Voltage Tracking of a Single-phase Inverter in an Islanded Microgrid

Md. Alamgir Hossain*, Hemanshu R. Pota

School of Engineering and Information Technology,

The University of New South Wales, Canberra, ACT 2610, Australia

(alamgir_duet@hotmail.com / Md.Hossain6@student.adfa.edu.au , h.pota@adfa.edu.au)

*Corresponding Author: Md. Alamgir Hossain, SEIT, UNSW@Canberra, Tel: (+61) 2 626 88199, Fax: (+61) 2 626 88443

Md.Hossain6@student.adfa.edu.au

Received: 05.05.2015 Accepted:01.07.2015

Abstract- Voltage source inverters (VSIs) are generally used to interface distributed generators (DGs) with the microgrid. The voltage quality of the network is controlled based on the reference voltage tracking strategy of the VSI. In this paper, a mathematical relationship of a combined PI controller for an inverter is derived for the instantaneous voltage tracking strategy, and its validity and robustness are demonstrated for both steady-state and transient conditions. The tuning of the proposed controller is performed with the aid of root locus analysis. Moreover, the importance of a voltage controller has been addressed; without voltage controller, voltage waveform in a network may be distorted due to nonlinear loads and hence the power quality of the network too. The performance of the proposed combined PI controller is found to be effective to track the instantaneous reference grid voltage (V_g^*). The simulation work is carried out with the aid of MATLAB/Simulink SimPowerSystems.

Keywords - Voltage tracking, microgrid, inverter control, root locus analysis.

1. Introduction

The application of DG units is increasing rapidly all over the world due to the increased the reliability of electricity supply, low transmission losses, increased efficiency, economic and high power quality [1-3]. The greater portion of the distributed units - renewable source generators - utilizes inverter to transform from DC to AC voltage and synchronize with the microgrid. Microgrid consisting of distributed energy sources can be operated in either grid connected or islanded mode. In the case of large disturbances in the main grid caused by fault or voltage collapse, operation of microgrid generally is performed as an islanded mode. Moreover, for geographical reason such as remoteness, an islanded microgrid is considered because of transmission loss, large investment, environmental effect and economical perspective. In this paper, a microgrid has been treated as an islanded operation mode. The characteristics of microgrids are different from the conventional power system because of the additional application of power electronics with the renewable sources in microgrid and its control to manage the demand and supply. New controlling strategies are applied and/or required for reliable operation of the grid system [4, 5].

In islanded microgrids, distributed generation units with voltage source inverters are extensively used to supply AC voltage. The principal reason for applying VSIs is to control voltage [6]. In a standalone ac system, all inverters in the system are able to provide a stable voltage and frequency for random varying loads that is it does not required any exterior reference to restrain synchronization [7]. The controlling of AC voltage of a VSI is the chief issue of microgrid architecture. An effective control strategy for an inverter can improve frequency and voltage on the consumer side network.

There are number of publications on microgrid control [8-11]. The control of microgrids often means inverter control [12] that can

- inject active and reactive power into the network,
- be used as a voltage source with controlled frequency and magnitude, and
- control voltage and frequency during islanded operation.

The majority of the research papers regarding inverter controller are based on power sharing that is performed employing voltage and frequency droop control for the local network. The advantage of droop controller in the case of power/load sharing for a microgrid connected inverter is considered in [13]. The chief reason of developing different droop control algorithms for an inverter is that it can restore the voltage and frequency deviation while maintaining the system stability for most disturbances [8]. However, the contribution of the primary controller to maintain the inverter stability cannot be neglected, as it tracks the reference instantaneous grid voltage, V_g^*, that is determined from the droop control.

In the case of inverter controller, the synchronization of the rotating dq reference frame to the grid voltage has been used extensively [14-17]. In this process, harmonics of the fundamental frequency can pass through the low pass filter; and it has numerical complexity. The application of the Park and Clarke is to transform the rotating quantities of the balanced three phase system into a DC component that is easy to handle to control the system. But, these transformations do not work perfectly for an unbalance system and/or harmonic presence in the electrical quantities as it also requires references to convert. Furthermore, it cannot be used in the single phase system. Therefore, a simple control strategy [18] has emerged based on a PI-regulator in a time domain format without transforming into a dq frame. In this paper, grid voltage is controlled using inner current and outer voltage control loop, providing fast response priority to the inner current controller loop with separate control parameter values; however, the research in the field of voltage tracking is ongoing and is still open for obtaining the best performance in the case of controlling microgrids.

In this paper, a single phase voltage source microgrid model is completed first, and then a transfer function based on the model is derived to track the reference voltage that includes two simple PI controllers. Moreover, the controller tuning of the system has been accomplished analysing the root locus in the result section. Finally, the simulation of the controlling algorithm has been examined to track the reference voltage, and concluded with a commendable tracking observation.

2. Modelling and controlling design

2.1. Microgrid architecture

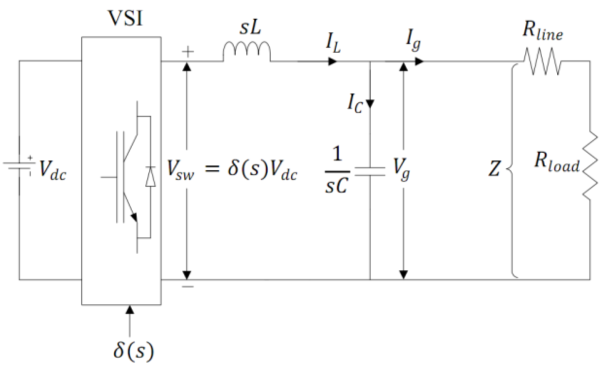


Fig. 1. A single phase single energy source microgrid.

