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Power Quality Improvement for Grid Connected Inverters under Distorted and Unbalanced Grids

Hyun-Sou Kim*, Jung-Su Kim*, and Kyeong-Hwa Kim†

*,†Dept. of Electrical and Information Eng., Seoul National University of Science and Technology, Seoul, Korea

Abstract

A power quality improvement scheme for grid connected inverters, even in the presence of the disturbances in grid voltages due to harmonic distortions and three-phase imbalance, is presented for distributed generation (DG) power systems. The control objective is to force the inverter currents to follow their references with robustness even under external disturbances in grid voltages. The proposed scheme is realized by a disturbance observer (DOB) based current control scheme. Since the uncertainty in a system can be effectively canceled out using an estimated disturbance by the DOB, the resultant system behaves like a closed-loop system consisting of a disturbance-free nominal model. For experimental verification, a 2 kVA laboratory prototype of a grid connected inverter has been built using a digital signal processor (DSP) TMS320F28335. Through comparative simulations and experimental results under grid disturbances such as harmonic distortion and imbalance, the effectiveness of the proposed DOB based current control scheme is demonstrated.

Key words: Distorted and unbalanced grid, Distributed generation, Disturbance observer, Grid connected inverter, Power quality

I. INTRODUCTION

As the penetration of renewable energy resources grows rapidly, the power quality has been becoming a main issue in distributed generation (DG) power systems. Moreover, increased nonlinear loads and renewable energy systems such as wind-power and photovoltaic generation have led to increased harmonic pollution in electrical networks. The harmonic pollution in electrical networks causes distorted grid voltage, power losses and increased heating in electrical equipment [1]. To limit the amount of harmonic current injected into utility grid below the specified values, harmonic restriction standards such as IEEE-519 or IEC 61000-3-2 have been published [2].

Grid connected inverters should control active and reactive powers while maintaining synchronization with the grid frequency for a grid connection. When a grid connected inverter is employed in a DG unit to deliver generated electrical energy to the grid, it should regulate the DC link voltage in order to maintain the power balance of the system [3]. In addition, an inverter should provide necessary control functions such as power quality and robustness to the grid voltage and frequency variations to meet the grid codes.

Conventionally, the proportional-integral (PI) decoupling control scheme is widely used to control grid-connected inverters. However, grid voltage often experiences disturbances due to harmonic distortion and imbalance. Considering that this control method has inherently poor disturbance rejection capability, it is not a suitable way to control grid-connected inverters under a grid voltage perturbed by disturbances [4].

In order to overcome this limitation, several studies on power quality improvement in the presence of disturbances in grid voltage have been investigated. These studies considered harmonic distortion or three-phase imbalance in grid voltages to be the main source of disturbances, and aimed to control grid-connected inverters so that the inverter output currents are not influenced by such disturbances [5]. The harmonic compensation techniques are divided into selective schemes, which only compensate a specific harmonic-order, and nonselective schemes [3], [6]-[12]. The selective harmonic compensation schemes basically use PI control in the rotating reference frame of the corresponding harmonic-order or the resonant controller. Even though these schemes show outstanding compensation performance for a specific

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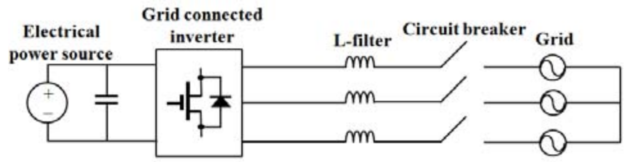
†Corresponding Author: k2h1@seoultech.ac.kr
Tel: +82-2-970-6406, Fax: +82-2-978-2754, Seoul National University of Science and Technology
*Dept. of Electrical and Information Eng., Seoul National University of Science and Technology, Korea

harmonic-order, the compensation capability for other harmonic components is not sufficient.

