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Published in:
The 2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia)

DOI (link to publication from Publisher):
10.1109/IPEMC-ECCEAsia48364.2020.9368224

Publication date:
2020

Document Version
Early version, also known as pre-print

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***Abstract*—Voltage source converters (VSCs) are one of the most adopted power converter topologies in power electronic-based power systems. Over the years, various control strategies are introduced for grid-connected VSCs, aiming to provide high quality sinusoidal current generation, bidirectional power flow, robustness to uncertainties and mismatches, acceptable steady-state and dynamic performances as well as simplicity and low computational burden. To meet these goals, this paper proposes a direct adaptive current control strategy for three-phase PWM-VSC in grid-connected applications. In the proposed control method, a simple adaption law for updating the feedback control gains based on the Lyapunov stability theory is proposed, to compensate system uncertainties. The performance of the proposed control method is evaluated under various conditions by extensive simulation and experimental tests and show that the method is powerful and robust.**

Keywords— Current control, model reference adaptive control, voltage source converter, grid-connected converters.

I. INTRODUCTION

Grid-connected power electronic systems are subject to various uncertainties and disturbances, which may degrade their performance or even cause instability. Therefore, developing a control method, which is known as the heart of power converters, to compensate system uncertainties and parameter variations, has attracted considerable attention in the past.

Nowadays, adaptive control methods are known as a powerful method in applications with unknown and variable parameters to successfully compensate system uncertainties. In these methods, controller gains are continuously updated with respect to system variations based on an appropriate strategy. Generally, adaptive control methods can be classified into two categories [1]; indirect adaptive control (IAC) and direct adaptive control (DAC). In IAC methods, firstly, an appropriate online identification method is used for system parameters estimation; afterward, control gains are updated based on the estimated values [2]-[14]. As yet, many different IACs based on various online identification methods are presented, like the Luenberger observer [2]-[6], the sliding mode observer [7], the Kalman filter [8], the neural network [9], the steepest descent [10], recursive least square estimator [11], estimator based on immersion and invariance (I&I) theory [12], and the Lyapunov stability theory [13].

These identification methods add extra computational burden to the control system. Contrary to the IAC, the DAC directly updates the controller gains based on a proper adaption law, without the need for any system identification, which brings simplicity and reduces the necessary computational burden [15]-[18]. Another advantage of the DAC over the IAC is the possibility of the straightforward theoretical stability analysis. In [16] and [17], a direct adaptive current controller for an LCL filtered grid-connected PWM-VSC with two different adaption laws is presented. The adaption law in [16] is based on the gradient algorithm, which is relatively easy to implement. However, in this method, the convergence of controller gains is not ensured. To overcome this problem, a more complex adaption law, based on the least square algorithm is proposed in [17]. While the complexity and high online computational requirements are the major drawbacks, the necessity of tuning at least five adaption gains and relevant parameters makes the design process too complicated. Thereby, commonly these gains are tuned through a trial and error approach, which is a hard and time-consuming task [17].

In this paper, a simple yet efficient model reference direct adaptive current control is presented, which only has one adaption gain in its structure. In the proposed control method and to compensate for the parameter variations as well as the system uncertainties, a simple adaption law, based on the Lyapunov stability theory, for updating the feedback control gains is utilized. Simple structure, ease of implementation, and obtaining desirable steady-state and dynamic performance are offered by the proposed control method, which are confirmed through experimental validations. The paper is organized as follows: Firstly, three-phase grid-connected VSC, theproposed control law, and related equations are described in Section II. Section III provides analysis regarding closed-loop stability and control system design. In Section VI, simulation and experimental validations are presented. Finally, conclusions are drawn in Section V.

