

Open-Source PSCAD Grid-Following and Grid-Forming Inverters and a Benchmark for Zero-Inertia Power System Simulations

Preprint

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Open-Source PSCAD Grid-Following and Grid-Forming Inverters and a Benchmark for Zero-Inertia Power System Simulations

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Abstract—This paper presents open-source, flexible, and easilyscalable models of grid following and grid forming inverters for the PSCAD software platform. The models are intended for system integration studies, particularly transient stability analyses of power systems with a high penetration of inverter-based generation. To verify the model functionality, they are implemented in a IEEE 9-bus system in a zero-inertia operational scenario of 100% inverter-based generation where the presence of gridforming inverters are necessary. The models, including the 9 bus network, have been made available open source at the PyPSCAD NREL GitHub page (https://github.com/NREL/PyPSCAD).

Index Terms—inverter-based resources, generic models, PSCAD, zero inertia, power system stability

I. INTRODUCTION

As power systems across the globe continue to realize the trend of increasing renewable, inverter-based resources, the frequency, magnitude, and duration of instantaneous shares of these resources similarly increases [1]. The resultant power system operating conditions are unprecedented, with the hitherto backbone of power system stability, the synchronous generator, being significantly displaced; associated practical considerations require redress prior to the low/zero inertia operation of larger power systems. Not only does this displacement posit significant questions about dynamic stability during low inertia conditions [2], there are substantial concerns about the capability of traditional power system dynamics software to capture faster dynamics in inverter dominated power systems [3]–[6]. These computational concerns have driven a shift towards a larger utilization of electromagnetic transient (EMT) software, e.g., Power Systems Computer Aided Design (PSCAD), for general power system dynamics analysis. EMT simulations treat power system lines as differential elements and include time travel delays as applicable. Additionally, the requisite time-steps to achieve such differential modelling are small enough to capture the inner current controller dynamics of inverters. Both the differential treatment and current controller modelling are not readily possible in positive sequence simulations. Within these EMT softwares, there is a substantial need for generic inverter models, of which this work provides a solution.

Broadly speaking, generic, transparent, and open-source dynamic models are essential to conducting comparable, reproducible, and insightful collaborative research within the broader power systems community because their input/output variables and dynamics are comprehensively explained and understood. Significant efforts to develop generic models are evident in the positive sequence software domain, both for traditional synchronous generator models (e.g., GENROU, GGOV1, AC1A, etc.), and more recently in the renewable energy device space [7], [8]. With increased use of EMT software, there remains a need for generic inverter models that are transparent, per unitized, and widely available. The need for generic models does not obviate the need for plant-specific models for interconnection studies, which are seldom available outside of project-specific non-disclosure agreements and are thus of minimal use to the research community. Therefore, generic, flexible and transparent EMT inverter models are required to enable the study and analysis of emerging and future power system dynamics.

This paper introduces two generic inverter models established in PSCAD for applications in system integration studies and stability analysis. The first model is for the ubiquitous grid-following (henceforth referred to as GFL) inverter, with the control objective to export a set power quantity into an energized power system. Although a detailed photovoltaic GFL inverter model, including solar cell operation and switching phenomenon, has been presented in [9], this model contains more detail than preferred for system studies, is not scalable, nor available to the public. The second model is a grid-forming (henceforth referred to as GFM) inverter, based on the multidroop configuration with the control objective to regulate the local frequency and voltage. These models, based on various academic resources, are fully transparent, entirely editable, and publicly available from the PyPSCAD NREL GitHub page [10]. These models are verified in the PSCAD environment using a modified IEEE 9-bus system operated with only these inverter models; i.e., a zero inertia system.

II. MATHEMATICAL FORMULATION OF PSCAD MODELS

In this section, we present the mathematics of the computational models. The PSCAD GFL and GFM inverter models have been constructed as library instances with complete parameter interaction via the component menus. These models are fully per unitized, with all passive component values and controller gains scaled according to the device voltage and power ratings. Values that have yielded stability in a variety of scenarios are the default settings. Switching dynamics are neglected; the current controller output voltage setpoints $(v_{i,*}^{dq})$ are direct commands to the ideal voltage sources on each phase (i.e., there is no pulse width modulation modeling, which is a reasonable and well established assumption in power electronics modelling [11]).