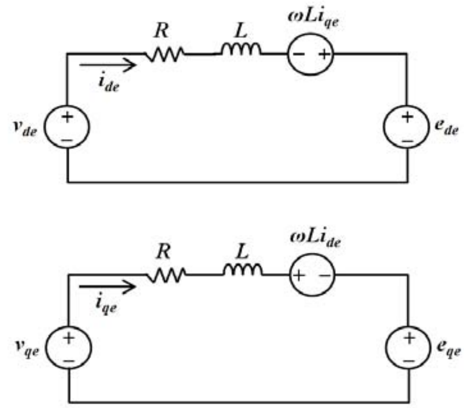
In terms of nonselective techniques, the repetitive control, predictive control, and sliding mode control (SMC) have been presented. Although the repetitive control is effective for rejecting periodic harmonics, it has a slow response and performance degradation in its disturbance rejection under non-periodic harmonics [4], [10]-[14]. The predictive control scheme may provide an instability problem due to parameter variations. The SMC scheme needs information on the bounds of the uncertainty.

Recently, for the purpose of enhancing the robust performance of systems with external disturbances and uncertain parameters, research effort has been directed to the disturbance observer (DOB) theory [15]. In order to develop a DOB based controller, first a nominal controller is devised that shows good control performance for a nominal plant. Then, the DOB is designed in a way that the interconnected system between the uncertain system and the DOB behaves like a nominal plant. Therefore, the closed-loop system performance of a uncertain system with the DOB based controller is almost the same as that of a nominal plant with a nominal controller. For instance, a DOB has been designed in an attempt to compensate the disturbance caused by the source voltage imbalances in PWM voltage source converters [16]. Another study has presented an observer-based control method for PWM voltage-source converters under source voltage harmonics and unbalanced disturbances [17].

In this paper, a novel DOB based control method is proposed to improve the power quality of grid connected inverters in the presence of disturbances in the grid voltages. As primary disturbances in the grid voltages, the harmonic distortion and three-phase imbalance are considered. As pointed out in many studies, these voltage disturbances are stochastic in nature, with durations that vary from a fraction of a cycle to a few cycles. In view of the control of grid connected inverters, their effects have to be quickly compensated since they act as nonlinear disturbances in the current control loop and have a severe influence on the control performance, and eventually, on the power quality of DG systems. For the purpose of controller design, the system model is first transformed into a new model in terms of new control inputs. Using this mathematical model, the proposed DOB based current control scheme is designed for robust tracking. The objective is to force the inverter currents to follow their references even under the external disturbances caused by harmonics and imbalances in the grid voltages. Since the estimated disturbance effectively cancels out the real uncertainty existing in a system, the dynamic behavior of the resulting system is quite similar to that of the disturbance-free nominal model. To demonstrate the effectiveness of the proposed DOB based current control scheme, a 2 kVA grid connected inverter prototype has been built using a digital signal processor (DSP) TMS320F28335. Comparative simulations and experimental results show that the proposed scheme is an effective way to control grid-connected inverters even under harmonic-distorted and unbalanced grid conditions.



(a)



(b)

Fig. 1. Configuration of a grid connected inverter and the equivalent circuits. (a) configuration of a grid connected inverter, (b) the equivalent circuits in the synchronous reference frame.

II. Modeling of a Grid Connected Inverter

Fig. 1(a) shows the configuration of a grid connected inverter that is connected to a utility grid through an L filter to interface with a DG unit. Fig. 1(b) shows the equivalent circuit of a grid connected inverter with a grid connection in the synchronous reference frame. From Fig. 1(b), the mathematical model of a three-phase grid connected inverter can be expressed as follows:

$$v_{qe} = Ri_{qe} + L\dot{i}_{qe} + \omega L i_{de} + e_{qe} \tag{1}$$

$$v_{de} = Ri_{de} + L\dot{i}_{de} - \omega L i_{qe} + e_{de} . \tag{2}$$

where v_{qe} and v_{de} are the q-axis and d-axis inverter voltages, respectively, i_{qe} and i_{de} are the q-axis and d-axis inverter currents, respectively, e_{qe} and e_{de} are the q-axis and d-axis grid voltages, respectively, ω is the angular frequency of the grid voltage, and R and L represent the equivalent resistance and inductance of the ac filter and connection cables.

