Preprints of the 5th IEEE Conference on Energy Internet and Energy System Integration
October 22- October 25, 2021. Taiyuan, China

Impacts of VSG Control on Frequency Response in Power Systems with High-Penetration Renewables

Jinning Wang
Department of Electrical Eng. & Computer Eng.
University of Tennessee, Knoxville
Knoxville, USA
jwang175@vols.utk.edu

Fangxing Li*
Department of Electrical Eng. & Computer Eng.
University of Tennessee, Knoxville
Knoxville, USA
fli6@utk.edu

Hantao Cui
Department of Electrical Eng. & Computer Eng.
University of Tennessee, Knoxville
Knoxville, USA
hcui7@utk.edu

Qiwei Zhang
Department of Electrical Eng. & Computer Eng.
University of Tennessee, Knoxville
Knoxville, USA
qzhang41@vols.utk.edu

***Abstract*— With the increase of renewable energy into power systems, the system inertia continuously decreases, which poses challenges to the existing frequency regulating strategy. To improve system frequency response in the low-inertia system, Virtual Synchronous Generator (VSG) has been proposed in the literature. This paper investigates the VSG frequency response model and verifies the implementation at large scale. First, the frequency response model of VSC is investigated. In addition, the frequency response performance of the conventional synchronous generator (SG), the renewable power plant, and the renewable power plant with VSG are compared under different penetration levels of renewable energy. The simulation results show the capability of the CURENT Large-scale Testbed (LTB) for real-world, large-scale power system simulation in future scenarios and indicate that VSG-configured renewable power plants can provide the power grid with adequate frequency regulation ability under high renewable energy penetration.**

Keywords—VSG, frequency response, power system simulation, high renewable penetration.

I. Introduction

In recent years, renewable power generation has emerged as an important power generation resource. Solar and wind power generations are 39% and 31% out of the newly installed power generation capacity in the US, respectively, in 2021 [1]. At the same time, the conventional power generation units have been gradually retired. As a consequence, the system frequency stability is threatened by the decreased system inertia [2]. To guarantee sufficient reserve for securing system frequency, emerging technologies are used to provide frequency support. An inertia emulation control strategy for VSC-HVDC was proposed in [3]. Research work addressing the second frequency drop in wind power plant frequency response was compensated by a frequency compensation strategy [4]. Frequency reserve can be shared across the interconnected system [5], and the proposed corrective frequency control can secure the system frequency in a predefined range. For a renewable power plant, the Virtual Synchronous Generator (VSG) control has drawn research interests, which is also named synchro-converters [6] or VISMA (Virtual Synchronous Machine) [7]. The study in [8] proposed a novel VSC (Voltage Source Converter) which can behave as a conventional synchronous generator (SG) with power synchronization control, and thus can provide the system with strong support. Current source controlled VSG was reported to be prone to instability, whereas voltage-controlled VSG has the advantage of maintaining stability [9]. However, these studies focused on small-scale renewable power and left the verification of VSG uninvestigated in large-scale system with high renewables.

The power grid develops towards integrating renewable power generation and wide-area monitoring and control [10][11], which challenges the system modeling by enlarging the system complexity. As a result, it is desired to develop a closed-loop testing tool to simulate the actual power grid. Integrating different packages for co-simulation is an economical solution that can reduce the development investment. Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) is a low-cost way for users to utilize multiple modules [12], but not all the modules follow the same assumptions. Thus the validity of the results may not be guaranteed. Another solution is to design different modules in a common environment for numeric iteration and module interfaces, like iTesla, [13]. However, it requires high-level multi-domain knowledge. Therefore, the newly developed close-loop co-simulation software called CURENT Large-Scale Testbed (LTB) [14]-[16] is used for the research purpose as a virtual grid. The CURENT LTB consists of independent packages, and such decoupled structure ensures the platform flexibility and fidelity.

