Robust Single Primary Control Loop for AC Microgrids

Yousef Khayat, Mobin Naderi, Qobad Shafiee, Mohammad Fathi, and Hassan Bevrani

Published (to be published) in: Proceedings of the 9th IEEE conference on Power Electronics, Drives Systems and Technologies, PEDSTC 2018

(Expected) publication date: 2018

Citation format for published version:

M. Naderi, Y. Khayat, Q. Shafiee, M. Fathi, and H. Bevrani, ‘‘Robust Single Primary Control Loop for AC Microgrids,’’ In Proc. 9th IEEE Power Electronics, Drives Systems, and Technologies Conference (PEDSTC 2018), Tehran, Iran, Feb. 2018, pp. 505-509.

Robust Single Primary Control Loop for AC Microgrids

Yousef Khayat, Mobin Naderi, Qobad Shafiee, Mohammad Fathi, Hassan Bevrani
Smart/Micro Grids Research Center (SMGRC), smgrc.uok.ac.ir
Department of Electrical Engineering, University of Kurdistan, Sanandaj P.C.: 6617715175, Iran
Emails: y.khayat@eng.uok.ac.ir, m.naderi@eng.uok.ac.ir, mfathi@uok.ac.ir, q.shafiee@uok.ac.ir, bevrani@uok.ac.ir

Abstract— **In this paper, a robust single primary control loop is proposed for ac microgrids. There are no work in primary control layer which presents a systematic tuning method based on the modelling of the system. As we know, tuning of this loops are very sensitive to their elements' value of nominal system (like LCL filter and load variations). In other words, tuning of these cascade loops always challenged the designers to close the system appropriately. Lack of a systematic and robust approach to controller design at primary layer, encouraged us to incline and design robust controllers and represent a systematic primary control. Unlike previous works, it is shown that the proposed controller covers all functions of both voltage and current controller loops in primary control. Moreover, with this solution, all the possible uncertainty of a microgrid is considered and the systematic designed controller renders an optimal/suboptimal robust performance. Simulation results in simpower environment of MATLAB validate our claims.**

Index Terms—**AC microgrids, H_2, H_∞, and mixed H_2/H_∞, robust control, primary control, uncertainty.**

I. INTRODUCTION

Effective integration of renewable energy resources (RERs) and their compromising utilization, has become a significant driving force toward realization of the green world. Following the introduction of microgrid concept, integration, control, and operation of RERs have been more and more considered by the researchers. Usage of distributed generators (DGs) increases the reliability of the system and reduces the need of expansion and reinforcement of the grid in the future. Moreover, local power quality for active distribution systems is more flexible rather than conventional centralized power plants[1], [2].

Meanwhile, because of various uncertainties in microgrids, and their dynamic equilibrium point, conventional control methods are not effective enough. Robust operation of each DG in microgrids can be a good solution in comparison with other control approaches [3].

In microgrids, for both islanded and grid connected modes, different control objectives are often defined and implemented by a multi-layer hierarchical structure (e.g., voltage and frequency regulation, and accurate active/reactive power sharing. Primary as the first layer to maintain the stability, secondary as a restoration layer, microgrid central control (MGCC) as a central command layer and global control like an SCADA layer are the main control layers of this hierarchy [4]–[7].

Local control of voltage amplitude in the output filter of each DG, frequency synchronization, and power sharing are the main control objectives in the first layer in islanded microgrids [8], [9]. These goals are layered and acted by current loop control, voltage loop control, and often droop control [7].

Hierarchical and multi-layered control strategies have been investigated for both operation modes of a microgrid, i.e. grid connected and autonomous modes. However, the introduced control techniques so far do not mostly accommodate the effects of output filter's parameter variations and the other uncertainties of the system such as line parameters variation, local and common loads changes, and so on [10], [11].

One of the fundamental robust control frameworks introduced in several power electronic-based applications is H_∞ control method [12]. Conventional two-layered cascade control frameworks composed of a robust outer voltage controller is proposed in [13] to increase microgrid robustness against overall system uncertainties. Moreover, different primary voltage controllers, including robust servomechanism controllers , full-order H_∞ robust control, robust two-degree-of-freedom control strategy, multivariable voltage control framework based on loop-shaping [14], decentralized state feedbacks for microgrids with meshed topology [15], and robust fixed-order decentralized H_∞ [16], have been proposed for such systems. These methods are mostly deal with regulation of voltage in either a single-DG or a microgrid.