A. Common Control Mechanisms

The control mechanisms are implemented in the dq frame, which is accomplished via the transformation of the three phase voltage and current waveforms according to (1):

$$\bar{x}_{dq} = T_{dq}\bar{x}_{abc} \tag{1}$$

where \bar{x}_{abc} is a column vector of the sinusoidal three phase quantities, \bar{x}_{dq} is a column vector of the d and q axis quantities, with the over-bar to distinguish from the subsequently used imaginary plane representation, and T_{dq} is the 2 × 3 transformation matrix, given in (2):

$$T_{dq} = \frac{2}{3} \begin{bmatrix} Cos(\theta_r) & Cos(\theta_r - \frac{2\pi}{3}) & Cos(\theta_r + \frac{2\pi}{3}) \\ Sin(\theta_r) & Sin(\theta_r - \frac{2\pi}{3}) & Sin(\theta_r + \frac{2\pi}{3}) \end{bmatrix}$$
(2)

The reference phase, θ_r , is the output of the phase-locked loop (PLL) for the GFL implementation (see (12), (13), and (14)). For the GFM model, θ_r is the resultant frequency from the frequency droop equation (16). The instantaneous real (*p*) and reactive (*q*) powers in the *dq* frame are calculated as p = $\Re(v_g^{dq}i_o^{dq,*})^1$ and $q = \Im(v_g^{dq}i_o^{dq,*})$, where v_g^{dq} and i_o^{dq} are the *dq* frame grid voltage and coupling filter current, respectively. *p* and *q* are passed through a low-pass filter (LPF) with cutoff frequency ω_{meas} , as shown in (3) and (4)²:

$$\dot{p}_{avg} = \omega_{meas}(p - p_{avg}) \tag{3}$$

$$\dot{q}_{avg} = \omega_{meas}(q - q_{avg}) \tag{4}$$

In the GFM implementation, the cutoff frequency heavily impacts the resultant frequency response of the device. For notation purposes, all dq vectors are now represented in the complex plane (i.e. $x^{dq} = x^d + jx^q$), where $j = \sqrt{-1}$.

In both models, the output filter is an LC design, with a grid coupling inductor. This constitutes six state variables: the two filter inductor currents i_f^{dq} , the two coupling inductor currents i_o^{dq} , and the filter capacitor voltages v_o^{dq} . The element values, R_f and L_f for the filter resistance and inductance, R_c and L_c for the coupling resistance and inductance, and R_{cap} and C_f for the capacitor resistance and capacitance are consistent

with the labeling in Figs. 1 and 2. The LC filter and coupling inductor dynamic equations are well documented in [12]–[14].

A current controller is common to both models, which is implemented as a proportional-integral (PI) controller based on current set points resultant from either the power or voltage controller, for the GFL and GFM models, respectively. The PI controller architecture is well documented; see [9], [12]–[15]. The current controller dynamic equations are shown in (5) and (6):

$$\dot{\gamma}^{dq} = i_f^{dq} - i_{f,*}^{dq} \tag{5}$$

$$v_{i,*}^{dq} = k_C^i \gamma^{dq} + k_C^p \dot{\gamma}^{dq} - j\omega_r L_f i_f^{dq} + G_C v_o^{dq} \tag{6}$$

where k_C^i and k_C^p are the integral and proportional gains, respectively, G_C is the voltage feed forward gain, ω_r is the radian frequency ($\dot{\omega}_r = \theta_r$), and γ^{dq} are the integrator error states (not mapped in the imaginary plane). A basic current limiting scheme is used wherein the dq current commands are proportionally scaled according to the commanded violation, as shown in (7):

$$i_{f,*,lim}^{dq} = \begin{cases} i_{f,*}^{dq} & \text{if } ||i_{f,*}^{dq}|| \le i_{max} \\ \alpha i_{f,*}^{dq} & \text{if } ||i_{f,*}^{dq}|| > i_{max} \end{cases}$$
(7)

where $i_{f,*,lim}^{dq}$ represents the limited current reference, $i_{f,*}^{dq}$ is the current reference, and $\alpha = i_{max}||i_{f,*}^{dq}||^{-1}$, with i_{max} the current rating of the device. An anti-windup mechanism can be engaged during current limiting to prevent integrator error accumulation.