In this paper, the frequency response model of VSG is investigated and compared with conventional SG. In the frequency response, the VSG can be recognized as a conventional SG without turbine and governor. The VSG frequency response model is verified by the simulation results, which are implemented in the newly developed CURENT LTB. Also, the simulation results indicated that the LTB is capable of modernized power system simulation under emerging scenarios. The contribution of this paper can be summarized as follow:

1) Using the closed-loop simulation of the newly developed modernized power system co-simulation platform LTB, the VSG frequency response model is investigated in this paper.

2) Based on the LTB, the frequency response comparison between conventional SG, the renewable power plant, and the renewable power plant with VSG is conducted under different renewable penetration levels.

This paper is organized as follows: Section II reviewed the VSG control scheme and investigated the VSG frequency response model. Section III discussed the newly developed simulation platform LTB. Section IV conducted different renewable penetration level simulations using the LTB. Finally, Section V concluded this paper.

II. VSG Control Scheme and Frequency Response Model

A. VSG Control Scheme

A VSG-controlled VSC operates as a voltage source seen from the grid side. The terminal voltage and frequency are controlled by themselves rather than locked from the grid. Such characteristics enable the VSC to behave like a conventional generator. The droop control is used to generate the frequency reference, by which the virtual inertia is implemented to support the system frequency response.

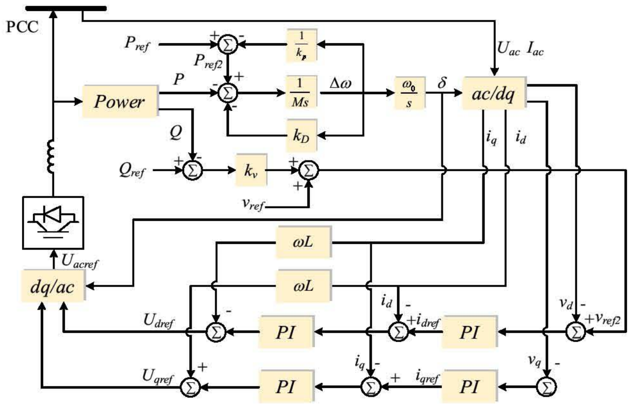

Fig.1. VSG Control Scheme

Fig.1.illustrates the VSG control scheme. The reactive power regulation loop realizes the automatic voltage control:

$$v_{ref2} = v_{ref} + k_v(Q_{ref} - Q) \tag{1}$$

where v_{ref} is the voltage reference, Q_{ref} is the reactive power reference, Q is the measured output reactive power from VSG, k_v is the voltage regulation coefficient, and v_{ref2} is the adjusted voltage reference.

The active power regulation loop is used to mimic the droop control, as shown in equation (1):

$$P_{ref2} = \mathrm{P}_{ref} - \frac{1}{k_p}\Delta\omega \tag{2}$$

where P_{ref} is the power reference, P_{ref2} is the adjusted power reference, k_p is the virtual droop coefficient, and $\Delta\omega$ is the speed deviation.

The virtual swing equation is used to emulate virtual inertia. The generated virtual speed and virtual power angle are used as the phase reference for the dq transformation:

$$Ms\Delta\omega = \mathrm{P}_{ref2} - P - k_D\Delta\omega \tag{3}$$

$$s\delta = \omega_0\Delta\omega \tag{4}$$

where M is the virtual inertia, k_D is the virtual damping coefficient, δ is the virtual power angle, P is the measured VSG active power output, and ω_0 is the nominal speed.

Then voltage reference is tracked by PI controllers:

$$i_{dref} = (k_p + k_i\frac{1}{s})(v_{ref2} - v_d) \tag{5}$$

$$i_{qref} = (k_{p2} + k_{i2}\frac{1}{s})(-v_q) \tag{6}$$

where v_d and v_q are the d and q axis voltage, and i_{dref} and i_{qref} are the d and q axis current reference.

The generated current reference is tracked by PI controllers and used to generate the converter modulation voltage reference:

$$u_{dref} = (k_{p3} + k_{i3}\frac{1}{s})(i_{dref} - i_d) + v_d + \omega L i_q \tag{7}$$

$$u_{qref} = (k_{p4} + k_{i4}\frac{1}{s})(i_{qref} - i_q) + v_q - \omega L i_d \tag{8}$$

where u_{dref} and u_{qref} are the d and q axis voltage reference, respectively.