II. SYSTEM EQUATIONS

The power stage of the three-phase grid-connected PWM-VSC and block diagram of the proposed control method are shown in Fig. 1. In this structure, an L-type low-pass filter is employed. Based on this figure, the system equation of VSC in the vector form can be given by:

$$v_c(t) = r_L i(t) + L\frac{di(t)}{dt} + v_g(t) \tag{1}$$

where L and r_L are the filter inductance and its equivalent series resistance, respectively. Also, i, v_g, and v_c are the grid current and voltage vectors, and output voltage vector of the converter, respectively. Moreover, the proposed control structure includes a reference model specifying the desired performance of the converter system, a feedback control with adjustable gains, and an adaption mechanism for updating the control gains. In Fig. 1, i_{ref}, i_m, e, k_1, and k_2 are the converter reference current, the reference output (output of the reference model), the tracking error ($e = i - i_m$), and control gains, respectively. The reference model (2) has the same structure as the plant with the poles and zeros located at the desired locations to provide the ideal response to the reference signal. The adaption algorithm (3) adjusts the controller parameters, k_1 and k_2, so that the response of the converter system, i, becomes the same as that of the reference model, i_m. In this paper, an adaption law to adjust the feedback control gains based on the Lyapunov stability theory is proposed. This ensures zero-tracking error as well as the convergence of the control gains to the bounded and take desired values. The proposed control equations are summarized as (i.e., reference model):

$$\frac{di_m(t)}{dt} = -a_m i_m(t) + b_m i_{ref}(t) \tag{2}$$

where a_m is the desired closed-loop pole location for this first-order system, and b_m is selected such that the closed-loop unity gain at the tracking frequency is achieved (frequency of the reference input). Moreover, the proposed feedback control law and Lyapunov based adaption mechanism for updating the control gains are:

$$\begin{cases} v_{c,ref}(t) = -k_1 i(t) + k_2 i_{ref}(t) + v_g(t) \\ \dot{k}_1 = \gamma \cdot i \cdot e \\ \dot{k}_2 = -\gamma \cdot i_{ref} \cdot e \end{cases} \tag{3}$$

where v_g is feed-forwarded to compensate the grid voltage disturbances and, at the same time to simplify the system modeling and controller design and γ is positive adaption gain. In grid-connected VSC, there is one and a half PWM period delay between the sampling and application. One sample measurement delay can be fully compensated using Luenberger and another conventional observer [3], [6]. Therefore, since only the remaining half sample control delay is negligible (less than 10 percent of the control period), the delay has a negligible impact on the control system, and consequently, it can be safely ignored [1].

III. CLOSED-LOOP STABILITY ANALYSIS

In order to analysis of closed-loop stability under proposed control and adaption laws, the Lyapunov stability theorem is employed in this section.

The dynamic tracking error is defined as:

$$\dot{e}(t) = \dot{i}(t) - \dot{i}_m(t) \tag{4}$$

By replacing (1), (2) and the proposed control law (3) into (4), the dynamic tracking error is obtained as:

$$\dot{e}(t) = -a_m e(t) + \psi(k - k_n) \tag{5}$$

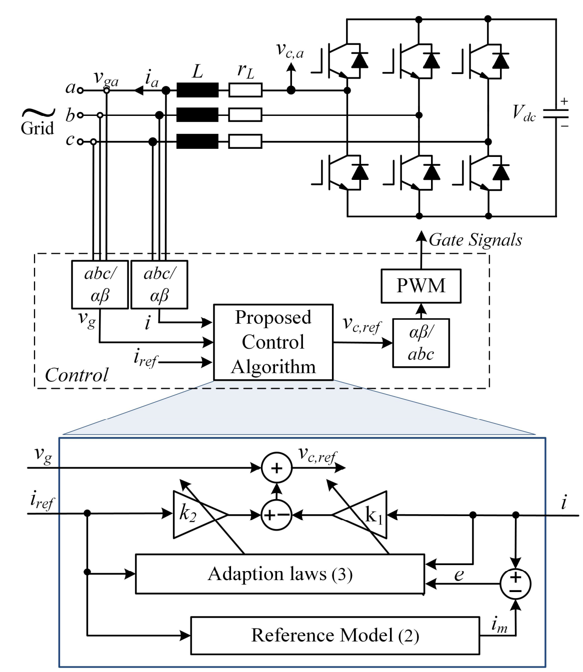

Fig. 1. Three-phase grid-connected voltage source converter and block diagram of the proposed direct adaptive current control scheme

where ψ and $k-k_n$ are defined as:

$$\psi = b\left[-i \quad i_{ref}\right] \tag{6}$$

$$(k-k_n) = \begin{bmatrix} k_1 - k_{1n} \\ k_2 - k_{2n} \end{bmatrix} \tag{7}$$

where, k_n is the nominal value of the controller gains which are:

$$\begin{cases} k_{1n} = \dfrac{a_m - a}{b} \\ k_{2n} = \dfrac{b_m}{b} \\ a = \dfrac{r_L}{L}, b = \dfrac{1}{L} \end{cases} \tag{8}$$

It is worth noting that due to the uncertainties of the plant parameters, (8) cannot be directly used for controller parameters calculation. So, to fine-tune the control gains, adaption law must be employed.