Although extensive studies have been carried out on the improvement of primary stability, performance, and control of microgrids, the problems with modelling, robustness, performance, voltage stabilization and providing a simple design approach are still open and can make a benefit for further research.

Motivated by the mentioned drawbacks and limitations, this paper introduces a detailed modeling approach in Laplace domain. Using the derived model a robust single-loop primary control framework, based on the robust theorems, i.e. H_2, H_∞, and mixed H_2/H_∞ , is proposed. Comparative analysis are reported to show the advantages of proposed approach over the conventional controller in maintaining robust stability as well as robust performance of the microgrids under parameter uncertainties. Effectiveness of the proposed controller is then investigated by simulation studies.

The organization of the rest of this paper is as follows. The mathematical model of a microgrid in Laplace domain is presented in Section II. Section III is devoted to uncertainty

978-1-5386-4699-1/18/$31.00 ©2018 IEEE

model in an islanded microgrid. Robust controller design procedure based on the derived model is given in Section IV. Section V provides the simulation results. Finally, Section VI concludes the paper.

II. SYSTEM MODELLING

For this study, a simple and general model of microgrids, shown in Fig. 1, is considered. The case study is composed of two inverter-based DGs connected to a common bus via LC filter and distribution line. General scheme of a DG connected to an islanded microgrid with all elements including LC filter, local loads, common loads at PCC, and capacitor bank is illustrated in Fig. 2(a). For such a case study, schematic of the derived model in Laplace domain is presented (see Fig. 2(b)). Detail of the modeling procedure is provided in the following. An inverter based DG connected by an LC filter and a line to the rest of microgrid is considered to modelling the system. All elements including the output filter of the inverter, line impedance, local and common loads, capacitor bank at PCC are elements which uncertainties can be investigated. By considering all the possible uncertainties shown in Fig. 2(b), the transfer function V_f/V_{in} is obtained as

$$G=\frac{C_f.Z_{local}.s.(C_f.C_{pf}.Z_{line}.s+Z_f)}{As^2+Bs+Z_f+Z_{local}} \tag{1}$$

where

$$\begin{aligned}A&=C_f.C_{pf}.K_d.Z_{line}.Z_{local}\\&\quad+C_f.C_{pf}.Z_f.Z_{line}.Z_{local}\\B&=C_f.K_d.Z_{local}++C_f.Z_f.Z_{local}\\&\quad+C_{pf}.Z_f.Z_{line}+C_{pf}.Z_f.Z_{local}\\&\quad+C_{pf}.Z_{line}.Z_{local}\end{aligned} \tag{2}$$

Which it just matter to consider the output voltage of the DG, once we take into account only the output voltage of the DG, (1) can be simplified as (3).

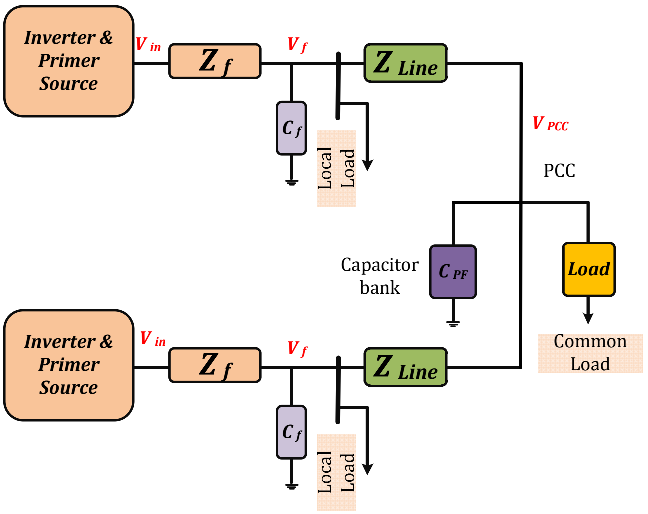


Fig.1. Overall schematic of the studied microgrid system.