B. Grid Following Inverter

The general control strategy of the GFL inverter is shown in Fig. 1, where the device is regulating the power export according to an external set point.



Fig. 1: High level control scheme of grid-following inverter.

Works upon which the basis of this model is built include [12], [14], [15]. The device receives power set point commands, which are then compared to the filtered power measurements ((8) and (9)) and passed through a PI power controller to generate current references for the current con-

^{1*} denotes the complex conjugate

²dot notation indicates time derivative; $\dot{x} = \frac{d}{dt}x$

troller previously discussed. The governing equations are (10), and (11):

$$\dot{\sigma}^P = p_* - p_{avg} \tag{8}$$

$$\dot{\sigma}^Q = q_* - q_{avg} \tag{9}$$

$$i_{f,*}^{q} = k_{PQ}^{p}(p_{*} - p_{avg}) + k_{PQ}^{i}\sigma^{P}$$
(10)

$$i_{f,*}^d = k_{PQ}^p(q_* - q_{avg}) + k_{PQ}^i \sigma^Q$$
(11)

where p_* and q_* are the reference powers, σ^P and σ^Q the integrator error states, k_{PQ}^i and k_{PQ}^p are the integral and proportional gains, and $i_{f,*}^q$ and $i_{f,*}^d$ are the resultant reference currents. Note that in this implementation, the q axis is the active power axis. The PLL acquires a phase reference by modulating the calculated phase until the *d*-axis voltage is zero (a steady state condition under balanced operation). The phase error $e^d = \theta_g - \theta_r$ is low-pass filtered (12), and then passed through a PI controller with the output integrated with the nominal frequency (ω_n), as shown in (13) and (14):

$$\dot{e}_{pll}^d = \omega_{c,pll} e^d \tag{12}$$

$$\dot{\phi}_{pll} = e^d_{pll} \tag{13}$$

$$\dot{\theta}_r = \omega_n + k_{pll}^i \phi_{pll} + k_{pll}^p e_{pll}^d \tag{14}$$

where $\omega_{c,pll}$ is the LPF cutoff frequency, e_{pll}^d the filtered error, ϕ_{pll} the integrator state, k_{pll}^i the integral gain, k_{pll}^p the proportional gain, and ω_n the nominal frequency.

A variety of grid support mechanisms are implemented in this GFL model, which adjust power setpoints based on measured grid conditions. Frequency droop support, which is implemented in these tests, changes the set point according to frequency deviations as shown in (15):

$$p_* = p^{set} + (\omega_n - \dot{\theta_r})m_P = p^{set} + \Delta P \tag{15}$$

where p^{set} is the initial power set point, and m_P is the droop gain. ΔP is passed through an LPF (with configurable cutoff frequency) to mitigate minor stability issues otherwise present.

Additional GFL functionality included in the model, but not discussed in detail in this paper, is provided in the following list:

- Filter Reconfiguration can disengage the filter capacitor.
- *Anti-Windup* anti-windup conditional integration/back calculation on the power controller during limiting.
- Power Limiting limiting with power priority selection.
- Grid Support: Synthetic Inertia adjusting power set point according to the local rate of change of frequency.
- *Grid Support: Voltage Control* closed loop voltage regulation incorporated via a PI controller.
- Ride Through multi-level frequency and voltage ride through thresholds and timers.
- Controller Reduction Can bypass the current and/or the power loops to emulate larger timestep simulators.

C. Grid Forming Inverter

The GFM model is based on the multi-loop droop control scheme discussed in [16] and [13], wherein the filter inductor (L_f) current is regulated by the current controller, and the filter

TABLE I: GFL default parameters; all in per unit.