A single phase energy source microgrid consisting of a DC source, voltage source inverter (VSI), LC filter, line and load impedance is considered for modelling, analysis and to predict the performance of the microgrid shown in the Fig. 1. The VSIs used in the microgrid are required to interface the DC energy sources to the grid network for transferring power from DC side to AC side. For simplicity, in this analysis, DC voltage source and switching action of IGBT have been represented using $V_{sw} = \delta(s)V_{dc}$, here $\delta(s) \in$ {-1, 1} represents switching action, and V_{dc} represents a DC voltage source. Microgrid is represented as a resistive line and load because we assume low voltage operation, the reactance of the line can be neglected [19, 20]. The LC filter introduction after the voltage source attenuates the harmonics of high frequency switching.

2.2. Voltage control

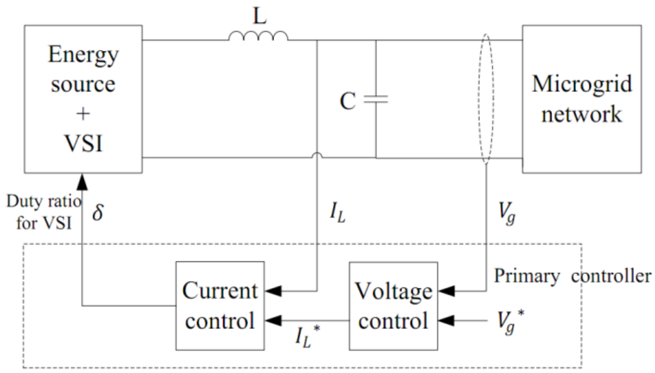


Fig. 2. Voltage Source Inverter control loop.

Fig. 2 shows the control strategy block diagram of the microgrid connected VSI, in which two closed-loop control systems control the amplitude and frequency of the grid voltage. The outer control loop is the voltage controller that sets the reference inductor current, and the inner control loop is the current controller that controls the duty ratio of pulse width modulation (PWM). The current controller has been used to speed up the response, while the voltage controller is used for voltage tracking.

To achieve accurate reference voltage tracking, the duty ratios of the PWM should be determined accurately; therefore, close loop feedback of the grid voltage is compared with the reference voltage, and the error is permitted to pass through the voltage controller to obtain the reference current. The current through the inductor is injected into the current controller that compares the inductor current (I_L) with reference current (I_L^*) to produce desired duty ratios (δ).

The control in the VSI enables the grid voltage to be in line with the reference grid voltage. The load in the microgrid is considered as a black box, where the load variation is not known. This control strategy operates perfectly to follow the reference grid voltage for changes in load.

2.3. Control strategy

The inductor current in Fig. 1 can be written as:

$$I_L = \frac{V_{sw} - V_g}{sL} \quad (1)$$

The source voltage (V_{sw}), consisting of a DC bus voltage (V_{dc}) and duty ratio (δ), can be written:

$$V_{sw} = \delta(s)V_{dc} \quad (2)$$

The duty ratios of PWM can be found from the control loop Fig. 2 is:

$$\delta(s) = C_c(I_L^* - I_L) \quad (3)$$

The error between inductor current (I_L) and set value current (I_L^*) are corrected by the inner PI regulator is tuned using the following transfer function derived from current through the inductor:

$$\frac{I_L}{\delta(s)} = \frac{V_{dc}}{sL} \quad (4)$$

C_c represents as a PI current controller and can be written:

$$C_c = \frac{K_{ii}+sK_{pi}}{s} \quad (5)$$

K_{ii} and K_{pi} are the integral and proportional gain of the inner PI controller loop. The duty ratio is calculated based on the output of the inner PI regulator.

I_L^* is the reference current of the inductor and represented from Fig. 2 as:

$$I_L^* = C_v(V_g^* - V_g) \quad (6)$$

V_g^* is reference grid voltage determined by the secondary control strategy, which is out of the scope of this paper. The difference between reference grid voltage and measured grid voltage is controlled by the outer PI regulator, and the following transfer function of the capacitor current to the grid voltage is used for tuning the regulator to control the grid voltage derived across the capacitor voltage.

$$\frac{V_g}{I_c} = \frac{1}{sC} \quad (7)$$

C_v is the PI voltage controller and can be written:

$$C_v = \frac{K_{io}+sK_{po}}{s} \quad (8)$$

K_{io} and K_{po} are the integral and proportional gain of the outer PI controller loop.

Substituting (6) into (3), duty ratio can be modified as:

$$\delta(s) = K_1\left(V_g^* - V_g\right) - C_c I_L \quad (9)$$

where $K_1 = C_c C_v$

Substituting (2) and (3) into (1), the inductor current can be calculated by:

$$I_L = K_3\left(V_g^* - V_g\right) - K_2 V_g \quad (10)$$

where $K_2 = \frac{1}{sL+C_cV_{dc}}$; $K_3 = K_1K_2V_{dc}$

The input voltage, V_{sw}, can be calculated from (2) using (9) and (10)

$$V_{sw} = \left(V_g^* - V_g\right)(K_6 - K_4) - K_5 V_g \quad (11)$$

where $K_4 = K_3C_cV_{dc}$; $K_5 = K_2C_cV_{dc}$; $K_6 = K_1V_{dc}$

Applying KCL at a node in the Fig. 1, the transfer function, $\frac{V_g}{V_g^*}$, can be determined:

$$\frac{V_g}{V_g^*} = \frac{K_7}{T+K_5+K_7} \quad (12)$$

where $K_7 = K_6 - K_4$; $T = LC\{s^2 + \frac{s}{ZC} + \frac{1}{LC}\}$

Using this combined controller strategy of the two control loops in series; good reference grid voltage tracking can be achieved. The aim of this control strategy is to minimize the error between the measured grid voltage V_g and the reference grid voltage V_g^*.