The converter switching modulation behavior introduces a time delay T_c between the voltage reference and the actual converter terminal voltage:

$$u_d = \frac{1}{1+sT_c}u_{dref} \tag{9}$$

$$u_q = \frac{1}{1+sT_c}u_{qref} \tag{10}$$

where u_d and u_q are the d and q axis voltage output, respectively.

B. Frequency Response Model Comparison between SG and VSG

In the primary frequency control, the active power reference point is considered unchanged, thus (3) can be written as:

$$Ms\Delta\omega = -\Delta P - \frac{1}{k_p}\Delta\omega \tag{11}$$

where ΔP is the load change.

The load change is considered as frequency insensitive load and frequency sensitive load:

$$\Delta P = \Delta P_L + D\Delta\omega \tag{12}$$

where D is the system damping constant.

Thus, the frequency response from the VSG can be obtained as:

$$\frac{\Delta\omega_{VSG}}{-\Delta P_L} = \frac{1}{Ms + D + \frac{1}{k_P}} \tag{13}$$

In contrast, the frequency response from the conventional synchronous generator with TGOV1 turbine and governor model is given by:

$$\frac{\Delta\omega_{SG}}{-\Delta P_L} = \frac{1}{Ms + D + \frac{1}{R}\frac{1}{1+sT_1}\frac{1+sT_2}{1+sT_3} + D_t} \tag{14}$$

The steady frequency response to sudden load change can be obtained as:

$$\lim_{s\to 0} s\Delta\omega_{VSG}\frac{-\Delta P_L}{s} = \frac{1}{D + \frac{1}{k_P}} \tag{15}$$

$$\lim_{s\to 0} s\Delta\omega_{SG}\frac{-\Delta P_L}{s} = \frac{1}{D + \frac{1}{R} + D_t} \tag{16}$$

It can be seen that the stable frequency point from VSG and SG are similar. Thus, the VSG control can provide the system with adequate frequency support during the frequency excursion.

III. Cyber-Physical Close-Loop Co-Simulation Software: CURENT LTB

The CURENT LTB is a cyber-physical close-loop co-simulation software designed to emulate the actual power system and communication network for research purposes. The platform aims at large-scale power grid and cyber network modeling that involves a large number of buses, power system devices, and cyber networks.

A. LTB Platform Structure

The LTB is designed in a decoupled manner to represent the modernized large-scale power system closed-loop dynamics. It consists of distributed packages, i.e., power system simulation engine - LTB ANDES [16] [17], distributed messaging environment - LTB DiME, virtual cyber network - LTB Network, and virtual control room – LTB Control Center. Each package works independently and simultaneously to simulate the actual power grid.

The platform structure is demonstrated in Fig.2. LTB ANDES is capable of power flow analysis, time-domain simulation, and eigenvalue analysis. It enables LTB to acquire the power system dynamics. LTB DiME provides communication clients and servers for the devices that need communication. Then, the data can be transferred to the virtual control room through the LTB Network. Further, the virtual control room will feedback the control signal generated by a predefined control algorithm to the actuators through the LTB Network.

B. Power System Simulation Engine – LTB ANDES

LTB ANDES is an open-source power system simulation package based on Python. The differential algebraic equations (DAE) are modeled through the hybrid symbolic-numeric framework.

The hybrid symbolic-numeric framework allows descriptive DAE modeling and fully automated code generation. The model library provides a rich source for transfer functions and non-linear components. It enables fast prototyping by manufacturing given pieces. The renewable power generation library is developed as industry-grade such as type III and type IV wind turbine with aerodynamics, distributed photovoltaic power generation, and energy storage system.