Parameter	Value	Parameter	Value	Parameter	Value
L_f	0.009	R_f	0.016	C_f	2.5
R _{cap}	0.001	L_c	0.002	R_c	0.003
k_C^i	0.7	k_C^p	0.38	G_C	1.0
k_{PQ}^i	20	k_{PQ}^p	2	ω_{meas}	0.132
k^i_{pll}	410	k_{pll}^p	50	$\omega_{c,pll}$	1.32

capacitor (C_f) voltage is regulated by the voltage controller. This control strategy (shown in Fig. 2) results in a voltage source coupled to the network through the coupling impedance $(Z_c = R_c + j\omega_r L_f)$. The droop equations that govern the frequency and voltage according to deviations in the sourced real and reactive power with respect to setpoint values are given in (16) and (17):

$$\dot{\theta}_r = \omega_n + M_p (p^{set} - p_{avg}) \tag{16}$$

$$v_{o,*}^q = v_{o,set}^q + M_q(q^{set} - q_{avg})$$
 (17)

where θ_r is the internal angle used for control, M_p is the frequency droop gain, p^{set} and q^{set} are the pre-disturbance power set points, p_{avg} and q_{avg} are as defined in (3) and (4), $v_{o,*}^q$ is the set point for the voltage controller (capacitor voltage), $v_{o,set}^q$ is the pre-disturbance steady state voltage, and M_q is the voltage droop gain. The voltage controller is a PI controller, as depicted by (18) and (19):



Fig. 2: High level control scheme of grid-forming inverter.

$$\dot{\xi}^{dq} = v_o^{dq} - v_{o,*}^{dq} \tag{18}$$

$${}^{dq}_{f,*} = k_V^i \xi^{dq} + k_V^p \dot{\xi}^{dq} - j\omega_r C_f v_o^{dq} + G_V i_o^{dq} \qquad (19)$$

where ξ^{dq} are the integrator error states (not mapped in the imaginary plane), k_V^i the integral gain, k_V^p the proportional gain, and G_V the current feed forward gain. Additional GFM functionality included in the model, but not discussed in detail in this paper, is provided in the following list:

- *Dual Voltage Control* either a voltage droop relationship (17), or closed loop control of the terminal voltage.
- Dual Start-Up Methods (1) as an ideal source with initial phase and voltage, or (2) by locking on to an energized system and ramping up to an initial power setpoint. Method 2 is critical for exploring EMT simulations of systems not directly tied to a power flow software; the need for initial phase and voltage information is absolved.
- Power Limiting CERTS power limiter for rapid frequency reduction upon power violation [17].

- Automatic Generation Control (AGC) following a frequency disturbance, the devices can be configured to recover back to the nominal setting.
- *Virtual Resistor* a method to attenuate active power oscillations present in certain operating conditions.

Parameter	value	Parameter	value	Parameter	value
L_f	0.15	R_f	0.005	C_f	2.5
Rcap	0.005	Lc	0.15	R_c	0.005
k_C^i	1.19	k_C^p	0.73	G_C	1.0
k_V^i	1.16	$k_V^{\widetilde{p}}$	0.52	G_V	1.0

TABLE II: GFM default parameters; all in per unit.

III. SYSTEM IMPLEMENTATION

The original IEEE 9-Bus test system is a standard dynamics test system that has been used for decades to assess new dynamic elements and concepts in power system operations. A modified IEEE 9-Bus test system is used to verify these models. The PSCAD 9-Bus network with ideal sources, used as the network basis for this paper, is found at [18]. The GFL and GFM models developed in PSCAD and described in Section II are installed on this system with a GFM at bus 1, a GFL at bus 2, and a GFM at bus 3. All three devices have an equal rating of 200 MVA, with an assumed ample positive and negative headroom. The loads are modelled as constant power. Device and load specifications are presented in Table III. Line and transformer specifications can be found in [18]. Fig. 3 depicts the layout of the system topology, loads, and the GFL and GFM inverters.



Fig. 3: Modified IEEE 9-bus test system with grid-forming and grid-following inverters.