3. Simulation results

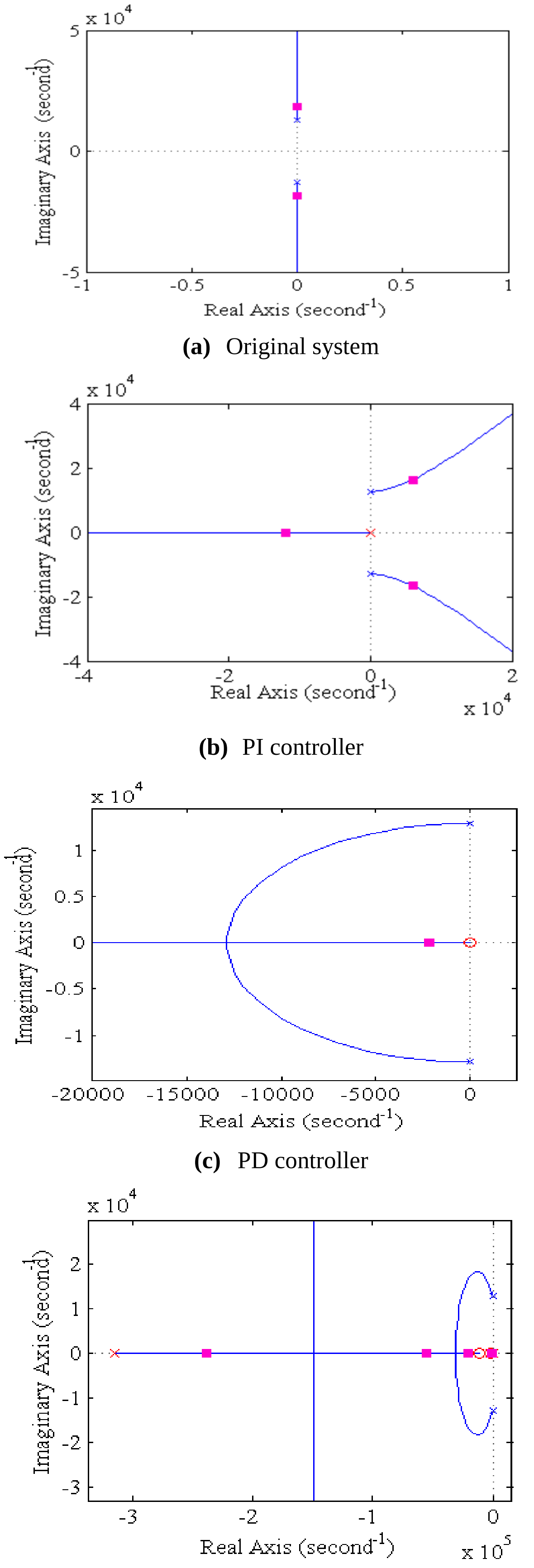
For the simulation of control strategy, the source DC voltage and grid voltage are considered 300 V and 155.57 V, respectively, having a frequency 50 Hz. The resistance of transmission line, in series with the 40 Ω resistive consumer loads, is 0.45 Ω considering 1 km in length.

3.1. Controller tuning

Tuning a controller is an important task in the control system because a good controller tuning can provide high efficiency, low energy cost, increased production rate and reduced process variability. Tuning a controller means the selection of tuning parameters that provide the best result for the system. Controller tuning can be achieved using root locus analysis of a system. The following section will deal with root locus of an inverter that can be connected to the microgrid.

In the open-loop poles of the inverter are on the imaginary axis as seen in Fig. 3a and it requires a controller to bring the system into stable part. In this analysis, the effect of the load has been neglected as it is unpredictable and cannot be implemented directly in the practical controller. This is the worst case scenario and the load is likely to increase the damping of the system. The poles of the system cannot be moved to the stable region by constant gain controller or a simple PI controller because PI places a pole at the origin of the axis illustrated in the Fig. 3b. In Fig. 3c, the PD controller provides a zero in the negative real axis; consequently the system is stabilised for small positive controller gains. But the derivative term in the PD controller makes the system high noise in the presence of small noise. The application of PID controller can bring the system poles into the acceptable region shown in the Fig. 3d; but the difficulty associated with it - only the output voltage is a controllable parameter. The current flow through the network can damage the physical system during the faults as it is uncontrollable parameter; consequently, cascaded controller emerged to control the both current and voltage.

The increasing values of inner proportional gain of the cascaded controller system, K_{pi}, provides less damping in the system that has been demonstrated in Fig. 4a. For the some values of K_{pi}, the system response is overdamped in the stable part of the root locus that has been zoomed in the Fig. 4b. For the small values and the higher values of K_{po}, the system behaviour is observed oscillatory in Fig. 4c and 4d.