The differential equation (5) contains adjustable parameters (k) and dynamic tracking error (e). So, the main goal is to select a proper Lyapunov function and afterward examine the stability of the closed-loop system under proposed control law. One solution for the positive-definite Lyapunov function is [1]

$$V(e,k) = 0.5\left[e^2 + (k-k_n)^T \Gamma^{-1}(k-k_n)\right] \tag{9}$$

where Γ is a positive matrix as

$$\Gamma = \begin{bmatrix} \gamma' & 0 \\ 0 & \gamma' \end{bmatrix} > 0 \tag{10}$$

To be a Lyapunov function, the time derivative of (9), defined in (11), must be negative-definite.

$$\dot{V}(e,k) = -a_m e^2 + (k-k_n)^T\left[\Gamma^{-1}\dot{k} + \psi^T e\right] \tag{11}$$

By assuming $\gamma = \gamma' b$ and substituting the adaption law of (3) into (11), the time derivative of the Lyapunov function can be simplified as:

$$\dot{V}(e,k) = -a_m e^2 \tag{12}$$

So, while e is not zero, the time derivative of the Lyapunov function is negative-definite, which translates to $V(t) \leq V(0)$ for $t > 0$. Therefore e, k, and ψ in (11) are all bounded. Moreover, using the Barbalat's lemma, one has [1]

$$\ddot{V}(e,k) = -2a_m e(-a_m e(t) + \psi(k-k_n)) \tag{13}$$

This is bounded since e, k, and ψ are bounded. This implies that $\dot{V}(e,k) \to 0$ as $t \to \infty$ and subsequently $e(t) \to 0$ [1]. Consequently, (9) is a Lyapunov function, and the overall control system under the adaption law of (3) is asymptotically stable. Also, $e(t) \to 0$ and all signals are bounded.

IV. RESULTS AND DISCUSSIONS

To validate the performance of the proposed control method, simulation and experimental tests are performed under various operating conditions. Table I summarizes the studied system specification and the employed control parameters, which are identical for both simulations and experiments.

To further illustrate the effectiveness of the proposed method, a comparison is made with the well-known proportional-resonant (PR) current control technique as described in [19]-[20]:

$$G_{PR}(s) = k_p + k_i \frac{\omega_c s}{s^2 + 2\omega_c s + \omega^2} \tag{9}$$

where, k_p, k_i, ω_c, and ω are proportional gain, resonant gain, cutoff frequency, and resonance frequency, respectively. Control gains of the PR current control are calculated using the design algorithm of [20] and system parameters in Table I. To do this, the closed-loop bandwidth and PM are selected as 4000 rad/s and 41°, respectively.

The steady-state performance of the proposed and the PR control methods are investigated and shown in Fig. 2. As can be seen, the three-phase grid currents (i_{abc}) with an ideal grid voltage (v_{ga}) are shown in this figure. Fig. 2 shows how both control methods can produce high-quality sinusoidal output currents with minimum distortion.

It is worth noting that the results of the proposed method are achieved without full knowledge of the inductor parameters. The control gains k_1 and k_2 are obtained from the adaption law (3) with at least 50% errors for the initial conditions. In contrast, the PR control method needs nominal values of the filter parameters in the design step, and its good performance in tests is achieved under nominal conditions.

Therefore, any changes in system parameters may affect its performance. To examine this issue, the transient performance of the proposed and the PR control methods under various step changes in the references current is studied in Fig. 3, when the inductance value is different from the initial design value of the PR controller.