TABLE III: IEEE 9 Bus Test System Settings

		Rating	Base Voltage	P	Q
Bus	Device	(MVA)	(kV, LL)	(MW)	(Mvar)
1	GFM	200	16.5	66.9	16.1
2	GFL	200	18.0	163.6	5.0
3	GFM	200	13.8	89.9	-5.0
5	Fixed Load	n/a	230	-125.0	-50.0
6	Fixed Load	n/a	230	-90.0	-30.0
8	Fixed Load	n/a	230	-100.0	-35.0

The startup for this system obeys the following procedure:

- 1) Energize the system with GFM 1 acting as an ideal source (strict voltage and frequency regulation).
- 2) Ramp up the GFL output to power set points.

- 3) Energize GFM 3 and release the frequency dynamics, then ramp the power set point to the desired quantity; the associated local frequency deviations enable the power flow change, while GFM 1 ensures the system frequency remains at nominal.
- 4) Once all power flow transients have damped out, release the droop dynamics of GFM 1.

The network model developed and used in this study, including the startup procedure, is publicly available at the *PyPSCAD* NREL GitHub page [10].

A. System Frequency

Frequency in a zero-inertia system requires electrical measurement, as opposed to measurement of the rotational speed of a synchronous machine shaft. The PLL derived frequency from the GFL is used as the frequency at bus 2, while the derived frequency via the droop equation (15) is reported as the frequency for buses 1 and 3. To arrive at a system average frequency, f(t), each device frequency is weighted according to the device rating, as shown in (20):

$$f(t) = \frac{\sum_{i=1}^{3} (MVA_i * f_i(t))}{\sum_{i=1}^{3} MVA_i}$$
(20)

where $f_i(t)$ is the frequency of inverter *i* at time *t*, and MVA_i is the inverter *i* rating.

An MVA weighted average system frequency is calculated. The rate of change of frequency (ROCOF) is calculated with a sliding window averaging method, as shown in (21):

$$ROCOF(t) := \frac{f(t + T_{ROCOF}) - f(t)}{T_{ROCOF}}$$
(21)

where f is the frequency, and T_{ROCOF} is the size, in seconds, of the sliding window. A $T_{ROCOF} = 100 \text{ ms}$ window is used, in accordance with [19].

B. Computer Simulations

Two simulations are presented to validate the models and a brief investigation of frequency dynamics with zero inertia. The GFM inverters are configured for frequency (5%) and voltage (5%) droop control, with $\omega_{meas} = 120$ rad/s [13]. The two simulations are distinguished by the GFL frequency 5% droop grid support; it is disabled in the first simulation, and enabled in the second simulation. The system is subject to a 10% load step change (-31.5 MW, -11.5 Mvar) at bus 6. The step change occurs after all start up transients have damped out.

IV. RESULTS AND DISCUSSION

Power deviation, frequency, and ROCOF traces are provided for both of the cases described in Section III-B in Figs. 4 and 5. The load step occurs at 0.1 s in these plots, all of which share a common simulation time axis. Frequency metrics are provided in Table IV.

Fig. 4 represents the response of the three devices with the GFL grid support disabled. The power deviation traces (top plot) show that the two GFM inverters meet the load increase, while the GFL, after small fluctuations, maintains the power



Fig. 4: Power deviation, frequency, and ROCOF for the test with GFL frequency droop grid support disabled.

set point. The GFM outputs briefly oscillate out of phase, indicating the presence of damped, inter-area oscillations. With the algebraic relationship between frequency and power deviation with the GFMs (16), the frequency traces (middle plot) of the GFMs exhibit inverted symmetry with respect to the power deviation traces; because the GFL 2 inverter is tracking a power set point and not directly regulating frequency, the GFL 2 frequency is the result of power flow dynamics (i.e., to increase power export, a frequency increase is required to change the power angle (t = 0.25 - 0.40 s)). The nadir and settling frequency are close, which is the result of the power imbalance being immediately rectified; a synchronous generator experiences overshoot because the mechanical power response substantially lags the electrical response. Note that the frequency transients have completely damped out within 0.9 s following the disturbance; the same network with three, generic synchronous generators (system inertia, H = 3s) requires 7 s for the transients to damp out. The ROCOF traces (bottom plot), show a substantial difference (2 times greater) between the GFL 2 and GFM 3 inverters, indicating that local frequency deviations may require heightened attention in zero inertia systems.