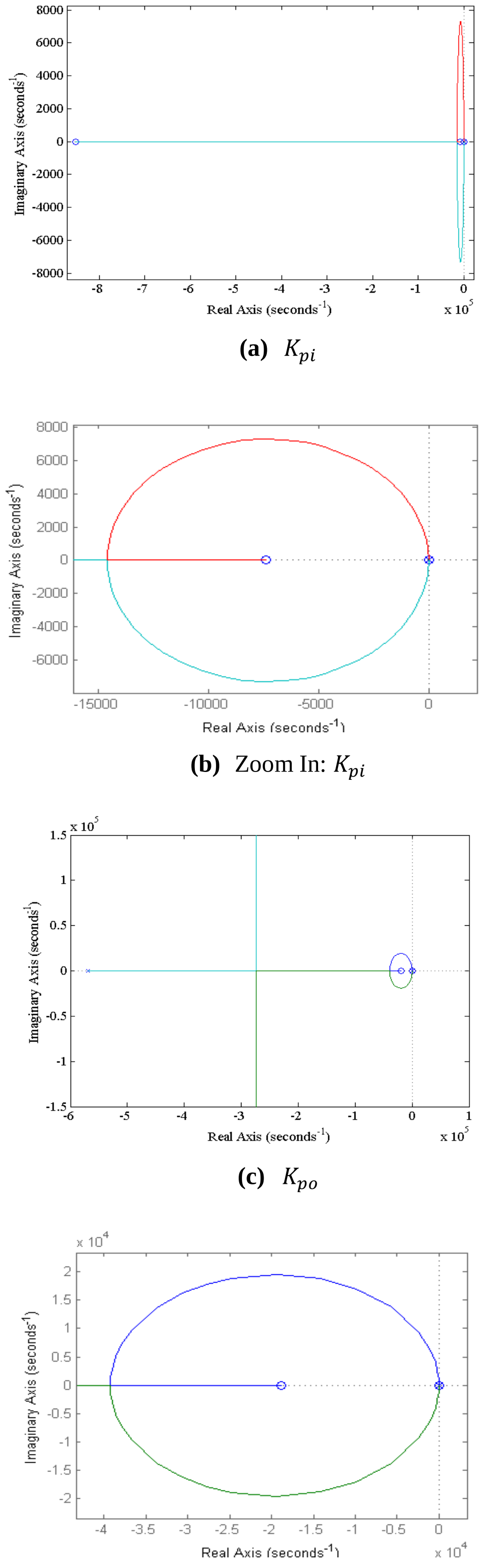
(a) Original system

(b) PI controller

(c) PD controller

(d) PID controller

Fig. 3. Root locus analysis for different controllers in an inverter.



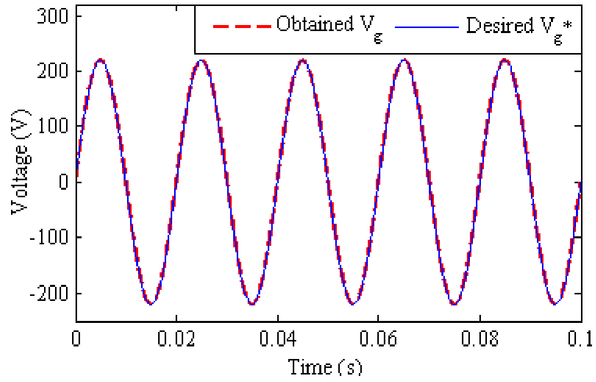
(a) K_{pi}

(b) Zoom In: K_{pi}

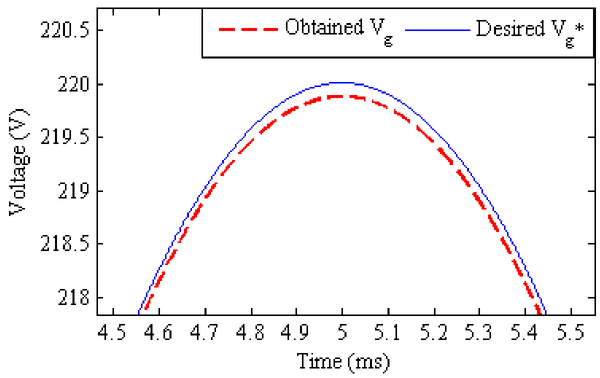
(c) K_{po}

(d) Zoom In: K_{po}

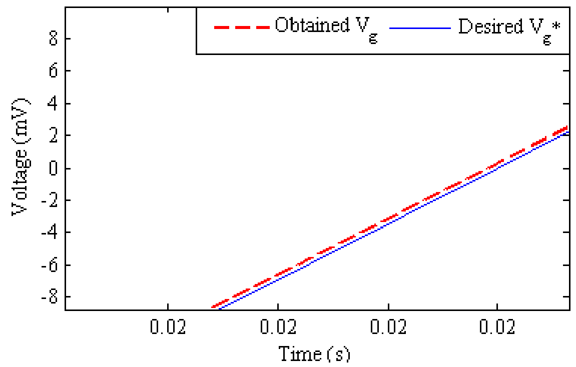
Fig. 4. Parameters effects of a proposed controller on a system.



(a) Overview



(b) Zoom In: magnitude different



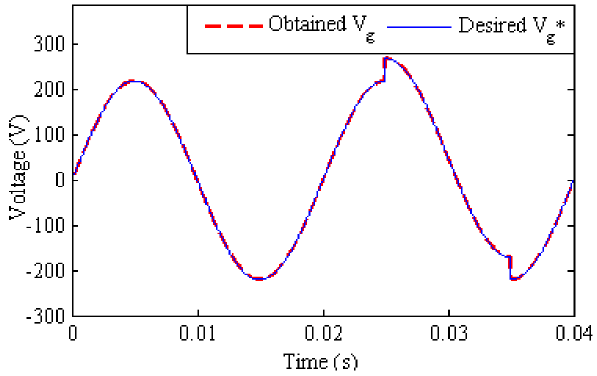
(c) Zoom In: phase different

Fig. 5. Steady state voltage tracking waveform.