A grid connected inverter should control the active and reactive powers while maintaining synchronization with the grid frequency for a grid connection. A grid connected inverter should also regulate the DC link voltage in order to maintain the power balance between the grid and DG unit. In addition, it should deliver high-quality generated power to a grid by controlling the inverter output current.

As the conventional current controller, the PI decoupling

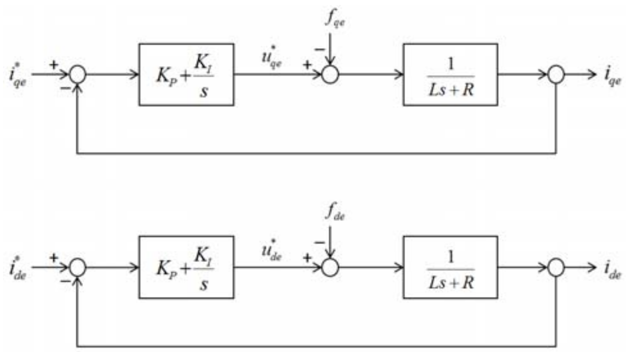


Fig. 2. Simplified block diagram for the controller design.

control is employed in the synchronous reference frame as follows:

$$v^*_{qe} = u^*_{qe} + \omega L i_{de} + e_{qe} \tag{3}$$

$$v^*_{de} = u^*_{de} - \omega L i_{qe} + e_{de} \tag{4}$$

where $u^*_{qe} = (K_P + K_I / s)\cdot(i^*_{qe} - i_{qe})$

$u^*_{de} = (K_P + K_I / s)\cdot(i^*_{de} - i_{de})$

and the symbol '*' denotes the reference quantities, K_P and K_I are the proportional and integral gains of the PI control, respectively, and s is a Laplace operator. The computed reference voltages are applied through a PWM technique. For the simplification of analysis, it is reasonable to assume that the reference voltages are applied to the terminals of the inverter without any loss or deformation in the PWM inverter, i.e., $v^*_{qe} = v_{qe}$ and $v^*_{de} = v_{de}$. Based on this assumption, the substitution of (3) and (4) into (1) and (2) transforms the system model into a simplified model having new control inputs u^*_{qe} and u^*_{de}, which facilitates the controller design [18]. Fig. 2 shows a simplified block diagram for the controller design. When the controller parameters in (3) and (4) are well matched with the inverter model in (1) and (2), f_{qe} and f_{de} are zero and the closed-loop transfer function for the q-axis current can be obtained from Fig. 2 as follows:

$$T(s) = \frac{i_{qe}(s)}{i^*_{qe}(s)} = \frac{K_P s + K_I}{Ls^2 + (R + K_P)s + K_I}\,. \tag{5}$$

The closed-loop transfer function for the d-axis current can be determined in a similar way, and the bandwidth of the current controller can be selected using (5).

However, the grid voltage often experiences disturbances such as harmonic distortion and imbalance. The increasing use of nonlinear loads such as adjustable speed drives and power electronics converters causes a lot of harmonics in distribution systems. Severe and random voltage disturbances might be initiated by the intermittent generation of a DG system or by time-varying loads such as arc furnaces and voltage transients associated with parallel connected loads. These voltage disturbances are stochastic in nature, and have durations that vary from a fraction of a cycle to a few cycles [19]. In this case, f_{qe} and f_{de} act as nonlinear disturbances in the current control loop. Because such disturbances have a severe influence on the current control performance, and eventually, on the power quality of DG systems, their effects have to be quickly compensated.