TABLE I. SYSTEM SPECIFICATION AND PARAMETERS

Nominal power	5 [kVA]
Line voltage (rms)	400 [V]
Grid frequency	50 [Hz]
Inductor (L) and the series resistance (r_L)	5 [mH], 0.25 [Ω]
DC-link voltage (V_{dc})	700 [V]
Sampling and switching frequencies	10 [kHz]
Control Parameters	
a_m, b_m	4000 [rad/s], 4012.3
γ	20
k_{1n}, k_{2n}	19.8 [Ω], 20.1 [Ω]
k_p, k_i	22 [Ω], 10000 [Ω/s]
ω_c	1 [rad/s]

In Fig. 3, the filter inductance is increased by +60%, and due to the presence of this uncertainty, the grid current under the PR control method encountered an overshoot (OV = 11.2%) during a step-change in the reference current. Besides the existence of the current OV, the current error lasts longer than expected from the nominal test when the reference current returns to zero. While the proposed control method keeps the desired system performance under these conditions, and the grid currents will successfully follow the desired system response.

Moreover, it is remarkable that the effect of the grid inductance variation can be considered as uncertainty in the filter inductance. Therefore, the same conclusion can be drawn from Fig. 3 to confirm the system's robustness against the grid inductance uncertainties.

The most severe transient situation occurs at the startup, which is shown in Fig. 4. Clearly, following the startup command, the grid current quickly changes from 0 to 7.25 Arms with minimum waveform distortions that confirms a fast and smooth startup of the proposed adaption and control methods. Also, the estimated control gains converge to the nominal values. However, they differ slightly from the nominal ones, since the correct values of the inductance and series resistance of inductor filter are not precisely known in practice.

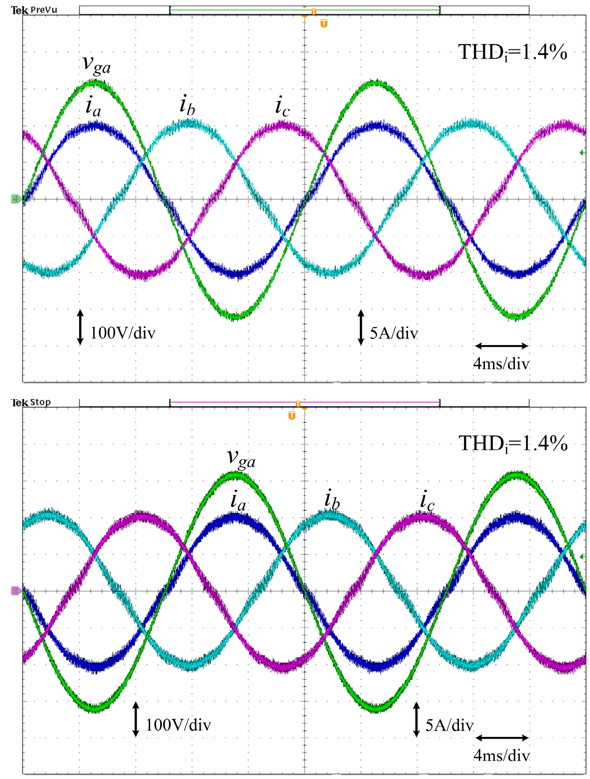

Fig. 2. Experimental results showing the steady-state performance of the proposed (above) and PR (bottom) control methods (P = 5 kW)