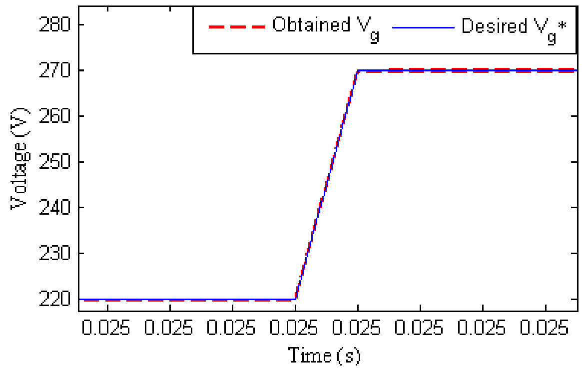
From the root loci of the plant, it is concluded that the closed-loop system with cascaded controller is stable and provides satisfactory performance.

3.2. Voltage tracking

As the operation of a microgrid is with the AC voltage; so, AC grid voltage tracking is implemented throughout the study to evaluate the performance of the control system. Fig. 5a shows the steady state voltage tracking waveform for reference grid voltage, and Fig. 5b and 5c demonstrate its detail; there is minor magnitude and phase error in the tracking voltage which can be reduced to zero. In the Fig. 5c, the phase difference is displayed near the zero crossing of the grid voltage, and it is concluded that the high performance controlling is achieved to follow the reference grid voltage.

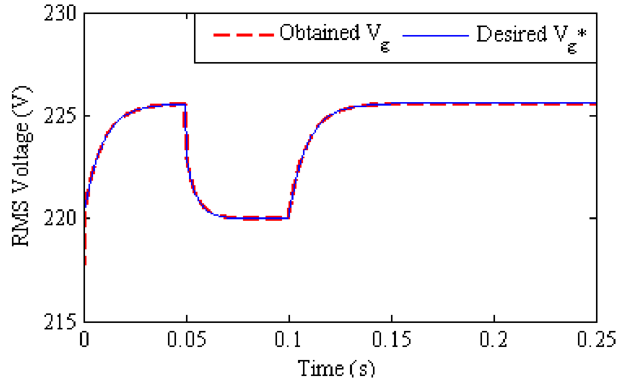


(a) Overview

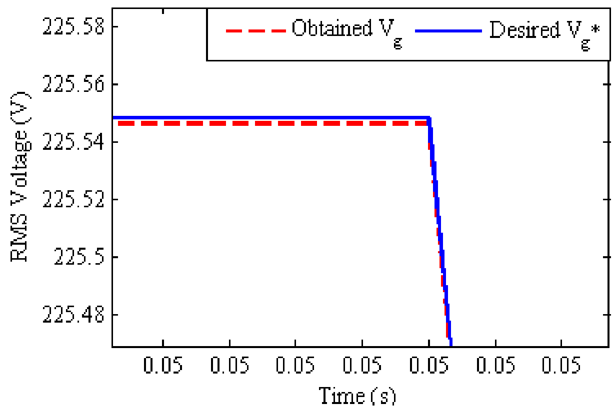


(b) Zoom In: magnitude difference

Fig. 6. Voltage tracking waveform during disturbance.

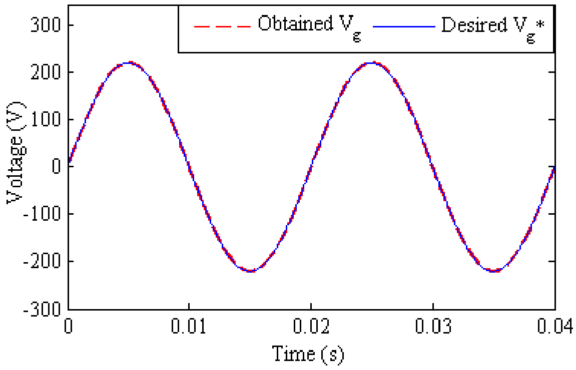


(a) Overview

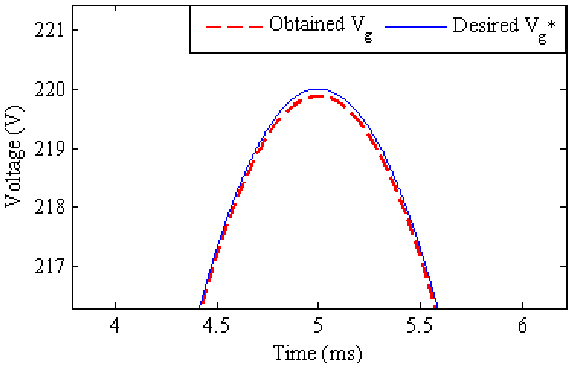


(b) Zoom In: magnitude difference

Fig. 7. RMS voltage tracking.



(a) Overview



(b) Zoom In: magnitude difference

Fig. 8. Robustness: voltage tracking.

The voltage of a microgrid is not in steady state all the time because of connection and disconnection of consumer load as well as various disturbances. The change of reference voltage has been studied to observe the transient effect on grid voltage. At time 0.025 s and 0.035 s, the disturbance voltage waveforms have been introduced as observed in Fig. 6 and noticed that it follows the reference voltage as described in the Fig. 5a. The detail of switching voltage is given in the Fig. 6b, and found negligible error in amplitude and phase. It is concluded that without any overshooting and phase shift, effective voltage tracking is achieved.

All the loads in the network consider only the rms value of the electrical quantities for evaluating their working capacity, and all the sensors also measure the rms voltage at a given point. Accordingly, rms voltage tracking, shown in Fig. 7, is taken into consideration. In this figure, voltage deviations from their nominal voltage have been depicted at 0.05 s and 0.1 s, respectively, in the microgrid due to load parameter changes. It is concluded that the response of the control system is effective in order to track the reference voltage.