III. DOB BASED DISTURBANCE ESTIMATION

Let $e_{qe} + f_{qe}$ and $e_{de} + f_{de}$ denote the perturbed values of the grid voltages e_{qe} and e_{de} due to harmonic distortion and imbalance. Then, substitution of (3) and (4) into (1) and (2), which results in the following state equation:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} - \boldsymbol{B}\boldsymbol{d} \tag{6}$$

where $\boldsymbol{x} = \boldsymbol{i}_{qd} = [i_{qe} \quad i_{de}]^T$, $\boldsymbol{u} = [u^*_{qe} \quad u^*_{de}]^T$

$\boldsymbol{d} = [f_{qe} \quad f_{de}]^T$

$$\boldsymbol{A} = \begin{pmatrix} -\dfrac{R}{L} & 0 \\ 0 & -\dfrac{R}{L} \end{pmatrix}, \quad \boldsymbol{B} = \begin{pmatrix} \dfrac{1}{L} & 0 \\ 0 & \dfrac{1}{L} \end{pmatrix}.$$

Based on this mathematical model, the proposed DOB based current control scheme is presented. The objective of the control is to steer state $\boldsymbol{x}$ to a desired value with external disturbances $\boldsymbol{d}$ which is generated by harmonics and imbalance. Therefore, it is necessary to design a robust tracking control against external disturbances $\boldsymbol{d}$.

In accordance with the design steps in [20], the design of the proposed DOB based control is comprised of two steps: the nominal control design and feedforward compensation for disturbance rejection. In order to construct the DOB based control scheme, a PI controller is designed for the nominal model, which corresponds to (6) with no disturbances, i.e., $\boldsymbol{d} = 0$ as follows:

$$\boldsymbol{u}_r = \left(K_P + \frac{K_I}{s}\right)\cdot(\boldsymbol{i}^*_{qd} - \boldsymbol{i}_{qd}) \tag{7}$$

where $\boldsymbol{u}_r = [u^*_{r,qe} \quad u^*_{r,de}]^T$, $\boldsymbol{i}^*_{qd} = [i^*_{qe} \quad i^*_{de}]^T$

$\boldsymbol{i}_{qd} = [i_{qe} \quad i_{de}]^T$.

In light of the control theory, the PI controller in (7) achieves reference tracking without a DOB if $\boldsymbol{d} = 0$. In order to devise a feedforward control for eliminating disturbances $\boldsymbol{d}$, a high-gain DOB is designed. The idea behind the high-gain DOB is that if the disturbed system input $\boldsymbol{u} - \boldsymbol{d}$ can be estimated, the disturbance $\boldsymbol{d}$ can also be estimated by comparing $\boldsymbol{u} - \boldsymbol{d}$ with the known control input $\boldsymbol{u}$. Let $\boldsymbol{P}_n(s)$ be the transfer function from the control input $\boldsymbol{u}$ to state $\boldsymbol{x}$ of the nominal model, and $\boldsymbol{P}_n^{-1}(s)$ denote an inverse model of $\boldsymbol{P}_n(s)$. Then, the input of $\boldsymbol{P}_n^{-1}(s)$ is the measurement, and the output of $\boldsymbol{P}_n^{-1}(s)$ is the disturbed input $\boldsymbol{u} - \boldsymbol{d}$. In theory, $\boldsymbol{u} - \boldsymbol{d}$ can be calculated from $\boldsymbol{P}_n^{-1}(s)$ and the measurement if $\boldsymbol{P}_n^{-1}(s)$ is available. However, because $\boldsymbol{P}_n^{-1}(s)$ is not proper in general, a stable filter is designed so that $\boldsymbol{P}_n^{-1}(s)\boldsymbol{Q}_B(s)$ is proper and its input/output behavior is the same as that of $\boldsymbol{P}_n^{-1}(s)$ in the steady state. According to [21], the state space realization of $\boldsymbol{P}_n^{-1}(s)\boldsymbol{Q}_B(s)$ is given by:

$$\dot{\boldsymbol{q}} = \boldsymbol{A}_q\boldsymbol{q} + \boldsymbol{B}_q\boldsymbol{x} \tag{8}$$

$$\begin{aligned}\hat{\boldsymbol{u}}_p &= \boldsymbol{B}^{-1}(\dot{\boldsymbol{x}} - \boldsymbol{A}\boldsymbol{x}) = \boldsymbol{B}^{-1}(\dot{\boldsymbol{q}} - \boldsymbol{A}\boldsymbol{q}) \\ &= \boldsymbol{B}^{-1}(\boldsymbol{A}_q\boldsymbol{q} + \boldsymbol{B}_q\boldsymbol{x} - \boldsymbol{A}\boldsymbol{q})\end{aligned} \tag{9}$$