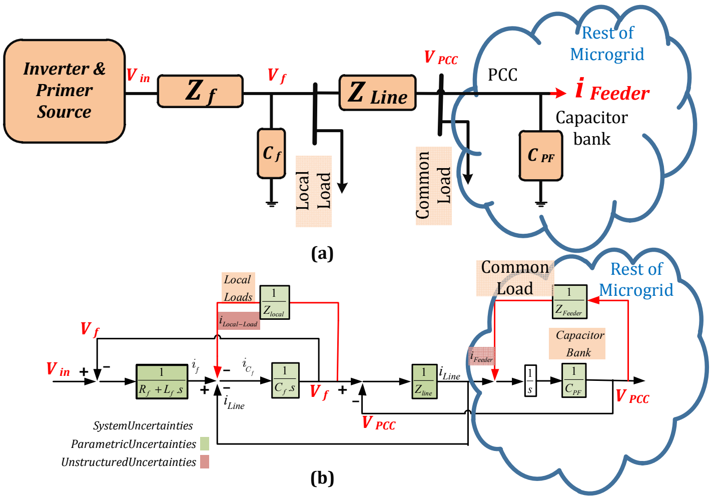


Fig. 2. (a) A DG connected to an islanded microgrid, and (b) its modelling in Laplace domain.

$$G_N=\frac{V_f}{V_{inv}}=\frac{1}{C_f.L_f.s^2+C_f.(R_f).s+1} \tag{3}$$

III. SYSTEM UNCERTAINTY MODEL

All uncertainties correspond to a DG, including filter and line parameters or local or common loads are highlighted in Fig. 2. In the presence of these uncertainties, a robust controller is necessary to improve the stability and performance of the system. There are several methods to deal with uncertainties to appropriate modeling of a system. However, modeling a system with inherent uncertainties or dynamic perturbations can be generally arranged as "un-modeled dynamics" and "modeling errors". Here, dynamic parametric perturbations considered for the LCL filter and distribution line, while local/common loads are lumped into perturbation of $\Delta_m(s)$ which is a type of unstructured uncertainties. Additive, inverse additive, input multiplicative, and output multiplicative perturbations approaches are the most popular methods in robust control theory for modeling of the system uncertainties. In this paper, the multiplicative perturbation procedure is utilized. Thus, transfer function of the system in the presence of uncertainties can be considered as

$$\begin{gathered}G_\Delta(s)=[1+W_u(s).\Delta_m(s)]G_n(s),\\ \bar{\sigma}[\Delta(j\omega)]<1,\ \ \forall\omega\geq 0\end{gathered} \tag{4}$$

where $W_u(s)$ is a stable scalar transfer function which specify the frequency structure and spatial of the uncertainties, spans the $G_\Delta(s)$ to a neighborhood of $G_n(s)$, and $\bar{\sigma}$ is the largest singular value of $\Delta_m(s)$. It should be noted that (4) will not implied any mechanism or structure for the uncertainty disk of $\Delta_m(s)$.

In order to capture an unstructured uncertainty upper bound for the proposed system using the multiplicative uncertainty

$\Delta_m(\mathrm{s})$, a $W_u(\mathrm{s})$ can be found by *fitmag(G_Δ)* Matlab function such that $|\Delta_m(j\omega)| \le |W_u(j\omega)|$, where $W_u(\mathrm{s})$ is given by

$$W_u = \frac{86.3(s+0.2)(s^2+26s+1874)}{(s+3417)(s+9.2)(s+0.14)} \qquad (5)$$

IV. ROBUST H₂, H∞ & MIXED H₂/ H∞ CONTROLLER DESIGN

H_∞, H_2, and mixed H_2/H_∞ voltage controllers are designed for the system in Fig. 2, such that by using a feedback signal from the output voltage of the LC filter, V_f, all control objectives are achieved using a single primary control loop. These controllers specify a feasible robust controller by minimizing the corresponding norms of the linear fractional transformation of system, $F_L(\mathrm{G,K})$ (see Table I).