3.3. Robustness

The robustness of the proposed control algorithm has been executed with the variation of load and capacitor parameters. In the simulation process, capacitor value for filtering was considered 12 μF; but, for practical perspective, the capacitor value is taken 30 μF; that is, there is a parame -

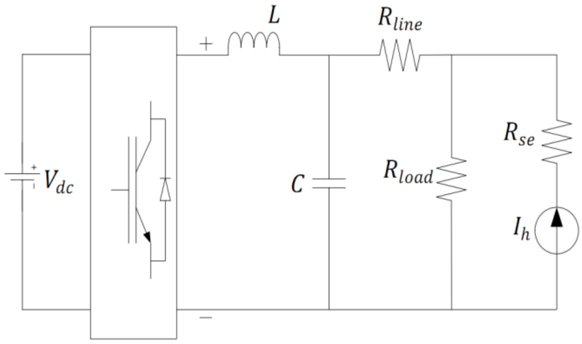
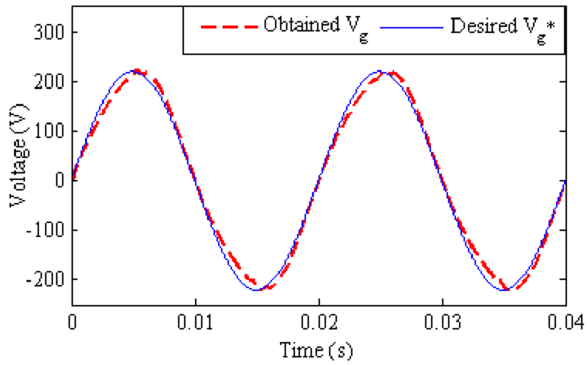
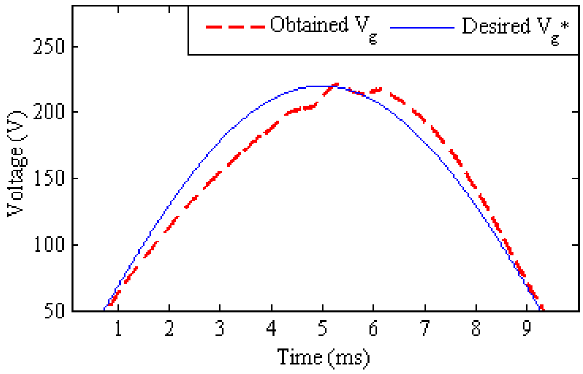


Fig. 9. Simulation model: harmonic loads.



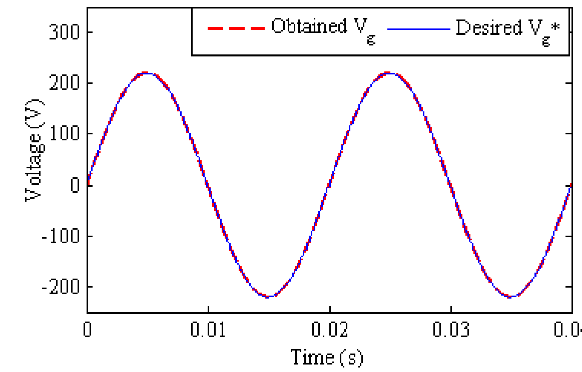
(a) Overview



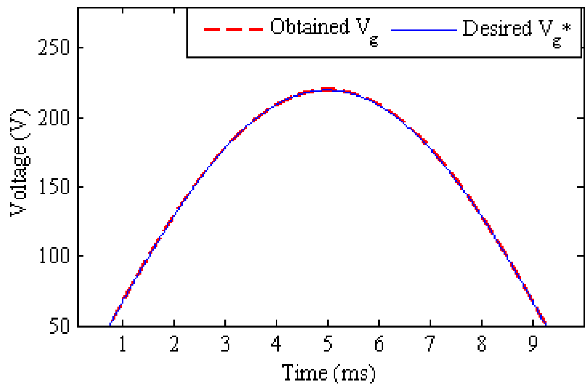
(b) Zoom In: magnitude distortion

Fig. 10. Harmonic load: without voltage controller.

ter variation. In the Fig. 8, the controller is observed robust in the case of capacitor value changes because the magnitude and phase variation of the desired and obtained values are within the acceptable range having similarity with the previous one. The effect of load impedance on the control algorithm is almost negligible, and the performance of the tracking voltage is an identical with the voltage tracking in Fig. 5 except in short circuit - R $\leq$ 0.015 - for this reason, redundant figures are avoided. Consequently, the robustness of the proposed combined PI controllers to the parameter variation and changing load is effective.



(a) Overview



(b) Zoom In: magnitude

Fig. 11. Harmonic load: with voltage controller.

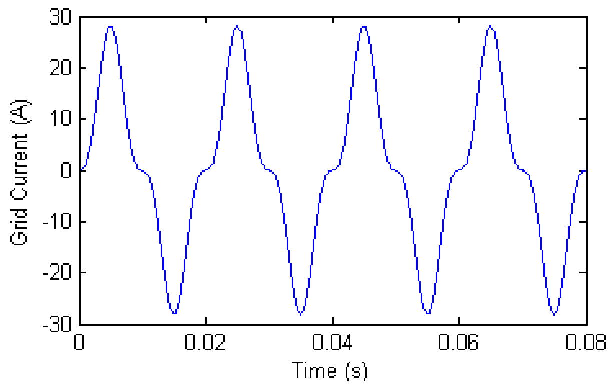
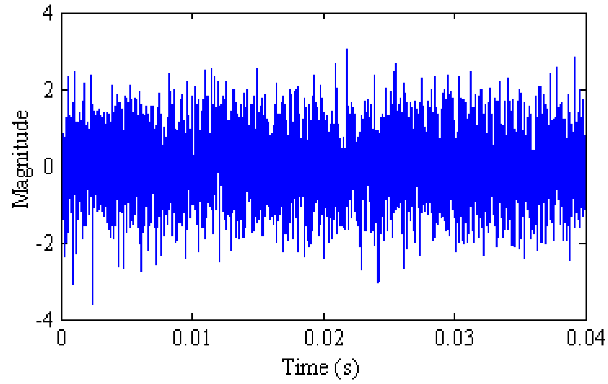


Fig. 12. 3rd harmonic in the grid current.