where $\boldsymbol{q}$ is the state of the filter $\boldsymbol{Q}_B(s)$, and a_0 and τ are the controller parameters expressed as:

$$A_q = \begin{bmatrix} -\frac{a_0}{\tau} & 0 \\ 0 & -\frac{a_0}{\tau} \end{bmatrix}, \quad B_q = \begin{bmatrix} \frac{a_0}{\tau} & 0 \\ 0 & \frac{a_0}{\tau} \end{bmatrix}.$$

Since $\boldsymbol{q}$ is also a state estimate of the nominal model, $\boldsymbol{x}$ is replaced by $\boldsymbol{q}$ in the second equation. Then the output $\hat{\boldsymbol{u}}_p$ of this filter is an estimate of $\boldsymbol{u} - \boldsymbol{d}$.

In addition, the input filter is designed for the known control signal $\boldsymbol{u}$ as follows:

$$\dot{\boldsymbol{p}} = \begin{bmatrix} -\frac{a_0}{\tau} & 0 \\ 0 & -\frac{a_0}{\tau} \end{bmatrix}\boldsymbol{p} + \begin{bmatrix} \frac{a_0}{\tau} & 0 \\ 0 & \frac{a_0}{\tau} \end{bmatrix}\boldsymbol{u} \tag{10}$$

$$\boldsymbol{u}^+ = \boldsymbol{p} \tag{11}$$

where $\boldsymbol{p}$ is the state of the input filter $\boldsymbol{Q}_A(s)$.

Then, the estimated disturbance can be computed as:

$$\hat{\boldsymbol{d}} = \hat{\boldsymbol{u}}_p + \boldsymbol{u}^+ . \tag{12}$$

Note that this estimated disturbance can be used as the feedforward control. Using this estimated disturbance, the disturbances $\boldsymbol{d}$ can be rejected efficiently by adding it to the nominal control input $\boldsymbol{u}$. Finally, the proposed DOB based control, achieving robust tracking, is given by:

$$\boldsymbol{u} = \boldsymbol{u}_r + sat(\hat{\boldsymbol{d}}) \tag{13}$$

where $sat(\cdot)$ designates the saturation function. The saturation function is employed at the output of the DOB in order to avoid the peaking phenomenon which means that a very large controller state due to a small τ can make the system state very large as well. Since the DOB designed in this paper is a high-gain observer type, employing such a saturation function is necessary [22].

IV. SYSTEM CONFIGURATION

Fig. 3 shows an overall block diagram of the proposed DOB based current control scheme. The entire system consists of a DC source, a grid connected inverter, a magnetic circuit breaker, and a three-phase programmable AC power source that can emulate an ideal utility grid as well as distorted and unbalanced grid voltages. For the current control algorithm, the synchronous PI decoupling control with the DOB based disturbance compensation is used. During operation, the disturbances caused by distorted and unbalanced grid voltages are estimated, and the estimated values are used for feedforward control. The computed reference voltages are applied through the symmetrical space vector PWM technique.

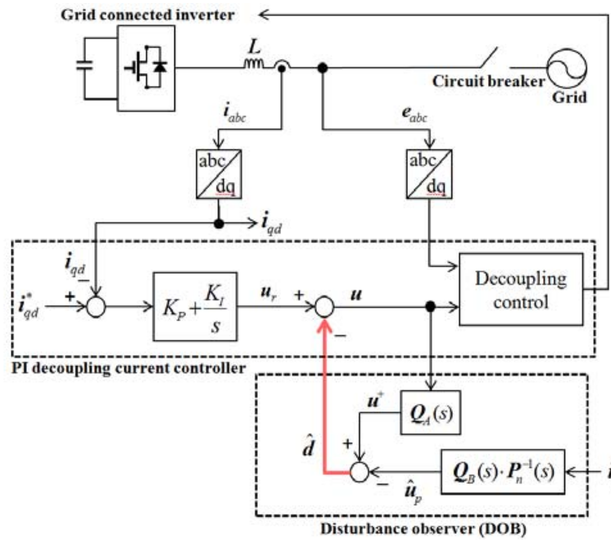


Fig. 3. The overall block diagram for the proposed DOB based control scheme.

