and battery voltage. The control strategy considers one switch called "leading'' for each operating condition which dictates the bus inductor current gain for the represented operational mode.

The DC-bus voltage is allowed to fluctuate within an acceptable margin which dictates whether the battery module should deliver or consume power from the system. Thus, the

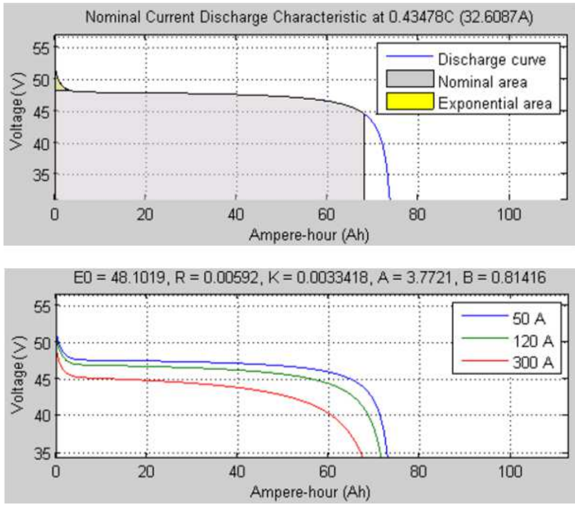

Fig. 4. Operational Characteristic Curves for 44.4V Battery Module (Single Battery Module).

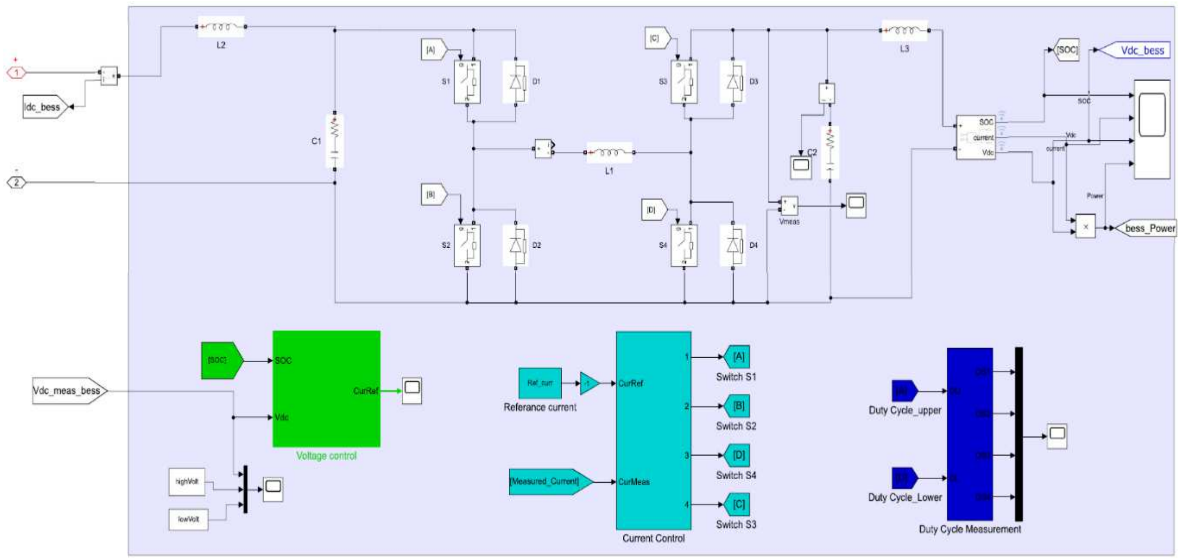

Fig. 3. Configuration of Battery Energy Storage Bidirectional DC-DC Conversion and Its Controls.

voltage control loop shall regulate the converter's reference current utilizing the bus voltage measurement and battery SOC%. The voltage control block is shown in Fig. 3. The DC-link voltage is intended to be maintained in the range of 880V-1050V, without the battery delivering or consuming power. Otherwise, when voltage violates the upper limit or lower limits the PI controller performs its function. Another controller input variable is the battery's SOC condition. The strategy used for regulating the output current reference is outlined in Table IV.