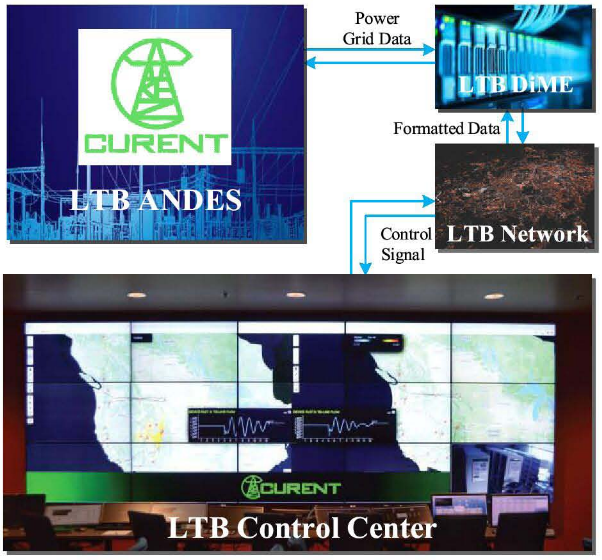

Fig.2. The CURENT LTB structure

In conventional commercial software for power system simulation such as PSS/E, users are not able to access the detailed implementation source code although detailed documentation is provided. It limits the user's degree of freedom when developing a power system model. In contrast, LTB ANDES supports a fully user-defined system, which means the users are allowed to model as wish either with existing models or easily implemented a new prototype model.

C. Distributed Messaging Environment – LTB DiME

LTB DiME is a distributed messaging environment for communication between modules. In the DiME, each module is equipped with a distributed messaging client, and all the clients exchange messages through the data server. It should be noted that DiME only serves as the communication channel for data exchange, whereas the data formats are defined by the modules rather than the server and client.

D. Virtual Cyber Network – LTB Network

The cyber networks, including hardware and software, are essential for wide-area monitoring and control study. LTB Network provides the ability to model the network and emulate the communication behaviors. Simulating the network by software provides a low-cost and high feasibility approach for research and prototyping purposes.

E. Virtual Control Room – LTB Control Center

The virtual control room is constructed as the virtual power grid control center of the LTB, as shown in the bottom subfigure of Fig.2. The objective of the virtual control room is to monitor the system operation and achieve the real-time visualization of the real-time simulated operating conditions and the obtained results based on the advanced LTB functions. The real-time visualization example of the LTB is shown in Fig.3. The system frequeny deviation can be displayed for real-time visualization and monitoring.

IV. Case Study

A. Test System

NPCC 140 bus system shown in Fig.4.is used as the benchmark system in this paper. The system model contains 140 buses and 48 synchronous generators. The generators are modeled as 21 GENCLS and 27 GENROU. Some of the synchronous generators are equipped with turbine governor model TGOV1 and exciter IEEEX1.

The three renewable energy source penetration levels, 20%, 40%, and 60%, are realized by replacing the conventional synchronous generator with the renewable power plant. To simplify the simulation, the VSG parameters are chosen the same as the replaced synchronous generators, including the droop rate, virtual inertia, and virtual damping coefficient.

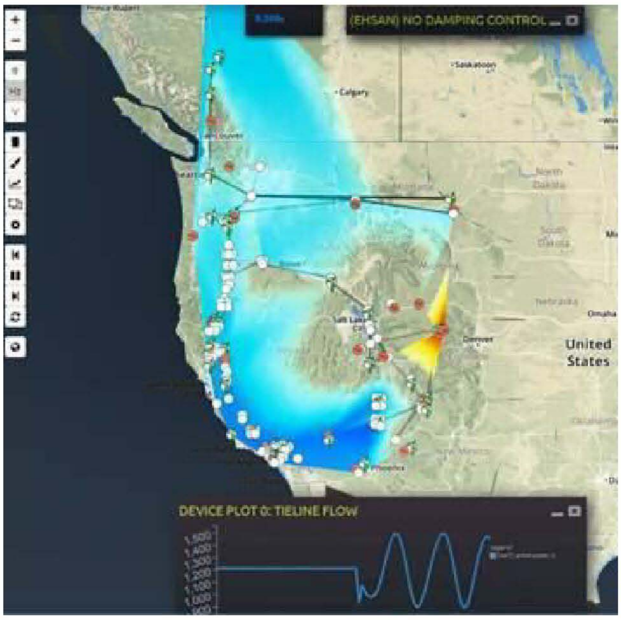

Fig.3. LTB Control Center Real-time Visualization

The test system is built in LTB 1.0 with LTB ANDES 1.3.6, on a computer with Intel(R) Core(TM) i7-8650U processors, clocking at 1.90 GHz, and 16 GB RAM.