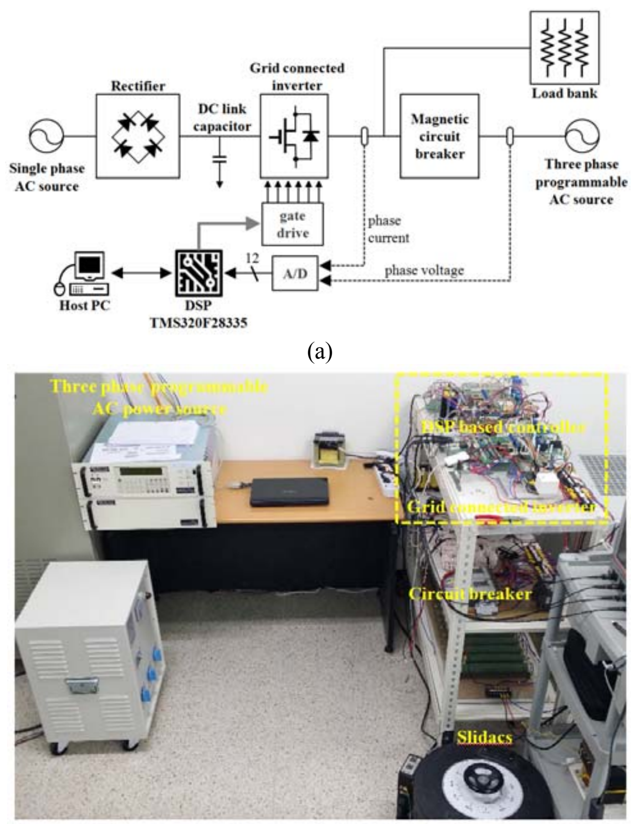


Fig. 4. Experimental system. (a) Configuration of the overall system. (b) Photograph of the experimental test setup.

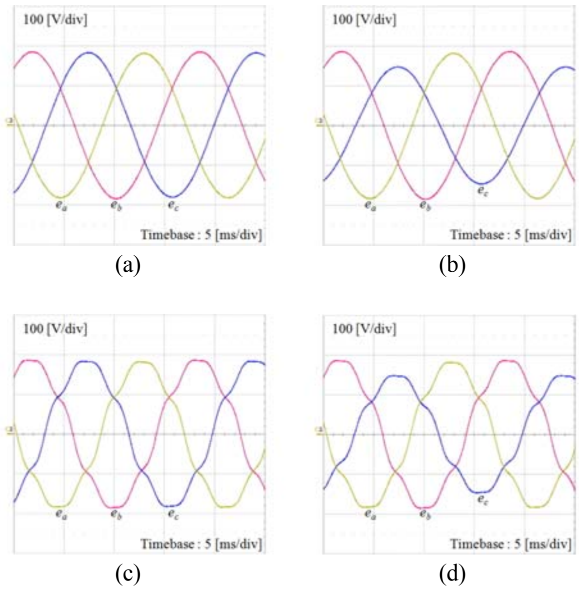


Fig. 5. Grid voltages used in simulations and experiments. (a) ideal grid voltages, (b) unbalanced grid voltages, (c) harmonic distorted grid voltages, (d) unbalanced and harmonic distorted gird voltages.

