Delft University of Technology

A Decentralized Frequency Regulation Scheme in AC Microgrids

Peyghami, Saeed; Zarei, Seyed Fariborz; Ghasemi, Mohammad Amin; Palensky, Peter; Blaabjerg, Frede

Citation (APA)
Peyghami, S., Zarei, S. F., Ghasemi, M. A., Palensky, P., & Blaabjerg, F. (2020). A Decentralized Frequency Regulation Scheme in AC Microgrids. In *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics, COMPEL 2020* Article 9265766 (2020 IEEE 21st Workshop on Control and Modeling for Power Electronics, COMPEL 2020). IEEE. https://doi.org/10.1109/COMPEL49091.2020.9265766

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

A Decentralized Frequency Regulation Scheme in AC Microgrids

Saeed Peyghami
Department of Energy Technology
Aalborg University
Aalborg, Denmark
sap@et.aau.dk

Seyed Fariborz Zarei
Department of Electrical and Computer
Engineering
Qom University of Technology
Qom, Iran
zarei@qut.ac.ir

Mohammad Amin Ghasemi
Department of Electrical Engineering
Bu-Ali Sina University
Hamadan, Iran
ma.ghasemi@basu.ac.ir

Peter Palensky
Department of Electrical, Electronic
and Computer Engineering
Technische Universiteit Delft
Delft, Netherlands
P.Palensky@tudelft.nl

Frede Blaabjerg
Department of Energy Technology
Aalborg University
Aalborg, Denmark
fbl@et.aau.dk

Abstract—**Microgrids (MGs) are becoming active segments of future power systems. Frequency regulation in islanded MGs is of high importance to guarantee stable and reliable operation under different loading conditions. This paper proposes a decentralized frequency regulation of AC MGs, which relies on the local information. Comparing to the conventional approaches, the proposed scheme does not require a communication system for frequency regulation, resulting in higher reliability and lower costs. Simulation results verify the effectiveness of the proposed frequency control strategy.**

Keywords— AC Microgrid, Frequency Regulation, Inverter-Based Microgrid, Power converter,

I. INTRODUCTION

The trend in the future power grids is towards using more and more distributed generation (DG) on the distribution side [1-3]. The DGs are mainly based on renewable energies offering higher efficiency, lower cost and also a green society [4-6]. In such a system, the off-grid operation is an interesting outcome, which can be realized by adding voltage and frequency control capabilities to the DGs. Practically, this can be done by defining new modern grids namely microgrids (MGs) [7-9]. In an MG, part of DGs contributes to voltage and frequency control, which are the most important requirements of MG systems [10], and other remaining units deliver the maximum power according to the maximum power point tracking scheme [11, 12]. Generally, two main control levels are provided to guarantee the stable operation of the MGs which are i) the primary control and ii) secondary control [13]. The primary control is responsible to regulate the output voltage and frequency of MG sources at certain reference values [14, 15]. However, the reference values obtained by droop characteristic inherently results in a non-zero steady-state error in voltage and frequency regulation. To avoid this deficiency, the voltage and frequency references are updated by another control level, the so-called secondary control. Generally, the solutions for secondary control are implemented either by the help of communication infrastructure and overall control center or locally by

sources using a decentralized control scheme [16]. The three well-known secondary control structures are given in Fig. 1. Detailed Explanation and classification are provided in the following.

The communication-assisted strategies are classified into two categories which are centralized and distributed secondary controls [16]. The functionality of a centralized strategy is highly dependent on the communication links for collecting information and sending the references from/to the MGs sources. Then, the communication system failure may threaten the whole system operation. Non-scalability, single point of failure, and low reliability are other problems associated with this scheme [16]. Compared to the centralized control strategy, the distributed control scheme incorporates point-to-point communication links between all DGs, which mitigate the need for the MG central control and provides more scalability and higher reliability. However, the dependency on communication infrastructure is still an issue. To avoid the use of the communication system and accordingly its related deficiencies, the decentralized control scheme is employed in the literature. Generally, three secondary control schemes based on decentralized control are introduced in the literature, which are [16]:

A. Washout Filter-Based decentralized control scheme:

In this scheme, the input powers are filtered by band-pass filters, instead of conventional low-pass ones. This scheme gives zero steady-state error in the voltage and frequency regulation [17]. For implementing the approach, first and second-order filters are used in [18, 19]. Although this scheme provided zero steady-state error, the robustness is not confirmed yet [16].