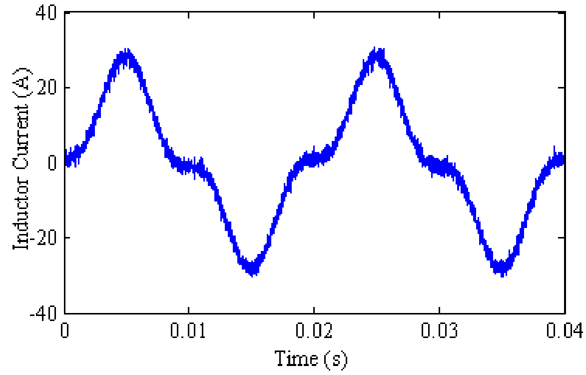
3.4. Harmonic load

The application of non-linear load such as computers, television, fluorescent lamps and rectifiers is increasing all over the world because of development of modern technologies. These non-linear loads produce harmonics that lead to voltage distortion in a circuit; hence the voltage quality is deteriorated. And this voltage is harmful for long life sustainability of any type of electric loads. Consequently, a voltage controller, in the presence of harmonics in a circuit, is necessary to control an inverter.

In the next simulation, non-linear loads are modelled as a harmonic current source of 7 A amplitude and 150 Hz frequency, shown in Fig. 9, to produce 3rd harmonics in the current waveform. A series resistance of 30 Ω is connected to

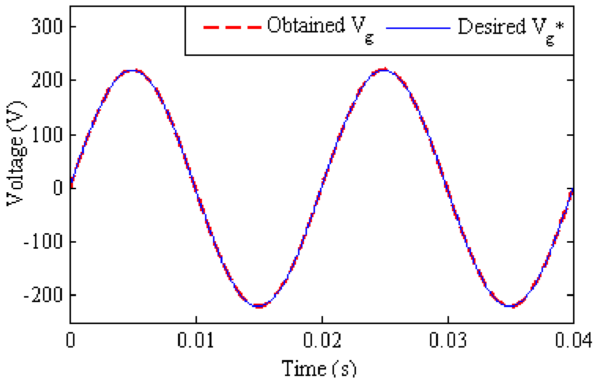


(a) Noise

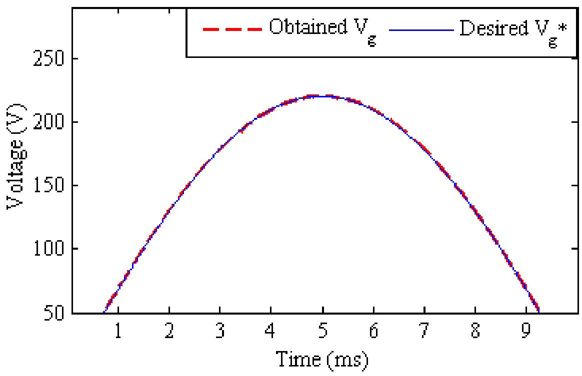


(b) Noise affected current

Fig. 13. Noise to the measured signal.



(a) Overview



(b) Zoom In: amplitude

Fig. 14. Noise: voltage tracking.

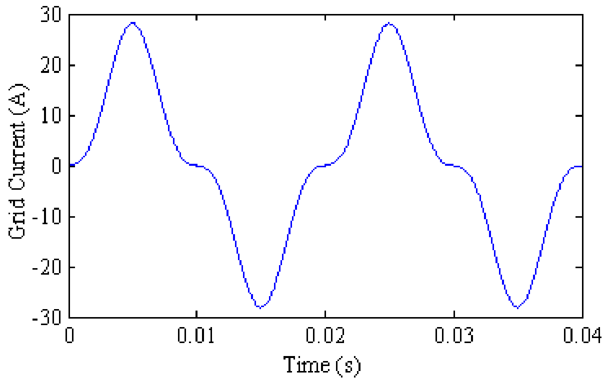


Fig. 15. Noise: grid current.

the current source, and a load of 10 Ω is considered parallel with the current source to analyse the effectiveness of a voltage controller.

The simulation results in the presence of a harmonic load without or with the application of a controller are presented in Fig: 10 and 11 to follow the desired grid voltage, V_g^*. In the absence of voltage controller, grid voltage magnitude and phase angle are distorted from the desired waveform shown in Fig. 10.

The effective voltage tracking is achieved without voltage waveform distortion in the presence of the proposed controller illustrated in Fig. 11. Due to a harmonic load, the corresponding 3rd harmonic is exited in the grid current demonstrated in Fig. 12. From the above result, it can be concluded that the proposed controller shows an effective tracking strategy for any types of load.