Fig.4. NPCC 140 Bus System Single-line Diagram

B. *Simulation Results of High Renewable Penetration System*

The generator with an active power reference set at 1650MW is tripped at 1s. The loss of active power out of the 5.9% of system total active power. The COI (center of inertia) frequency is calculated to illustrate the system frequency response. It should be noted that generally, the renewable power plant is not considered in the COI frequency calculation, whereas the renewable power plant with VSG control is included in the COI frequency calculation.

Fig. 5.shows the system frequency response under 20% renewable penetration. It can be seen that compared with the base case, the frequency nadir decrease from 59.912 Hz to 59.905 Hz, and the frequency stable point also decreased from 59.932 Hz to 59.920 Hz.

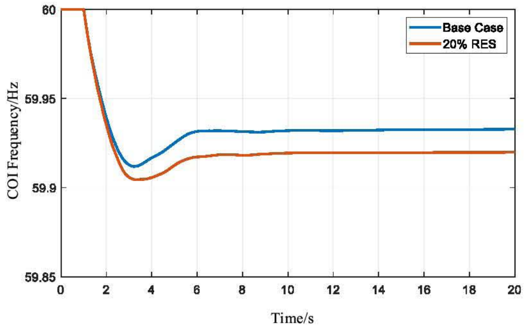

Fig.5. System frequency response with 20% renewable energy source penetration

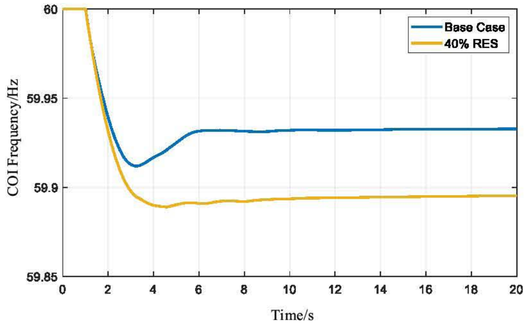

Fig.6. System frequency response with 40% renewable energy source penetration

Fig. 6.shows the system frequency response under 40% renewable penetration. It can be seen that compared with the base case, the frequency nadir decrease from 59.912 Hz to 59.889 Hz, and the frequency stable point decreased from 59.932 Hz to 59.895 Hz.

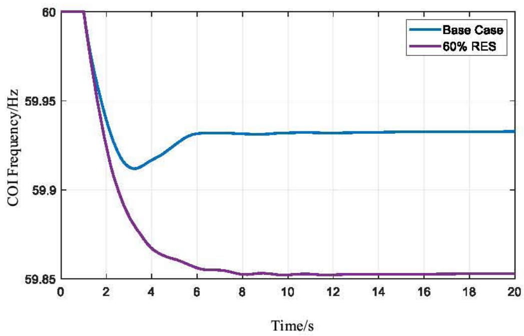

Fig.7. System frequency response with 60% renewable energy source penetration

Fig. 7.shows the system frequency response under 60% renewable penetration. It can be seen that, if compared with the base case, the frequency dropped more. The frequency stable point drops from 59.932 Hz to 59.853 Hz. The system takes a longer time to reach the stable point.

From Figures 5-7 it can be seen that the increased renewable energy source penetration level worsens the system frequency response. This is because the renewable power plant does not provide additional active power support, which would impose pressure on system frequency regulation.