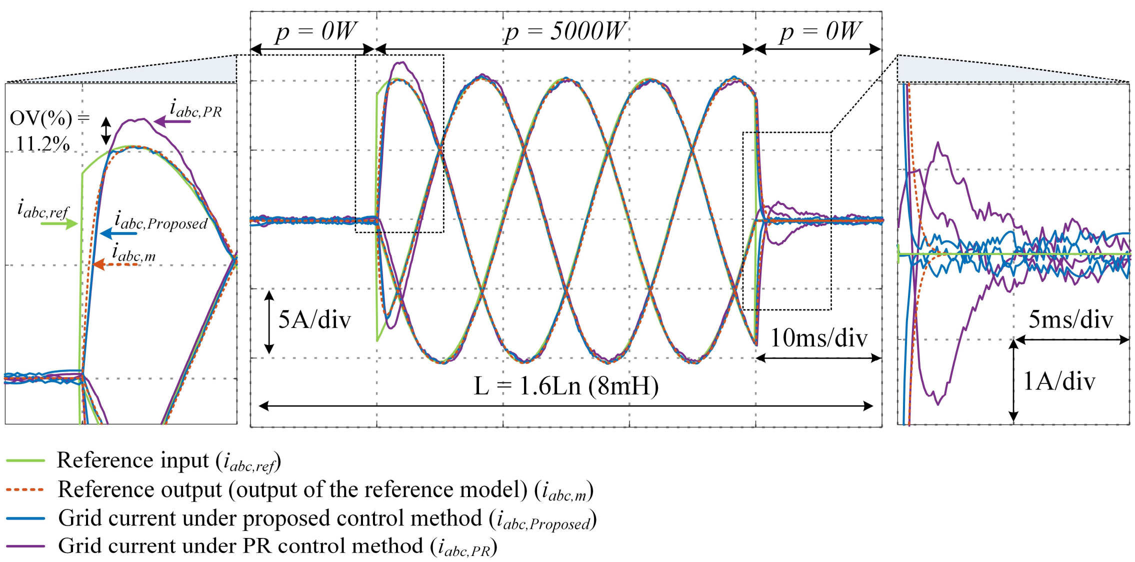

Fig. 3. Simulation results showing the transient performance, (Q = 0 Var, γ = 20) when inductance value is changed from the initial design of the PR controller (L = 1.6Ln (8 mH))

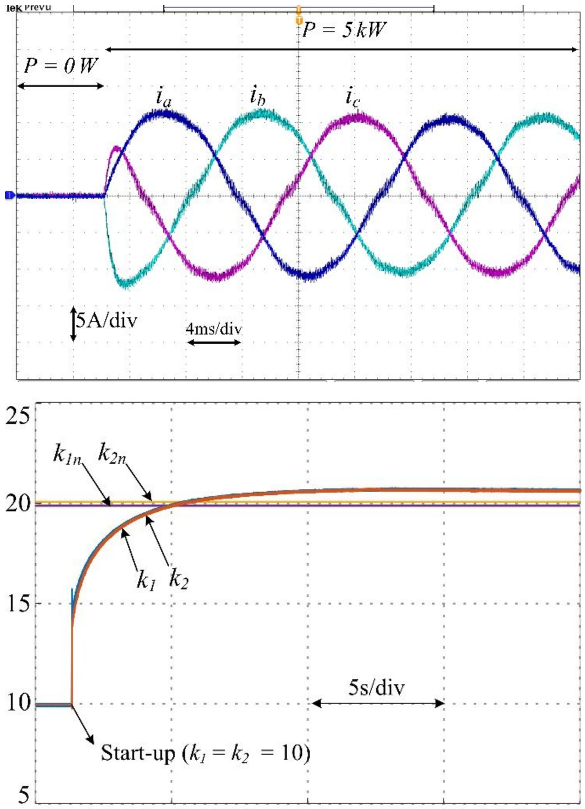

Fig. 4. Experimental results showing the startup performance of the proposed method (Q = 0 Var). above: three-phase grid currents, and bottom: control gains convergence

V. CONCLUSIONS

In this paper, a direct adaptive current control for grid-connected VSCs is proposed. In the proposed control method and in order to compensate for system uncertainties, control gains are adapted with respect to uncertainties. The adaption law is obtained based on the Lyapunov stability theory. In this paper, the stability of the whole system, output tracking, as well as convergence of the controller gains to desired values are verified. A simple concept with a good analytical support, low computational burden, superior steady-state performance, and good dynamic performance are the most important features of the proposed control method that are confirmed by extensive simulation and experimental tests. Moreover, it should be mentioned that the proposed control method can easily be used for VSC based power applications such as single-phase PVs, wind turbines, and active power filters.

ACKNOWLEDGMENT

The work is supported by the Reliable Power Electronic-Based Power System (REPEPS) project at the Department of Energy Technology, Aalborg University as a part of the Villum Investigator Program funded by the Villum Foundation.

REFERENCES

[1] K. J. Astrom and B. Wittenmark, "Adaptive control", Prentice-Hall, 1994.

[2] J. M. Espi, J. Castello, R. García-Gil, G. Garcera, and E. Figueres, "An adaptive robust predictive current control for three-phase grid-connected inverters," *IEEE Trans. Ind. Electron.*, vol. 58, no. 8, pp. 3537–3546, Aug. 2011.

[3] C. Xia, M. Wang, Z. Song, and T. Liu, "Robust model predictive current control of three-phase voltage source PWM rectifier with online disturbance observation," *IEEE Trans. Ind. Informatics*, vol. 8, no. 3, pp. 459–471, Aug. 2012.