TABLE III
SWITCHING SCHEME FOR THE BATTERY UNDER DIFFERENT OPERATING CONDITIONS

Current Reference Status	Vbus > Vbattery	Vbus < Vbattery
Positive (Battery Charge Mode)	Buck mode S1 – Pulsing (leading) S2 – Pulsing S3 – On S4 – Off	Boost mode S1 – On S2 – Off S3 – Pulsing S4 – Pulsing (leading)
Negative (Battery Discharge Mode)	Boost mode S1 – Pulsing S2 – Pulsing (leading) S3 –On S4 – Off	Buck mode S1 – On S2 – Off S3 – Pulsing (leading) S4 – Pulsing

TABLE IV
LIMITS OF THE CURRENT CONTROL LOOP REFERENCE FOR THE GIVEN SOC

Range of SOC%	Imax	Imin
95%-100%	0	-110
65%-95%	110	-110
0-65%	110	0

III. REAL-TIME SIMULATION OF VARIOUS CASE-STUDIES

Several case studies have been executed using OPAL-RT and the obtained results are evaluated to verify acceptable performance of the microgrid and its different subsystems. Fig. 5 illustrates real power measurement for the Diesel Generator, BES and PV.

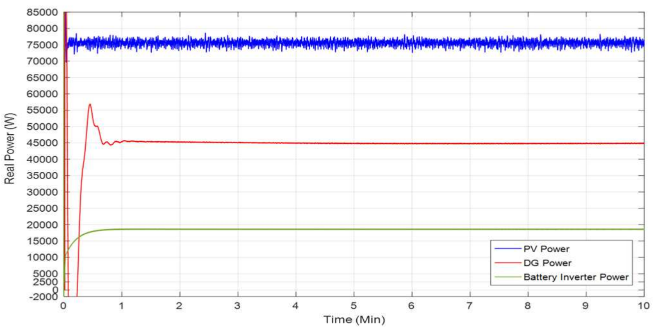

Fig. 5. Measured Active Power for Various Distributed Energy Resources.

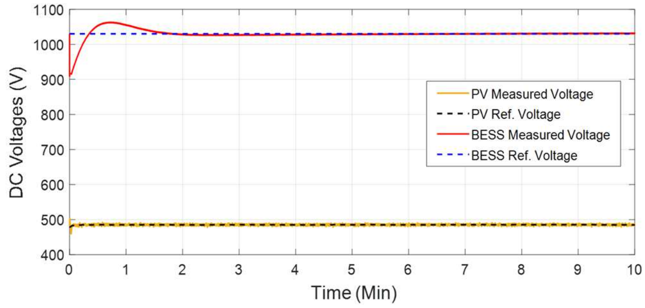

Fig. 6. DC Voltage Reference Tracking for BES and PV Generation. (BES Voltage Ref =1030V, and PV DC Voltage Ref =480V)

DC voltage reference tracking performance is compared with respective measured values for the battery energy storage and PV system indicating a reasonable controller performance as shown in Fig. 6. In the case of BES, a response time of 1min is assigned.

Fig. 7 provides the measured typical waveforms for a battery pack which includes four single batteries with operating characteristics given in Fig. 4.

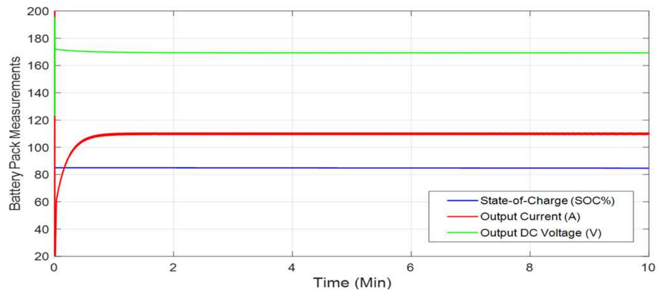

Fig. 7. Operating waveforms of the Battery Energy Storage During Charging Mode.