$F_L(\mathrm{G,K})$ is the nominal closed-loop transfer function matrix for (3) which is shown as T_{ZW}, such as Fig. 3. It should be noted that the solution for the corresponded minimization problems are not unique. The stabilizing controller is designed in a way that the corresponded norm of table 2 goes below one. Moreover, The parameters α and β (see the last row of Table I) determine the *H₂/ H∞* constraints and trade off criterion.

Fig. 4 illustrates the closed-loop system diagram to synthesis of the robust controllers. By rewriting the $F_L(\mathrm{G,K})$ as $z = T_{zw}w$, the closed-loop transfer function for *H∞* and *H₂* controllers in matrix form is

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} GK(1+\mathrm{GK})^{-1} & (1+\mathrm{GK})^{-1} \\ -G(1+GK(1+\mathrm{GK})^{-1}) & 1-G(1+\mathrm{GK})^{-1} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \qquad (6)$$

where *K* is the corresponded designed controller based on *H∞* or *H₂*. Similarly, the cloased loop transfer function for the mixed H₂/ H∞ can be written as

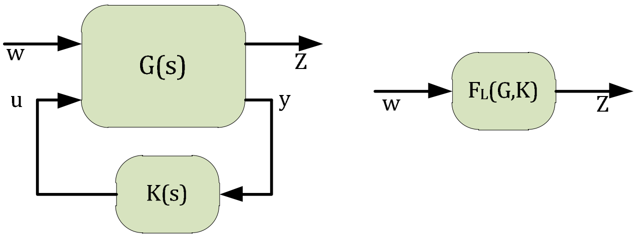


Fig. 3. Standard LFT configuration to design of robust controllers.

TABLE I
Optimization problems to related the controllers' designs

Approach	Corresponded norm
H₂	$\|F_L(\mathrm{G,K})\|_2 < 1$
H∞	$\|F_L(\mathrm{G,K})\|_\infty < 1$
Mixed H₂/ H∞	$\alpha.\|T_{ZW_\infty}\|_\infty^2 + \beta.\|T_{ZW_2}\|_2^2$

$$\begin{bmatrix} z_1^\infty \\ z_2^2 \\ z_3^2 \end{bmatrix} = \begin{bmatrix} K(1+\mathrm{GK})^{-1} & GK(1+\mathrm{GK})^{-1} \\ K(1+\mathrm{GK})^{-1} & GK(1+\mathrm{GK})^{-1} \\ (1+GK(1+\mathrm{GK})^{-1}) & -G(1-GK(1+\mathrm{GK})^{-1}) \end{bmatrix} \begin{bmatrix} w_\infty \\ w_2 \end{bmatrix} \qquad (7)$$

In order to design a controller with good tracking aim, robust controllers with regards to small gain theorem are considered. For instance, in the *H∞* controller, if $\|T_{ZW}\|_\infty < \gamma$, the system without any controller is robustly stable if and only if $\|\Delta_m\|_\infty \le 1/\gamma$. The same approach applies for the *H₂* and mixed *H₂/ H∞* controller.

The corresponded optimization problems based on these robust theories are placed at Table I. The designed robust controllers are then implemented on the test system shown in Fig. 5.

V. SIMULATION RESULTS

In order to test the designed robust single loop primary controllers, it is enough to closed them on the Fig.2b and draw their step response. Since, if the designed controllers have an appropriate step response without any steady state error or distortions, in the presence of uncertainties, an appropriate v_d will be the output of the controller, which it will be accompanied with v_q=0 and v_0=0 to *dq* transformation unit.