[4] K. J. Lee, B. G. Park, R. Y. Kim, and D. S. Hyun, "Robust predictive current controller based on a disturbance estimator in a three-phase grid-connected inverter," *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 276–283, 2012.

[5] Y. A.-R. I. Mohamed, M. A-Rahman, and R. Seethapathy, "Robust line-voltage sensorless control and synchronization of LCL -filtered distributed generation inverters for high power quality grid connection," *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 87–98, Jan. 2012.

[6] H. Gholami-Khesht and M. Monfared, "Adaptive predictive voltage control of three-phase PWM-VSCs in UPS applications," in *2016 International Siberian Conference on Control and Communications* (SIBCON), 2016, pp. 1–6.

[7] Y. A. R. I. Mohamed and E. F. El-Saadany, "Robust high bandwidth discrete-time predictive current control with predictive internal model - A unified approach for voltage-source PWM converters," *IEEE Trans. Power Electron.*, vol. 23, no. 1, pp. 126–136, 2008.

[8] N. Hoffmann and F. W. Fuchs, "Minimal invasive equivalent grid impedance estimation in inductive–resistive power networks using extended kalman filter," *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 631–641, Feb. 2014.

[9] Y. A.-R. I. Mohamed and E. F. El-Saadany, "Adaptive discrete-time grid-voltage sensorless interfacing scheme for grid-connected DG-inverters based on neural-network identification and deadbeat current regulation," *IEEE Trans. Power Electron.*, vol. 23, no. 1, pp. 308–321, Jan. 2008.

[10] Y. A.-R. I. Mohamed and E. F. El-Saadany, "An improved deadbeat current control scheme with a novel adaptive self-tuning load model for a three-phase PWM voltage-source inverter," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 747–759, Apr. 2007.

[11] Q. Liu and K. Hameyer, "High-performance adaptive torque control for an IPMSM with real-time MTPA operation," *IEEE Trans. Energy Convers.*, vol. 32, no. 2, pp. 571-581, June 2017.

[12] Y. A. Zúñiga-Ventura, D. Langarica-Córdoba, J. Leyva-Ramos, L. H. Díaz-Saldierna and V. M. Ramírez-Rivera, "Adaptive backstepping control for a fuel cell/boost converter system," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 6, no. 2, pp. 686-695, June 2018.

[13] R. M. Milasi, A. F. Lynch, and Y. W. Li, "Adaptive vector control for voltage source converters," *IET Control Theory Appl.*, vol. 7, no. 8, pp. 1110–1119, May 2013.

[14] Chen, J. Qiu and M. Jin, "Adaptive finite-control-set model predictive current control for IPMSM drives with inductance variation," *IET Electr. Power Appl.*, vol. 11, no. 5, pp. 874-884, 5 2017.

[15] R. M. Milasi, A. F. Lynch, and Y. W. Li, "Adaptive control of a voltage source converter for power factor correction," *IEEE Trans. Power Electron.*, vol. 28, no. 10, pp. 4767–4779, 2013.

[16] J. R. Massing, M. Stefanello, H. A. Grundling, and H. Pinheiro, "Adaptive current control for grid-connected converters with

LCL-filter," in *2009 35th Annual Conference of IEEE Industrial Electronics*, 2009, vol. 59, no. 12, pp. 166–172.

[17] J. R. Massing, M. Stefanello, H. A. Grundling, and H. Pinheiro, "Adaptive current control for grid-connected converters with LCL filter," *IEEE Trans. Ind. Electron*., vol. 59, no. 12, pp. 4681–4693, 2012.

[18] D. Xuan Ba, H. Yeom, J. Kim and J. Bae, "Gain-adaptive robust backstepping position control of a BLDC motor system," *IEEE/ASME Trans. Mechatronics*, vol. 23, no. 5, pp. 2470-2481, Oct. 2018.

[19] M. Lu, Y. Yang, B. Johnson and F. Blaabjerg, "An interaction-admittance model for multi-Inverter grid-connected systems," *IEEE Trans. Power Electron*., vol. 34, no. 8, pp. 7542-7557, Aug. 2019.

[20] H. Gholami-Khesht, S. Golestan, and M. Monfared, "Low computational burden grid voltage estimation for grid connected voltage source converter-based power applications," *IET Power Electron*., vol. 8, no. 5, pp. 656–664, 2015.