Another testing scenario is carried out to reflect performance of the entire system with respect to dynamic operating conditions. Therefore, the operating scenario is applied when the diesel genset is disconnected at t=4min and VSD motor torque is increased by 50% from 11 Nm to 16.5 Nm at t=7min. Measured VSD torque is compared with the reference value as presented in Fig. 8. Performance results of the diesel generator under this operating condition are also presented in Fig. 9 indicating an acceptable response that fulfills operational requirements.

The DOL motor load is represented by a fan load (induction motor), and the VSD motor load is represented by a pump load powered using an inverter controlled with space-vector modulation using a switching frequency of 4.5kHz. Finally, the response of the distribution loads during a sudden change in the residential variable load from 15kW to 25kW at t=7min has been monitored. In this test, the diesel genset is disconnected at t=4min. The obtained active power results are shown in Fig. 10.

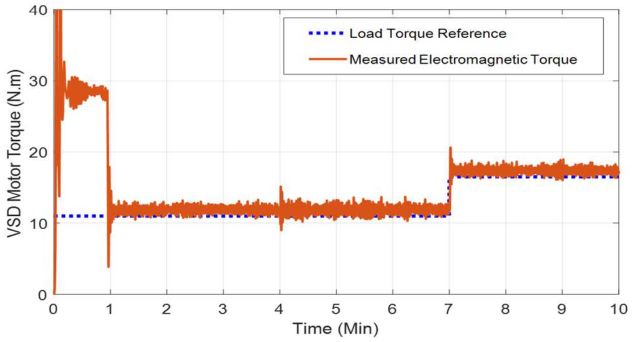

Fig. 8. Reference Torque Tracking in VSD Motor Load when Diesel Gen. Disconnected at t=4min, and Motor Torque Increased by 50% at t=7min.

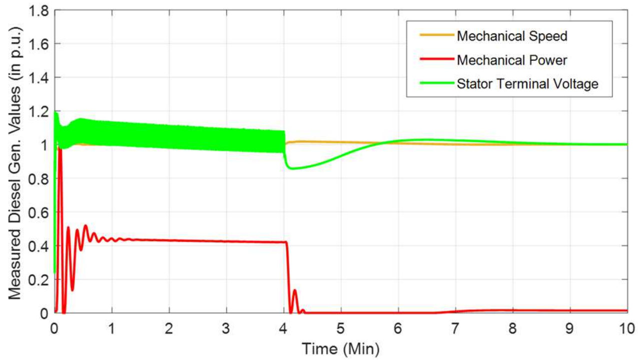

Fig. 9. Diesel Genset Waveforms in p.u. when Disconnected at t=4min, and VSD Motor Torque Increased by 50% at t=7min.

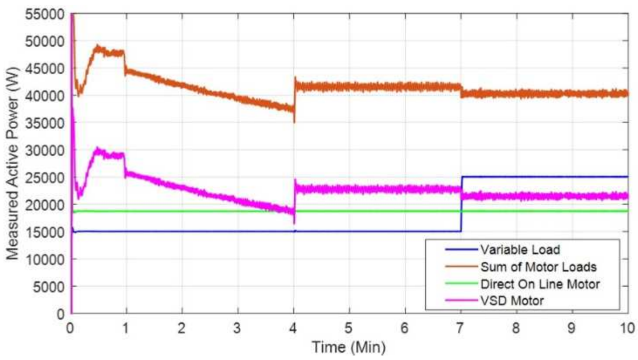

Fig. 10. Active Power Measurements when Diesel Generator Disconnected at t=4min, and Variable Load Capacity Increased by 70% at t=7min.