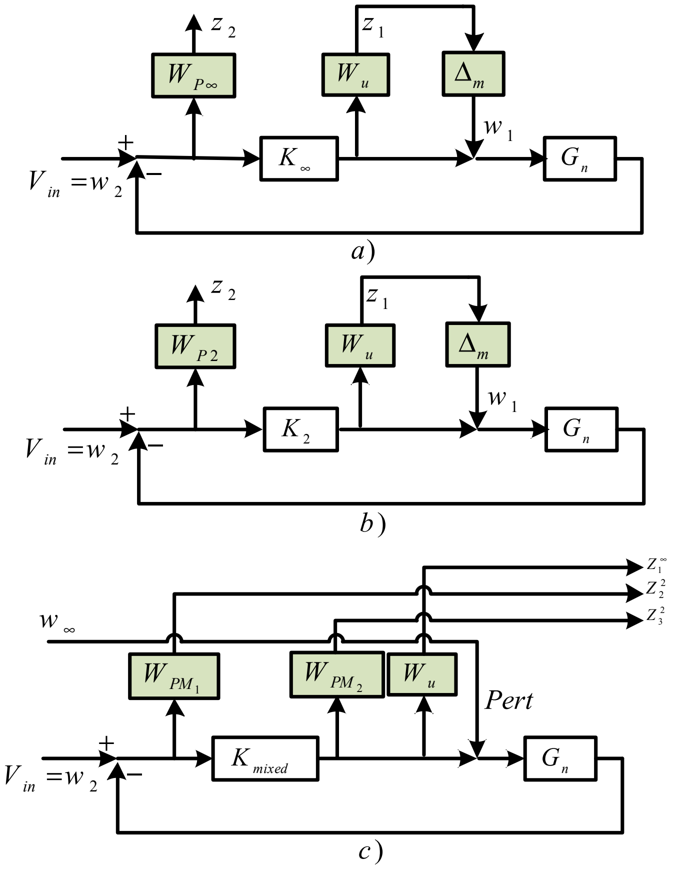
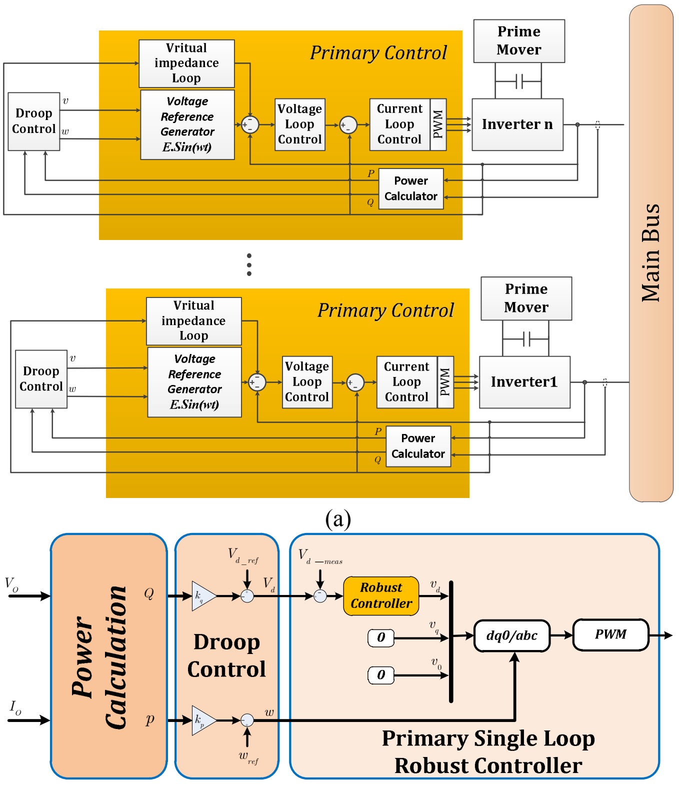


Fig. 4. Closed-loop system diagram to synthesis of robust controllers: a) *H∞*, b) *H₂* and c) mixed *H₂/ H∞*.



(a)

(b)

Fig. 5. Comparison of proposed and conventional primary controllers: (a) conventional primary control configuration, and (b) the proposed robust primary controller.