Fig. 8.shows the system frequency response under 20% renewable energy source penetration with VSG control. It can be seen that the frequency nadir increased from 59.912 Hz to

59.916 Hz. The frequency stable point remains almost the same.

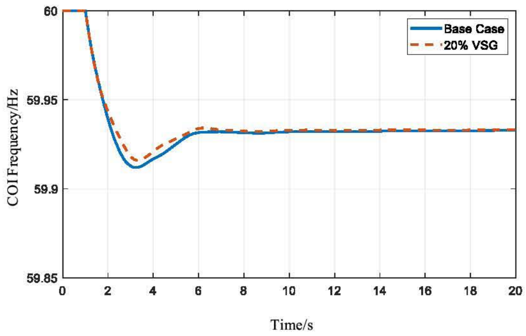

Fig.8. System frequency response with 20% VSG controlled renewable energy source penetration

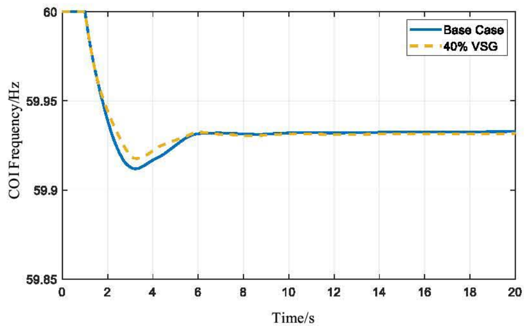

Fig.9. System frequency response with 40% VSG controlled renewable energy source penetration

Fig. 9.shows the system frequency response under 40% renewable energy source penetration with VSG control. It can be seen that the frequency nadir increased from 59.912 Hz to 59.917 Hz. Also, the frequency stable point remains almost the same.

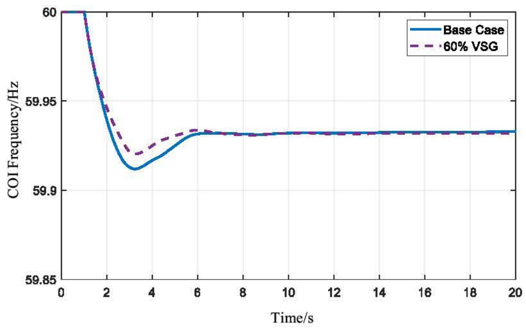

Fig.10. System frequency response with 60% VSG controlled renewable energy source penetration

Fig. 10.shows the system frequency response under 60% renewable energy source penetration with VSG control. It can be seen that the frequency nadir increased from 59.912 Hz to 59.920 Hz. Similar to the cases at 20% and 40% renewable penetration levels, the final steady-state frequency also remains the same.

The simulation results are summarized in the Table 1. It can be seen that the VSG frequency response is similar to the SG. The frequency response of VSG is slightly superior than the SG, because the VSG does not undergo the time lag introduced by the turbine and governor. The results also verify the proposed VSG frequency response model in Section II.

TABLE I. SIMULATION RESULTS

Simulation Results		Renewable Penetration Level		
		20%	40%	60%
Conventional Control	Nadir	59.905	59.889	59.853
	Stable Point	59.92	59.895	59.853
VSG Control	Nadir	59.916	59.917	59.92
	Stable Point	59.932	59.932	59.932

The simulation results show that the renewable power source without any additional control would impose great frequency response pressure on the power grid. In contrast, the VSG control is able to maintain the system frequency regulation ability. Thus it can be an adequate alternative in large-scale power systems under high renewable energy source penetration conditions.

The case study also indicates that CURENT LTB is capable of implementing large-scale power system simulations with emerging scenarios.

V. CONCLUSION

In this paper, the frequency response model of VSG is proposed and verified in a realistic power system. First, the frequency response model of VSG-controlled renewable power plants is investigated. The frequency response from SG and VSG are compared. Second, the open-source closed-loop power grid simulation software, CURENT LTB, is used. The case study shows that the VSG control is a convincing solution to provide the system with adequate frequency regulation ability under the high-penetration scenarios of renewable energy sources. The simulation study also indicates that the LTB is capable of large-scale realistic power grid simulation with emerging research challenges.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support provided by the Engineering Research Center Program of the National Science Foundation and the Department of Energy under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

REFERENCES

[1] U.S. Energy Information Administration (EIA), Renewables account for most new U.S. electricity generating capacity in 2021.