B. Modified decentralized control scheme by replacing P-Controller based droop with PI-controller:

In this scheme, replacing the proportional (P) droop controller by proportional-integral (PI) controller is the main idea behind this method. Although using PI-controller

ensures zero steady-state error in controlling the voltage and frequency, the system stability is not guaranteed since PI-controller (Unlike P-controller) turns the non-ideal sources into ideal ones [20].

C. Estimation-Based decentralized control scheme:

In this scheme, the decentralized scheme is implemented by utilizing state variable estimation methods [21-24]. Although this scheme provided a communication-free decentralized control scheme, its performance depends on the system modeling accuracy.

In this paper, a decentralized control scheme based on direct control of grid frequency via a feedback-based scheme is proposed. In this method, first, the actual grid frequency in the output terminal of each converter is extracted. Then, using a closed-loop control scheme, the frequency is controlled such that it settles at the nominal value. Employing this method inherently considers the impact of other sources in the MG, improving the system response and transient behavior. Simulation results demonstrate the effectiveness of the proposed method under different operating conditions.

II. FREQUENCY CONTROL OF AC MICROGRIDS

The typical structure of an AC MG with the proposed control method is shown in Fig. 2. The sources are connected to a common bus through power feeders and the MG loads are localized at the common bus. Each converter pursues different control goals such as voltage-frequency control, active-reactive power injection by producing proper terminal voltages. In this respect, internal control loops play a key role, where finally the control command appears in the produced terminal voltages [25-27]. Fig. 2 shows the control structure of the converter consisting of an inner current control loop, and an outer voltage control loop. The outer loop receives the voltage references from a supervisory control such as droop control and produces the proper current references. The inner loop regulates the output current by taking the current reference from the voltage loop, which finally results in output voltage regulation of the reference values. All the aforementioned control parts are related to the primary control. Using only this control level results in a deviation from nominal values in voltage and frequency in the MG. Then, the secondary control scheme is necessary to compensate for this deviation.

Droop control is the most robust primary control, which locally controls the power-sharing and voltage regulation in MGs. For instance, according to the droop method, the reference frequency, f_r is proportional to the output power of the converter, P_m as given in (1), where f^* is a set point, m is the droop slope and $G_{LPF}(S)$ is a low pass filter.

$$f_r = f^* - mP_m G_{LPF}(S) \qquad (1)$$

The term associated with the droop slope makes the frequency droop at a steady state. Then, the secondary
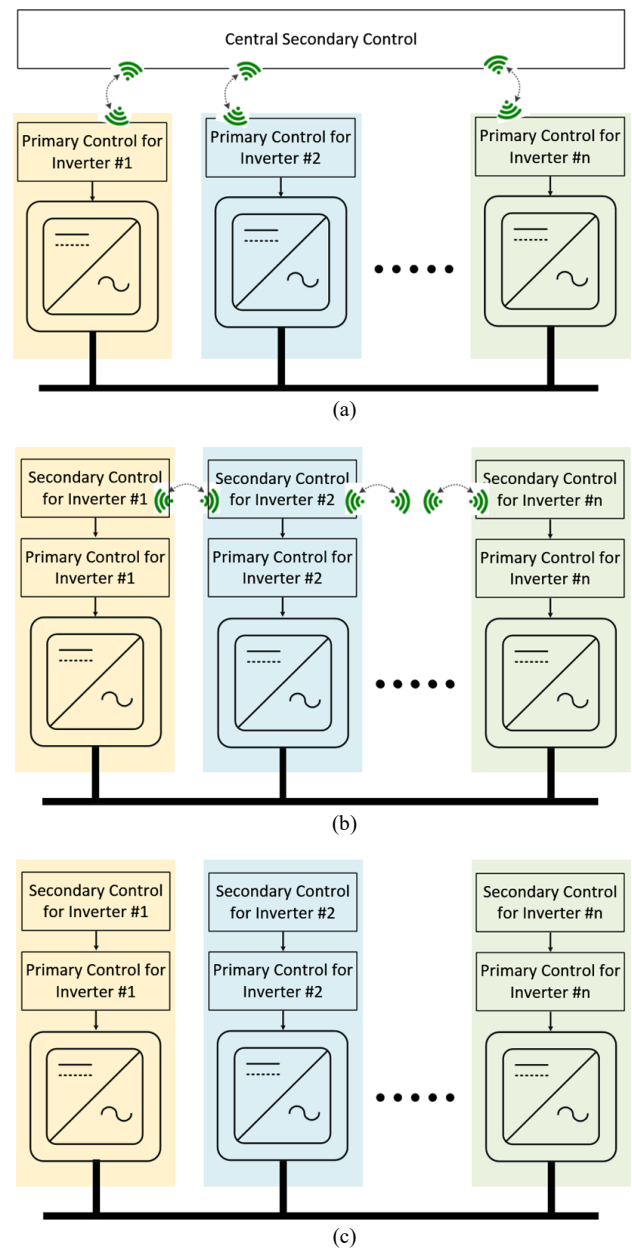