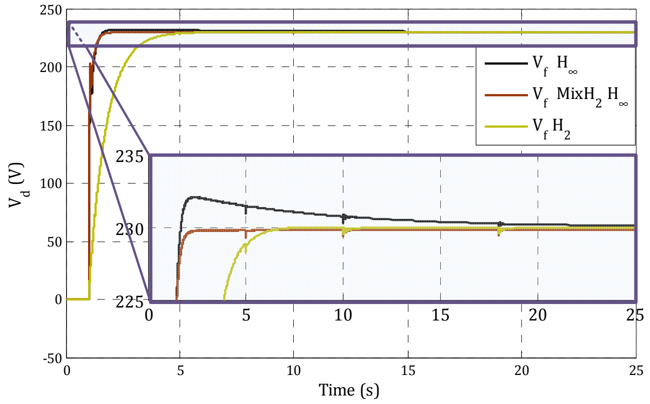
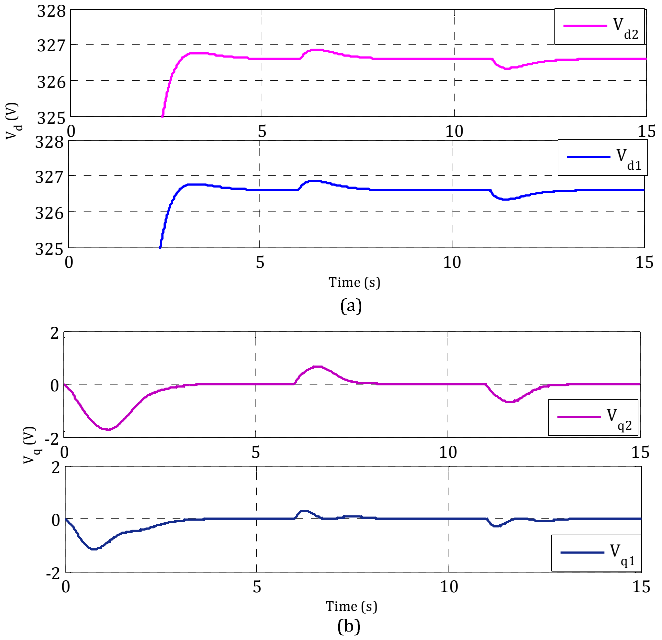


Fig. 6. Closed-loop *d* component of LC filter's voltage in the presence of robust controllers.

The v_d response of close loop system for robust designed controllers is shown at Fig. 6. Load changes are appeared at $t=10s$ and $t=18s$, while there is no significant impact on v_d.

The effectiveness of the proposed robust controllers is evaluated using a test system shown in Fig. 1. By implementing the proposed controllers on the real system at SimPower System environment of Matlab software, main parameters of system including, active and reactive power, system frequency, output voltages and currents in *dq* frame and *abc* phase-sequence can be analyzed as following.

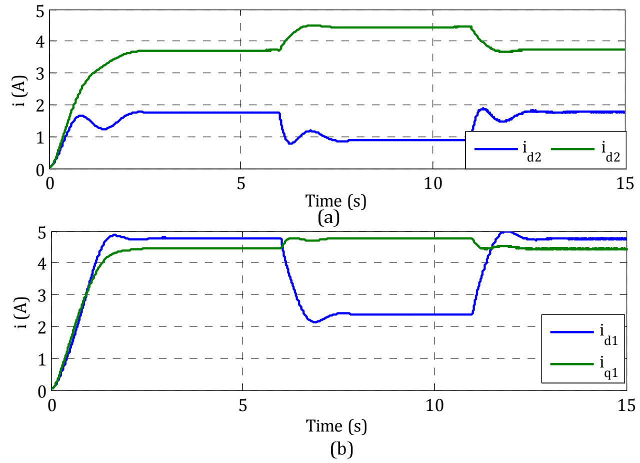
Performance of the controllers under frequent load change is illustrated in Fig. 7. The system load is decreased and then increased at $t=6$ *s* and $t=11$ *s* frequently.



(a)

(b)

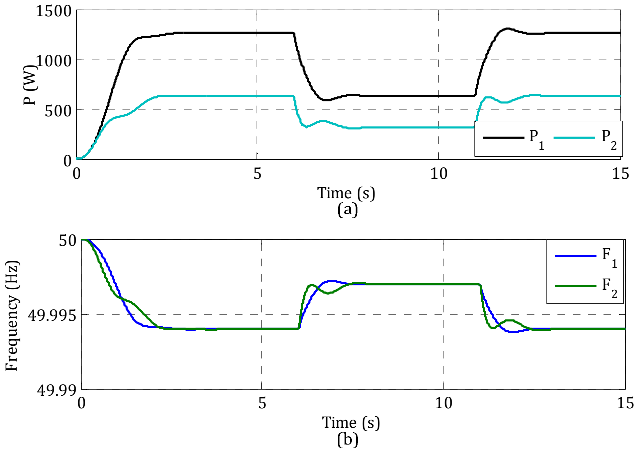
Fig. 7. Output voltages of both units: (a) in *d* axis, and (b) in *q* axis.