The same load step was simulated with GFL 1 frequency droop grid support enabled and the traces are shown in Fig. 5. The response of the GFL 2 results in a decrease in peak power export of GFM 3. The frequency nadir is higher (59.76 vs. 59.71 Hz) in the second simulation, while the overshoot is larger (70 mHz vs 40 mHz). Qualitatively, the frequency dynamics of GFM 1 are more volatile with respect to the average frequency, as compared to the previous simulation. The peak ROCOF values of the GFM inverters are similar, while the GFL 2 value is relatively diminished. Peak ROCOF of the system average frequency is decreased by 0.3 Hz/s.

As a display of the momentary cessation and low voltage reactive current control of the GFL, Figs. 6 and 7 are provided



Fig. 5: Power deviation, frequency, and ROCOF for the simulation with GFL frequency droop grid support enabled.

TABLE IV: Average Frequency Simulation Results Summary

	Grid S	upport
Attribute	Disabled	Enabled
Nadir (Hz)	59.71	59.76
Settling Frequency (Hz)	59.75	59.83
Peak $ ROCOF $ (Hz/s)	2.7	2.4

as the fault response of a single bus system with a 200 MVA synchronous generator and 50 MVA GFL, each with an active power dispatch of 0.55 per unit. A zero impedance, three phase fault is applied at the interconnecting bus for four cycles. The normal behavior of the GFL includes 1.1 per unit current limiting, with conditional integration as an anti-windup method on the power controller integrator. The active power response both with and without momentary cessation is shown in Fig. 6. The momentary cessation threshold is 0.5 p.u. and a 0.2 s delay post voltage recovery precedes a 1 per unit / per second ramp back to the pre-fault output.



Fig. 6: Fault behavior of grid-following inverter active power. Normal operation is with current limiting control only. Momentary cessation blocks inverter active power output and follows a one second ramp back to full output.

The reactive power response for the normal GFL implementation is shown in Fig. 7 with the additional trace representing a the low voltage reactive current control scheme is activated (these simulations are distinct from those in Fig. 6). For voltages below 0.7 per unit, the GFL reactive power controller is bypassed and the reactive current command is set to a specified value, in this case, 0.7 per unit of the limit. Due to the proximity of the fault and resultant near zero voltage, this does not yield an increase in reactive power until the fault clears. The reactive power increase is evident, with a 0.2 s recovery to normal operation upon voltage recovery. Both the low voltage reactive current and momentary cessation schemes are easily tuned in the PSCAD models developed.



Fig. 7: Fault behavior of grid-following inverter reactive power. Normal operation is with current limiting control only. Low voltage reactive current control commands a maximum reactive current with a rapid return to normal output after voltage recovers.

V. CONCLUSION

This paper presented the mathematical formulation of generic PSCAD models of the GFL inverter with grid-support functionality and the multi-loop droop GFM inverter, with discussions on auxiliary functionality associated with the respective models was provided. The models were verified and validated with computer simulations of a zero inertia 9-bus test system, showing that such a system can achieve steady state and maintain stability following a frequency disturbance with full order GFM inverters in the EMT domain. Additional supplementary fault control for the GFL were also demonstrated. These models, including a modified 9-bus system with installed power electronic devices compatible with PSCAD with no additional dependencies, have been made available open source at the NREL GitHub page [10] to provide generic models to the power systems community.