Fig. 1. Three main secondary control structures: (a) centralized secondary control, (b) distributed secondary control, and (c) decentralized secondary control.

control is required to compensate the frequency deviation in the steady-state. Accordingly, various secondary control schemes have been proposed in the literature. Among them, communication-based schemes are mostly used methods in the previous works. Despite the benefits coming from communication-assisted methods, the scalability and reliability of the whole system are degraded. For this reason, the decentralized control schemes are presented in the literature, which are explained in section I. To improve the existing decentralized secondary control schemes, a new modified control method is proposed in this paper, as given in the next section.

III. PROPOSED DECENTRALIZED SECONDARY CONTROL

Fig. 2 shows the proposed decentralized frequency control in AC power systems with 3 units. In this figure, the voltage and current control loops, are the inner loops in the
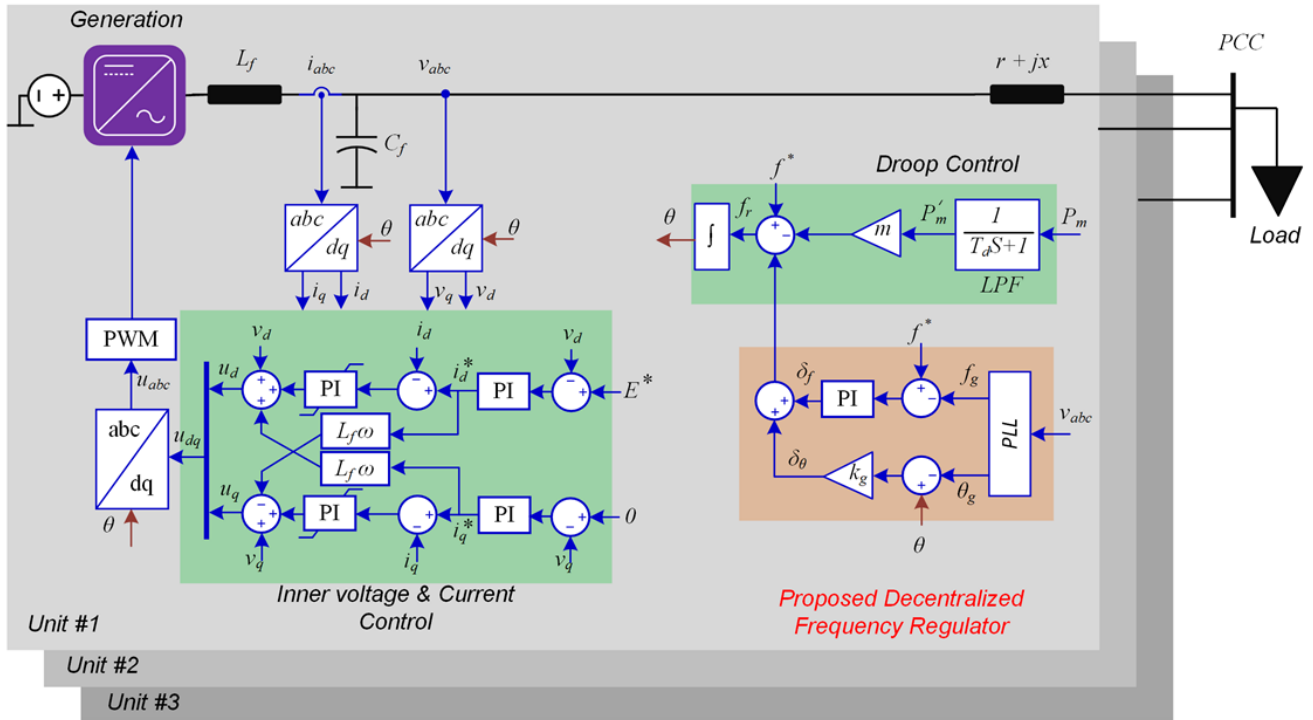
Fig. 2. Proposed decentralized frequency control in AC power systems with 3 units.