(a)

(b)

Fig. 8. Output currents of the units: (a) for unit 2, and (b) for unit 1.



(a)

(b)

Fig. 9. Performance of the proposed approach in controlling (a) Active

power, and (b) frequency of both units.

Fig. 8 shows the output currents of filter for both DGs in *dq* frame. Fig. 9 shows active power and frequency changes over the simulations. As can be seen, the controller helps regulating the frequency and voltage while respecting the droop control.

To evaluate the dynamic response of the proposed controller, transient response of the PCC voltage and the output currents is shown in Fig. 10, and Fig. 11, respectively. Soft transient is observed when a disturbance (load change) occurs at *t=6s*.

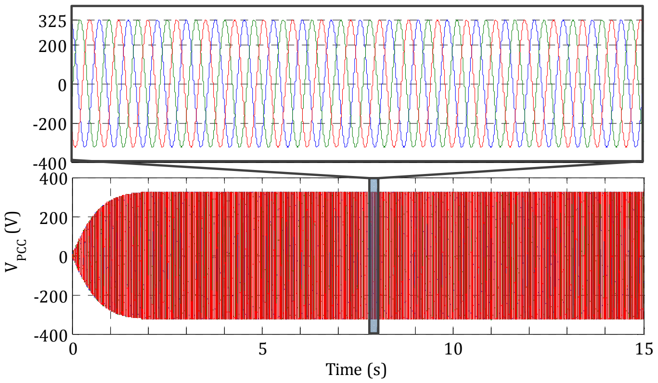
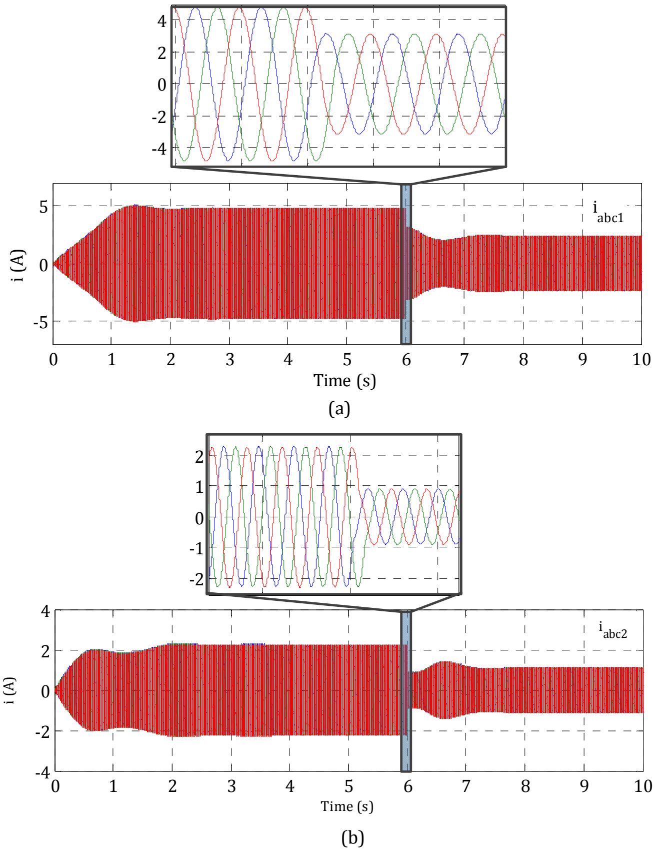


Fig. 10. PCC voltage waveform at *abc* phase-sequence.



(a)

(b)

Fig. 11. Output current waveforms, (a) for unit 1, and (b) for unit 2.