[2] S. Sharma, S.-H. Huang, and N. D. R. Sarma, "System Inertial Frequency Response estimation and impact of renewable resources in ERCOT interconnection," in *2011 IEEE Power and Energy Society General Meeting*, Detroit, MI, USA, Jul. 2011, pp. 1–6.

[3] J. Zhu, C. D. Booth, G. P. Adam, A. J. Roscoe, and C. G. Bright, "Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1277–1287, May 2013.

[4] K. Sun *et al.*, "Frequency secure control strategy for power grid with large-scale wind farms through HVDC links," *International Journal of Electrical Power & Energy Systems*, vol. 117, p. 105706, May 2020.

[5] K. Sun, H. Xiao, L. Sundaresh, J. Pan, K. Li, and Y. Liu, "Frequency response reserves sharing across asynchronous grids through MTDC system," *IET Generation, Transmission & Distribution*, vol. 13, no. 21, pp. 4952–4959, Nov. 2019.

[6] Q.-C. Zhong and G. Weiss, “Synchronverters: Inverters That Mimic Synchronous Generators,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011.

[7] H.-P. Beck and R. Hesse, “Virtual synchronous machine,” in *2007 9th International Conference on Electrical Power Quality and Utilisation*, Barcelona, Spain, Oct. 2007, pp. 1–6.

[8] L. Zhang, L. Harnefors, and H.-P. Nee, “Power-Synchronization Control of Grid-Connected Voltage-Source Converters,” *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 809–820, May 2010.

[9] W. Wu *et al.*, “Sequence Impedance Modeling and Stability Comparative Analysis of Voltage-Controlled VSGs and Current-Controlled VSGs,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 8, pp. 6460–6472, Aug. 2019.

[10] S. Poudel, Z. Ni, and N. Malla, “Real-time cyber physical system testbed for power system security and control,” *International Journal of Electrical Power & Energy Systems*, vol. 90, pp. 124–133, Sep. 2017.

[11] A. Ahadi, N. Ghadimi, and D. Mirabbasi, “An analytical methodology for assessment of smart monitoring impact on future electric power distribution system reliability,” *Complexity*, vol. 21, no. 1, pp. 99–113, Sep. 2015.

[12] B. Palmintier, D. Krishnamurthy, P. Top, S. Smith, J. Daily, and J. Fuller, “Design of the HELICS high-performance transmission-distribution-communication-market co-simulation framework,” in *2017 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES)*, Pittsburgh, PA, Apr. 2017, pp. 1–6.

[13] L. Vanfretti, T. Rabuzin, M. Baudette, and M. Murad, “iTesla Power Systems Library (iPSL): A Modelica library for phasor time-domain simulations,” *SoftwareX*, vol. 5, pp. 84–88, 2016.

[14] F. Li, K. Tomsovic, and H. Cui, “A Large-Scale Testbed as a Virtual Power Grid: For Closed-Loop Controls in Research and Testing,” *IEEE Power and Energy Mag.*, vol. 18, no. 2, pp. 60–68, Mar. 2020.

[15] H. Cui, F. Li, and K. Tomsovic, “Cyber-physical system testbed for power system monitoring and wide-area control verification,” *IET Energy Systems Integration*, vol. 2, no. 1, pp. 32–39, Mar. 2020.

[16] H. Cui, F. Li, and K. Tomsovic, “Hybrid Symbolic-Numeric Framework for Power System Modeling and Analysis,” *IEEE Trans. Power Syst.*, vol. 36, no. 2, pp. 1373–1384, Mar. 2021.

[17] H. Cui, F. Li, "ANDES: A Python-Based Cyber-Physical Power System Simulation Tool," North American Power Symposium (NAPS) 2018, 6 pages, Fargo, ND, Sept. 9-11, 2018.