Table I. Microgrid parameters.

Parameter	Symbol	Unit #1	Unit #2	Unit #3
Rated power	P_i (kW)	10	7.5	5
Droop gain	m_i (Hz/W)	0.0002	0.00027	0.0004
Current control	$k_{p,i} + k_{i,i}/s$	25+100/S		
Voltage control	$k_{p,v} + k_{i,v}/s$	1+20/S		
Frequency control	$k_{p,f} + k_{i,f}/s$	6+18/S		
Damping factor	k_g	15, 25		
Feeder impedance	$r_i + jx_i$ (Ω)	0.005+ j0.05	0.02+ j0.07	0.07+ j0.13
Rated frequency	f_r (Hz)	50		
Rated voltage	E (V$_{\text{line-line}}$)	400		
Filter (LC)	L_f (mH), C_f (μF)	5, 50		
Switching frequency	f_{sw} (kHz)	5		
Low Pass Filter delay	T_d (s)	0.03		
Load	P_{load} (kW)	10, 20		

converter. The frequency- and voltage- droop controls are the outer level control loops in this system. As the focus of this study is on the frequency control, the voltage droop control is not more elaborated. In the proposed method of Fig. 2, there are two modifications comparing to the conventional secondary control schemes, which are δ_f and δ_θ. The proposed secondary control compensates for the frequency drop by a term of δ_f according to (2).

$$f_r = f^* - mP_m G_{LPF}(S) + (\delta_f) + (\delta_\theta) \qquad (2)$$

To calculate the compensation term of δ_f, the frequency drop value is fed to a compensator, which guarantees the zero frequency deviation in the steady-state. The $G_{PI}(S)$ is a proportional-integrator regulator. To do so, the grid frequency is extracted using a PLL (phase-locked loop), which inherently considers the grid dynamics. Equation (3) shows the compensation term of δ_f.