VI. CONCLUSION

This paper proposes a robust primary control loop, which guarantees voltage control of microgrids at the presence of all possible uncertainties. Uncertainty modeling in Laplace domain is adopted for microgrids to facilitate the realization of robust controllers based on H_2, H_∞, and mixed H_2/H_∞ approaches. The salient features of the represented controllers are 1) robust stability and robust control performance; 2) single-loop primary voltage control, which simplifies the control structure and; and 3) effective mitigation of uncertainties, which in turns improves the power quality of the microgrid system. A theoretical analysis, comparative time domain and Laplace domain simulation studies and some numerical simulation studies are presented to show the effectiveness and robustness of the presented controller in microgrid applications.

REFERENCES

[1] H. Bevrani, B. Francois, and T. Ise, *Microgrid Dynamics and Control*. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2017.

[2] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Canizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. A. Jimenez-Estevez, and N. D. Hatziargyriou, “Trends in Microgrid Control,” *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, Jul. 2014.

[3] H. Bevrani, *Robust Power System Frequency Control*, Second. Cham: Springer International Publishing, 2014.

[4] A. Bidram and A. Davoudi, “Hierarchical Structure of Microgrids Control System,” *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1963–1976, Dec. 2012.

[5] Y. Han, H. Li, P. Shen, E. A. A. Coelho, and J. M. Guerrero, “Review of Active and Reactive Power Sharing Strategies in Hierarchical Controlled Microgrids,” *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 2427–2451, Mar. 2017.

[6] J. Guerrero, J. Vasquez, and J. Matas, “Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization,” *IEEE Trans.*, 2011.

[7] L. Meng, Q. Shafiee, G. Ferrari Trecate, H. Karimi, D. Fulwani, X. Lu, and J. M. Guerrero, “Review on Control of DC Microgrids,” *IEEE J. Emerg. Sel. Top. Power Electron.*, pp. 1–1, 2017.

[8] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, “Review of Power Sharing Control Strategies for Islanding Operation of AC Microgrids,” *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 200–215, Jan. 2016.

[9] M. S. Sadabadi, Q. Shafiee, and A. Karimi, “Plug-and-Play Voltage Stabilization in Inverter-Interfaced Microgrids via a Robust Control Strategy,” *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 3, pp. 781–791, May 2017.

[10] Y. Khayat, M. Naderi, Q. Shafiee, Y. Batmani, M. Fathi, and H. Bevrani, “Robust control of a DC-DC boost converter: H_2 and H_∞ approaches", *2017 8th Power Electronics, Drive Systems & Technologies Conference (PEDSTC)*, 2017, pp. 407–412.

[11] M.Naderi, Y.Khayat, Y.Batmani, and H. Bevrani “Robust Multivariable Microgrid Control Synthesis and Analysis,” *Energy Procedia*, vol. 100, pp. 375–387, Nov. 2016.

[12] G. Weiss, Q.-C. Zhong, T. C. Green, and J. Liang, “H/sup /spl infin// repetitive control of DC-AC converters in microgrids,” *IEEE Trans. Power Electron.*, vol. 19, no. 1, pp. 219–230, Jan. 2004.

[13] Y. W. Li, D. M. Vilathgamuwa, and P. C. Loh, “Robust Control Scheme for a Microgrid With PFC Capacitor Connected,” *IEEE Trans. Ind. Appl.*, vol. 43, no. 5, pp. 1172–1182, 2007.

[14] M. Babazadeh and H. Karimi, “A Robust Two-Degree-of-Freedom Control Strategy for an Islanded Microgrid,” *IEEE Trans. Power Deliv.*, vol. 28, no. 3, pp. 1339–1347, Jul. 2013.

[15] A. H. Etemadi, E. J. Davison, and R. Iravani, “A Decentralized Robust Control Strategy for Multi-DER Microgrids—Part I: Fundamental Concepts,” *IEEE Trans. Power Deliv.*, vol. 27, no. 4, pp. 1843–1853, Oct. 2012.

[16] S. Riverso, F. Sarzo, and G. Ferrari-Trecate, “Plug-and-Play Voltage and Frequency Control of Islanded Microgrids With Meshed Topology,” *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1176–1184, May 2015.