IV. Conclusions and Future Work

This work attempts to develop a real-time microgrid use case based on the IEEE PES-TR66 Technical Report to study emerging integration challenges of distribution systems with ramifications that reach consumers and DERs. The study of microgrids has become of utmost importance in electrical power research due to the bidirectional energy flow, islanded operation and the need for dynamics decoupling under significant presence of DERs. The real-time testing scenarios developed with the presented use-case aid in investigating the importance of the controls and load characteristics and their effects on microgrid stability analysis. A detailed model of each DER presented in this distribution feeder will be elaborated and supported by various real-time simulations and testing in our future publication.

V. Acknowledgment

This work was supported in part by the Center of Excellence for NEOM Research at the King Abdullah University of Science and Technology under grant OSR-2019-CoE-NEOM-4178.12, in part by NASA under award number 80NSSC19M0125 as part of the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA), and by the Engineering Research Center Program of the National Science Foundation and the Department of Energy under Award EEC-1041877, by the CURENT Industry Partnership Program.

References

[1] A. Benigni, T. Strasser, G. De Carne, M. Liserre, M. Cupelli, and A. Monti, "Real-Time Simulation-Based Testing of Modern Energy Systems: A Review and Discussion," *IEEE Industrial Electronics Magazine,* vol. 14, no. 2, pp. 28-39, June 2020.

[2] S. D. Silva, M. Shadmand, S. Bayhan, and H. Abu-Rub, "Towards Grid of Microgrids: Seamless Transition between Grid-Connected and Islanded Modes of Operation," *IEEE Open Journal of the Industrial Electronics Society,* vol. 1, pp. 66-81, April 2020.

[3] Q. C. Zhong, "*Power Electronics-Enabled Autonomous Power Systems-Next Generation Smart Grids*," Wiley-IEEE Press, 2020.

[4] K. Sebaa, Y. Zhou, Y. Li, A. Gelen, and H. Nouri, "Low-Frequency Oscillation Damping Control for Large-Scale Power System with Simplified Virtual Synchronous Machine," *Journal of Modern Power Systems and Clean Energy,* Early Access, pp. 1-12, May 2021.

[5] H. Nademi, K. Sedghisigarchi, and L. Vanfretti, "Coordinated Stability Assessment of Power Converter in Electric Vehicle Charging Station Using Predictive Control Reconfiguration," *in Proc. 28th IEEE International Symposium on Industrial Electronics (IEEE- ISIE 2019*), Vancouver, Canada, June 12-14, 2019.

[6] H. Nademi, K. Sedghisigarchi, and L. Vanfretti, "Real-time Validation of a DC-link Tuning Method for an AC-AC Wind Converter in Fractional Frequency Transmission System," *in Proc. 30th IEEE International Symposium on Industrial Electronics (IEEE- ISIE 2021*), Kyoto, Japan, June 20-23, 2021.

[7] IEEE PES Task Force on Microgrid Stability Analysis and Modeling, "TR66: Microgrid Stability Definitions, Analysis, and Modeling," June 2018.

[8] OPAL-RT Technologies. OP5600, Available at: https://www.opal-rt.com/simulator-platform-op5600/

[9] B. H. Xiao, "Overview of Transformerless Photovoltaic Grid-Connected Inverters," *IEEE Transactions on Power Electronics,* vol. 36, no. 1, pp. 533-548, Jan. 2021.

[10] Y. Yang, P. Enjeti, F. Blaabjerg, and H, Wang, "Wide-Scale Adoption of Photovoltaic Energy: Grid Code Modifications Are Explored in the Distribution Grid," *IEEE Industry Applications Magazine,* vol. 21, no. 5, pp. 21-31, Sept./Oct. 2015.

[11] N. Mohan, T. Undeland, W. Robins, "*Power Electronics- Converters, Applications, and Design*," John Wiley & Sons, Inc., 2003.

[12] Energy Corvus, "*Data sheet for AT6500*," Available at: http://www.corvus-energy.com/pdf/AT6500_Data_Sheet_2_page.pdf