$$\delta_f = (f^* - f_g) G_{PI}(S) \qquad (3)$$

Moreover, in order to damp the low-frequency oscillations, the output voltage phase angle, θ_g is controlled to follow the reference phase angle, θ generated by the droop controller (see Fig. 2). Therefore, a damping term is generated by (4) and added to the reference frequency following (2). The term θ in (4) is the reference phase angle, which can be obtained by using (5). The proposed damping scheme tries to decrease the angle difference between output voltages of converter (θ) and grid voltages (θ_g), which
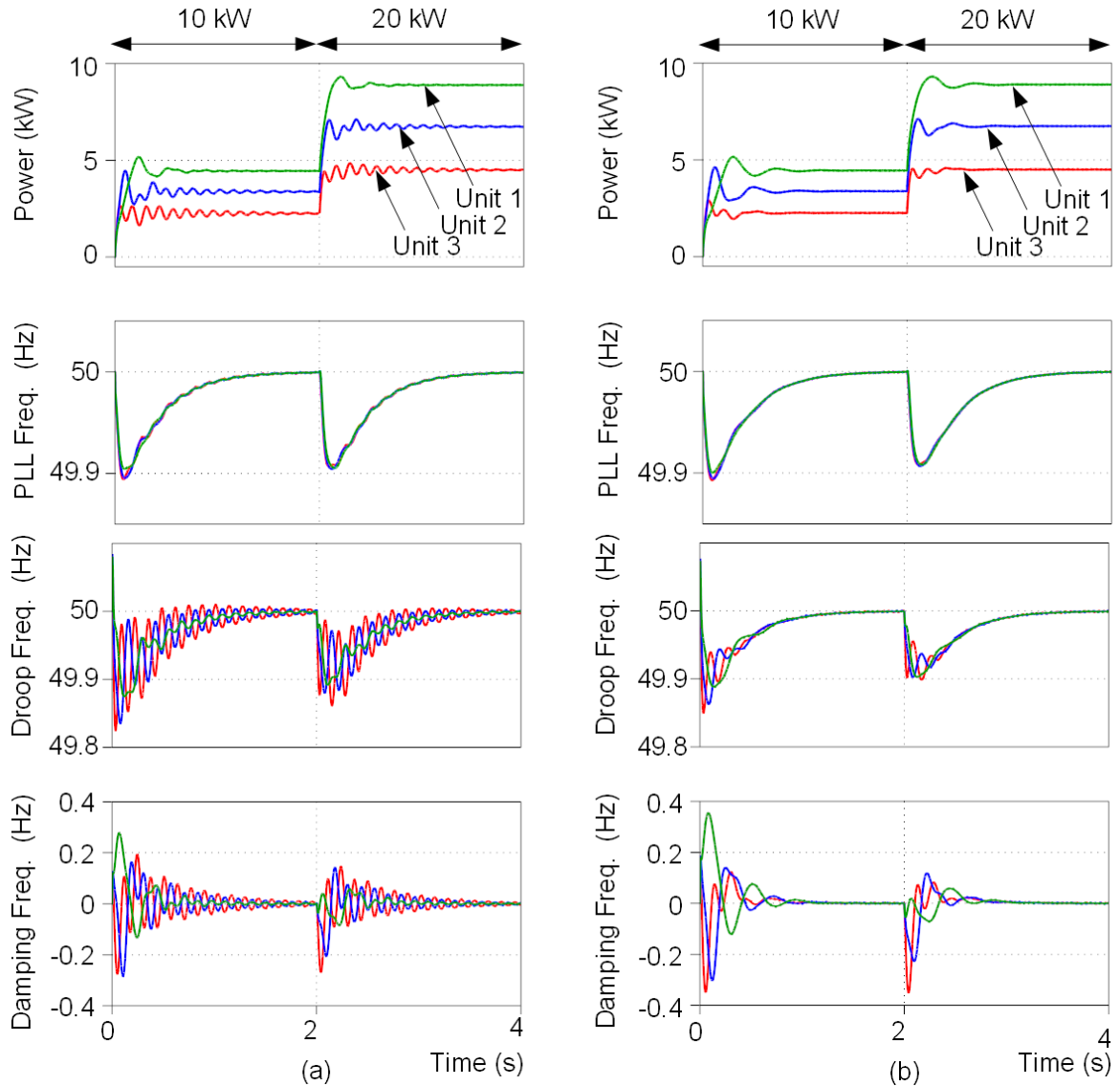
Fig. 3. Simulation results using the proposed secondary control scheme (a) $k_g = 15$, and (b) $k_g = 25$.

further improves the synchronization, and then the stability and damping of inverters.

$$\delta_\theta = k_g \left(\theta - \theta_g \right) \tag{4}$$

$$\theta(t) = \int_0^t f_r dt \tag{5}$$

In this paper, the main idea is taken from the fact that the frequency is a global quantity over the MG, and then, it can be fed to the control system without requiring any frequency sharing among the sources. In this approach, the frequency is measured in the converter terminal, and accordingly, the frequency reference is produced locally by the source. This scheme does not require estimation of variables, and also, it is based on the conventionally proved droop scheme in the primary control. Then, the related deficiency will be avoided.