3.5. Noise

In practice, the distance between the control unit and generation process of microgrid is far away. For controlling purpose, feedback signal is taken from the local network; hence there is a possibility of noise affected in a measured signal due to electromagnetic interference and so on. In the next simulation, noise is added to the measured signal coming from the local network to observe the capability of the proposed controller effectiveness on noise affected signal. Noise is accumulated in both current and voltage wires shown in Fig. 13. In the presence of noise to the measured signal, the performance of the proposed controller is still effective to follow the reference grid voltage, V_g^*, demonstrated in both overview and its detail in Fig. 14. The corresponding grid current, I_g, is found noise free shown in Fig. 15 where measured signal current, I_L, is noise affected shown in Fig. 13b. The reason for noise free grid current is that capacitor purifies the noise. In conclusion, it can be said that the proposed controller track the reference grid voltage effectively under the acceptable noise affected to the measured signal.

4. Conclusion

This paper proposed a combined PI controller to control the reference grid voltage of an inverter. The effectiveness of the proposed controller is examined through different conditions such as abrupt changes in steady state voltage waveform, change of parameter values, presence of a harmonic load and added noise to the measured signal. Moreover, the necessary of the voltage controller application in an inverter to control the grid voltage is also addressed. Furthermore, the effects of different gains to the control system have been illustrated using the root locus analysis. It is summarized that the control system is suitable for tracking the reference grid voltage, V_g^*. Multiple energy sources will be considered in the future work.

Acknowledgements

M. A. Hossain would like to thanks the organization body of The Dhaka University of Engineering & Technology (DUET) and The University of New South Wales (UNSW) to assist doing research with associated supports.

References

[1] R. Bayindir, E. Hossain, E. Kabalci, and R. Perez, “A comprehensive study on microgrid technology,” International Journal of Renewable Energy Research (IJRER), vol. 4, no. 4, pp. 1094–1107, 2014.

[2] M. A. Hossain and M. R. Ahmed, “Present energy scenario and potentiality of wind energy in Bangladesh,” World Academy of Science, Engineering and Technology, vol. 7, no. 11, pp. 1001– 1005, 2013.

[3] M. A. Hossain, M. Z. Hossain, and M. A. Rahman, “Perspective and challenge of tidal power in Bangladesh,” World Academy of Science, Engineering and Technology, vol. 8, no. 7, pp. 1127–1130, 2014.

[4] T. Green and M. Prodanovic, “Control of inverter-based microgrids,” Electric Power Systems Research, vol. 77, no. 9, pp. 1204– 1213, 2007.

[5] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, “Microgrids management,” Power and Energy Magazine, IEEE, vol. 6, no. 3, pp. 54–65, 2008.

[6] P. Villenueve, “Concerns generated by islanding [electric power generation],” Power and Energy Magazine, IEEE, vol. 2, no. 3, pp. 49–53, 2004.

[7] T. Kawabata and S. Higashino, “Parallel operation of voltage source inverters,” Industry Applications, IEEE Transactions on, vol. 24, no. 2, pp. 281–287, 1988.

[8] M. C. Chandorkar, D. M. Divan, and R. Adapa, “Control of parallel connected inverters in standalone ac supply systems,” Industry Applications, IEEE Transactions on, vol. 29, no. 1, pp. 136–143, 1993.

[9] J. Lopes, C. Moreira, and A. Madureira, “Defining control strategies for microgrids islanded

operation," Power Systems, IEEE Transactions on, vol. 21, no. 2, pp. 916–924, 2006.

[10] J. M. Guerrero, J. C. Vasquez, J. Matas, D. Vicuna, L. Garc´ıa, and M. Castilla, "Hierarchical control of droop-controlled ac and dc microgrids — a general approach toward standardization," Industrial Electronics, IEEE Transactions on, vol. 58, no. 1, pp. 158–172, 2011.

[11] J. Schiffer, R. Ortega, A. Astolfi, J. Raisch, and T. Sezi, "Conditions for stability of droop-controlled inverter-based microgrids," Automatica, vol. 50, no. 10, pp. 2457–2469, 2014.

[12] S. Barsali, M. Ceraolo, P. Pelacchi, and D. Poli, "Control techniques of dispersed generators to improve the continuity of electricity supply," in Power Engineering Society Winter Meeting, 2002. IEEE, vol. 2. IEEE, 2002, pp. 789–794.

[13] H. R. Pota, "Droop control for islanded microgrids," in Power and Energy Society General Meeting (PES), 2013 IEEE. IEEE, 2013, pp. 1–4.

[14] M. Prodanovic and T. C. Green, "High-quality power generation through distributed control of a power park microgrid," Industrial Electronics, IEEE Transactions on, vol. 53, no. 5, pp. 1471–1482, 2006.

[15] R. Teodorescu and F. Blaabjerg, "Flexible control of small wind turbines with grid failure detection operating in stand-alone and grid-connected mode," Power Electronics, IEEE Transactions on, vol. 19, no. 5, pp. 1323–1332, 2004.

[16] N. Pogaku and T. Green, "Harmonic mitigation throughout a distribution system: a distributed-generator-based solution," IEE Proceedings-Generation, Transmission and Distribution, vol. 153, no. 3, pp. 350–358, 2006.

[17] H. Camblong, A. Etxeberria, J. Ugartemendia, and O. Curea, "Gain scheduling control of an islanded microgrid voltage," Energies, vol. 7, no. 7, pp. 4498–4518, 2014.

[18] T. Vandoorn, B. Renders, F. De Belie, B. Meersman, and L. Van-develde, "A voltage-source inverter for microgrid applications with an inner current control loop and an outer voltage control loop," in International Conference on Renewable Energies, and Power Quality (ICREPQ09), 2009.

[19] A. Engler, O. Osika, M. Barnes, and N. Hatziargyriou, "DB2 evaluation of the local controller strategies," www.microgrids.eu/micro2000, 2005.

[20] A. Engler and N. Soultanis, "Droop control in LV-grids," in Future Power Systems, 2005 International Conference on. IEEE, 2005, pp. 6–pp.