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REFERENCES

- R. W. Kenyon, M. Bossart, M. Marković, K. Doubleday, R. Matsuda-Dunn, S. Mitova, S. A. Julien, E. T. Hale, and B.-M. Hodge, "Stability and control of power systems with high penetrations of inverter-based resources: An accessible review of current knowledge and open questions." [Online]. Available: http://www.sciencedirect.com/science/ article/pii/S0038092X20305442
- [2] A. Sajadi, L. Strezoski, V. Strezoski, M. Prica, and K. A. Loparo, "Integration of renewable energy systems and challenges for dynamics, control, and automation of electrical power systems," vol. 8, no. 1, p. e321, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/wene.321. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/ wene.321
- [3] NERC, "Integrating inverter based resources into low short circuit strength systems."
- [4] R. W. Kenyon, B. Wang, A. Hoke, J. Tan, C. Antonio, and B.-M. Hodge, "Validation of maui PSCAD model: Motivation, methodology, and lessons learned: Preprint," in *Renewable Energy*, p. 9. [Online]. Available: https://www.nrel.gov/docs/fy21osti/76808.pdf
- [5] A. Hoke, V. Gevorgian, S. Shah, P. Koralewicz, R. W. Kenyon, and B. Kroposki, "Island power systems with high levels of inverter-based resources: Stability and reliability challenges," vol. 9, no. 1, pp. 74–91, conference Name: IEEE Electrification Magazine.
- [6] B.-M. S. Hodge, H. Jain, C. Brancucci, G.-S. Seo, M. Korpås, J. Kiviluoma, H. Holttinen, J. C. Smith, A. Orths, A. Estanqueiro, L. Söder, D. Flynn, T. K. Vrana, R. W. Kenyon, and B. Kroposki, "Addressing technical challenges in 100% variable inverter-based renewable energy power systems," vol. 9, no. 5, p. e376, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/wene.376. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/ wene.376
- [7] P. Pourbeik, J. J. Sanchez-Gasca, J. Senthil, J. D. Weber, P. S. Zadehkhost, Y. Kazachkov, S. Tacke, J. Wen, and A. Ellis, "Generic dynamic models for modeling wind power plants and other renewable technologies in large-scale power system studies," vol. 32, no. 3, pp. 1108–1116, conference Name: IEEE Transactions on Energy Conversion.
- [8] WECC Renewable Energy Modeling Task Force, WECC Solar Plant Dynamic Modeling Guidelines. WECC.
- [9] E. Muljadi, M. Singh, and V. Gevorgian, "PSCAD modules representing PV generator," p. 64.
- [10] R. W. Kenyon, "PyPSCAD," original-date: 2020-11-09T20:50:43Z. [Online]. Available: https://github.com/NREL/PyPSCAD
- [11] R. W. Erickson and D. Maksimovic, Fundamentals of Power Electronics. Springer Science & Business Media, google-Books-ID: B4XhBwAAQBAJ.
- [12] M. Rasheduzzaman, J. A. Mueller, and J. W. Kimball, "Reduced-order small-signal model of microgrid systems," vol. 6, no. 4, pp. 1292–1305.
- [13] T. Qoria, Q. Cossart, C. Li, X. Guillaud, F. Gruson, and X. Kestelyn, Deliverable 3.2: Local Control and Simulation Tools for Large Transmission Systems. MIGRATE.
- [14] A. Yazdani and R. Iravani, Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications. John Wiley & Sons.
- [15] Y. Lin, B. Johnson, V. Gevorgian, V. Purba, and S. Dhople, "Stability assessment of a system comprising a single machine and inverter with scalable ratings," in 2017 North American Power Symposium (NAPS), pp. 1–6.
- [16] W. Du, Z. Chen, K. P. Schneider, R. H. Lasseter, S. Pushpak, F. K. Tuffner, and S. Kundu, "A comparative study of two widely used gridforming droop controls on microgrid small signal stability," pp. 1–1.
- [17] M. E. Elkhatib, W. Du, and R. H. Lasseter, "Evaluation of inverterbased grid frequency support using frequency-watt and grid-forming PV inverters," in 2018 IEEE Power Energy Society General Meeting (PESGM), pp. 1–5, ISSN: 1944-9925.
- [18] Manitoba Hydro International Ltd. IEEE 39 bus system. [Online]. Available: https://www.pscad.com/knowledge-base/article/28
- [19] Inverter-Based Resource Performance Task Force, "Fast frequency response concepts and bulk power system reliability needs."