IV. SIMULATION RESULTS

This section presents the selected simulation results to show the effectiveness of the proposed control scheme. The MG includes three converters as shown in Fig. 3. The converter and their control parameters are given in Table I. The MG is simulated under two load levels of 10 kW and 20 kW, and the obtained simulation results are shown in Fig. 3. During the simulation, a load change is applied at $t = 2$ s. As it is shown in Fig. 3 (a), the load is proportionally shared among the converters based on their rated values. Moreover, the grid frequency is appropriately regulated at the rated value of 50 Hz. Therefore, the proposed decentralized frequency control can control the grid frequency by locally measuring the grid frequency and compensating the frequency drop by employing local regulators.

Moreover, it can be seen from Fig. 3 (a) that the active power of converters has low-frequency oscillations. This is because of the relative swing of the output angle of converters. By increasing the damping factor of k_g from 15 to 25, the obtained results are shown in Fig. 3 (b). The

results imply that the low-frequency oscillations are effectively removed from the output power of converters. This is due to the fact that the proposed damping scheme retains the actual output angle of converter voltage to the phase angle generated by the droop controller. The simulation results show that the proposed damping term can properly eliminate the low-frequency oscillations.

V. Conclusion

This paper has proposed a decentralized frequency regulation scheme for AC microgrids. In the proposed method, using the actual measurements of the MG system, the MG frequency is extracted and fed to the control system. Then, the sources in the grid contribute to the frequency regulation locally without requiring information from other sources. Furthermore, a damping controller is proposed, which prevents the low-frequency oscillations of the converter output powers.

References

[1] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE transactions on Power Electronics,* vol. 19, no. 5, pp. 1184-1194, 2004.

[2] O. Ellabban, H. Abu-Rub, and F. Blaabjerg, "Renewable energy resources: Current status, future prospects and their enabling technology," *Renewable and Sustainable Energy Reviews,* vol. 39, pp. 748-764, 2014.

[3] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Transactions on industrial electronics,* vol. 53, no. 5, pp. 1398-1409, 2006.

[4] Z. Chen, J. M. Guerrero, and F. Blaabjerg, "A review of the state of the art of power electronics for wind turbines," *IEEE Transactions on power electronics,* vol. 24, no. 8, pp. 1859-1875, 2009.

[5] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, "Autonomous operation of hybrid microgrid with AC and DC subgrids," *IEEE transactions on power electronics,* vol. 28, no. 5, pp. 2214-2223, 2012.

[6] J. M. Guerrero, F. Blaabjerg, T. Zhelev, K. Hemmes, E. Monmasson, S. Jemei, *et al.*, "Distributed generation: Toward a new energy paradigm," *IEEE Industrial Electronics Magazine,* vol. 4, no. 1, pp. 52-64, 2010.

[7] J. He, Y. W. Li, and F. Blaabjerg, "An enhanced islanding microgrid reactive power, imbalance power, and harmonic power sharing scheme," *IEEE Transactions on Power Electronics,* vol. 30, no. 6, pp. 3389-3401, 2014.

[8] J. He, Y. W. Li, J. M. Guerrero, F. Blaabjerg, and J. C. Vasquez, "An islanding microgrid power sharing approach using enhanced virtual impedance control scheme," *IEEE Transactions on Power Electronics,* vol. 28, no. 11, pp. 5272-5282, 2013.

[9] X. Wang, J. M. Guerrero, F. Blaabjerg, and Z. Chen, "A review of power electronics based microgrids," *Journal of Power Electronics,* vol. 12, no. 1, pp. 181-192, 2012.

[10] S. F. Zarei, H. Mokhtari, M. A. Ghasemi, and F. Blaabjerg, "Reinforcing fault ride through capability of grid forming voltage source converters using an enhanced voltage control scheme," *IEEE Transactions on Power Delivery,* vol. 34, no. 5, pp. 1827-1842, 2018.

[11] M. A. Ghasemi, M. Parniani, S. F. Zarei, and H. M. Foroushani, "Fast maximum power point tracking for PV arrays under partial shaded conditions," in *18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe),* 2016, pp. 1-12.

[12] S. F. Zarei, M. A. Ghasemi, S. Peyghami, P. Davari, H. Mokhtari, and F. Blaabjerg, "Characterization of proportional-integral-resonant compensator for DC link voltage control," in *2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2018, pp. 1-8.

[13] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodriguez, "Control of power converters in AC microgrids," *IEEE transactions on power electronics,* vol. 27, no. 11, pp. 4734-4749, 2012.

[14] A. Yazdani and R. Iravani, *Voltage-sourced converters in power systems: modeling, control, and applications*: John Wiley & Sons, 2010.

[15] S. F. Zarei, H. Mokhtari, M. A. Ghasemi, S. Peyghami, P. Davari, and F. Blaabjerg, "DC-link loop bandwidth selection strategy for grid-connected inverters considering power quality requirements," *International Journal of Electrical Power & Energy Systems,* vol. 119, p. 105879, 2020.

[16] Y. Khayat, Q. Shafiee, R. Heydari, M. Naderi, T. Dragičević, J. W. Simpson-Porco, *et al.*, "On the secondary control architectures of AC microgrids: An overview," *IEEE Transactions on Power Electronics,* vol. 35, no. 6, pp. 6482-6500, 2019.

[17] Y. Sun, X. Hou, J. Yang, H. Han, M. Su, and J. M. Guerrero, "New perspectives on droop control in AC microgrid," *IEEE Transactions on Industrial Electronics,* vol. 64, no. 7, pp. 5741-5745, 2017.

[18] Y. Han, H. Li, L. Xu, X. Zhao, and J. M. Guerrero, "Analysis of washout filter-based power sharing strategy—An equivalent secondary controller for islanded microgrid without LBC lines," *IEEE Transactions on Smart Grid,* vol. 9, no. 5, pp. 4061-4076, 2017.

[19] J. Lu, M. Savaghebi, and J. M. Guerrero, "Second order washout filter based power sharing strategy for uninterruptible power supply," in *IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society,* 2017, pp. 7854-7859.

[20] Y. Khayat, M. Naderi, Q. Shafiee, M. Fathi, H. Bevrani, T. Dragicevic, *et al.*, "Communication-less optimal frequency control of islanded microgrids," in *20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe),* 2018, pp. P. 1-P. 8.

[21] G. Lou, W. Gu, L. Wang, B. Xu, M. Wu, and W. Sheng, "Decentralised secondary voltage and frequency control scheme for islanded microgrid based on adaptive state estimator," *IET Generation, Transmission & Distribution,* vol. 11, no. 15, pp. 3683-3693, 2017.

[22] N. Xia, H. B. Gooi, S. Chen, and W. Hu, "Decentralized state estimation for hybrid AC/DC microgrids," *IEEE Systems Journal,* vol. 12, no. 1, pp. 434-443, 2016.

[23] M. M. Rana and L. Li, "An overview of distributed microgrid state estimation and control for smart grids," *Sensors,* vol. 15, no. 2, pp. 4302-4325, 2015.

[24] A. Morattab, O. Akhrif, and M. Saad, "Decentralised coordinated secondary voltage control of multi-area power grids using model predictive control," *IET Generation, Transmission & Distribution,* vol. 11, no. 18, pp. 4546-4555, 2017.

[25] S. F. Zarei, M. A. Ghasemi, H. Mokhtari, and F. Blaabjerg, "Performance Improvement of AC-DC Power Converters under Unbalanced Conditions," *Scientia Iranica,* 2019.

[26] S. F. Zarei, H. Mokhtari, M. A. Ghasemi, S. Peyghami, P. Davari, and F. Blaabjerg, "Control of grid-following inverters under unbalanced grid conditions," *IEEE Transactions on Energy Conversion,* vol. 35, no. 1, pp. 184-192, 2019.

[27] S. F. Zarei, H. Mokhtari, and M. A. Ghasemi, "Enhanced control of grid forming VSCs in a micro-grid system under unbalanced conditions," in *2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC)*, 2018, pp. 380-385.