TABLE I
SYSTEM PRAMETERS OF THE EXPERIMENTAL SETUP

Rated power	2 kVA
DC-link voltage	420 V
DC-link capacitor	5500 μF
Switching frequency	10 kHz
Resistance of load bank	25 Ω
Filter resistance	0.5 Ω
Filter inductance	7 mH
Grid voltage	220 V RMS
Grid frequency	60 Hz

Fig. 4(a) shows the configuration of the overall system. The whole control algorithms are implemented using a 32-bit floating-point DSP TMS320F28335 with a clock frequency of 150 MHz for a 2 kVA laboratory prototype three-phase grid-connected inverter [23]. The sampling period is chosen as 100 μs in both the simulations and the experiments, which yields a switching frequency of 10 kHz. An intelligent power module (IPM) is employed for the three-phase grid-connected inverter. The inverter phase currents are detected by Hall-effect devices and are converted through internal 12-bit A/D converters, where the resolution of the current is $18/2^{11}$ [A].

Fig. 4(b) shows a photograph of the experimental test setup which consists of a DSP based controller, a three-phase grid-connected inverter, a magnetic contactor for grid-connected operation, and a three-phase programmable AC power source. The system parameters of the experimental setup are listed in Table I.

For a performance comparison with the conventional schemes, four types of grid voltages are employed in this paper. Fig. 5 shows the four types of grid voltages that are produced by the three-phase programmable AC power source. Fig. 5(a) shows the ideal three-phase balanced grid voltages, and Fig. 5(b) shows unbalanced grid voltages where the c-phase grid voltage is smaller than the other phases by 20%. Fig. 5(c) shows the grid voltages with a harmonic distortion, where 5% of the fifth-order harmonics and 5% of the seventh-order harmonics are added to the ideal grid voltage. Fig. 5(d) shows the grid voltages with harmonic distortion as well as three-phase imbalance.

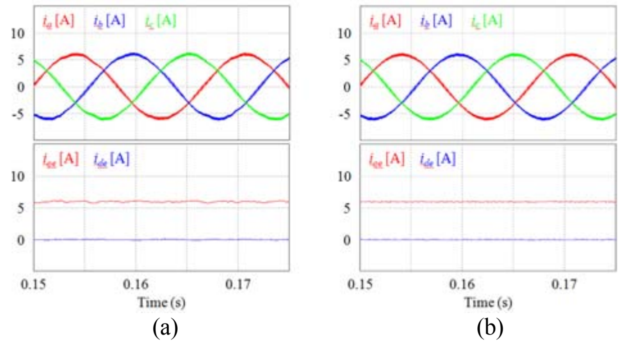


Fig. 6. Simulation results for grid connected inverter under the ideal grid voltages, (a) with the conventional PI controller, (b) with the proposed DOB based controller.

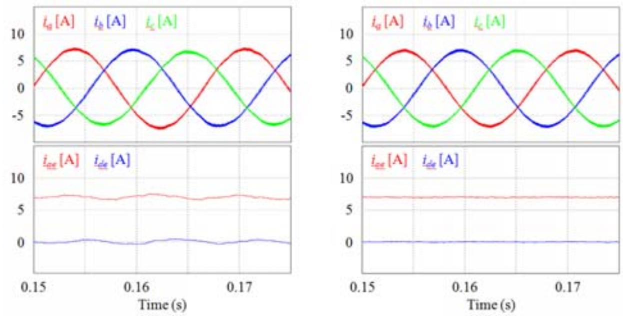
V. SIMULATION AND EXPERIMENTAL RESULTS

In this section, to verify the effectiveness of the proposed power quality improvement strategy for grid connected inverters, simulation and experimental results are presented. For this purpose, the performance of the proposed DOB based current controller is compared with that of the conventional PI decoupling current controller. The *q*-axis and *d*-axis current references of the grid connected inverter are chosen as 7 A and zero, respectively.

Fig. 6 shows simulation results under ideal grid voltages as in Fig. 5(a). Fig. 6(a) shows results obtained with the conventional PI decoupling controller. In this scheme, the gains of the PI controller are selected as $K_P = 9.3$ and $K_I = 7000$, which yields a system bandwidth of 1000 rad/sec and a damping ratio of 0.7. Also, the gains of the DOB are chosen as $a_0 = 1$ and $\tau = 1/9000$.

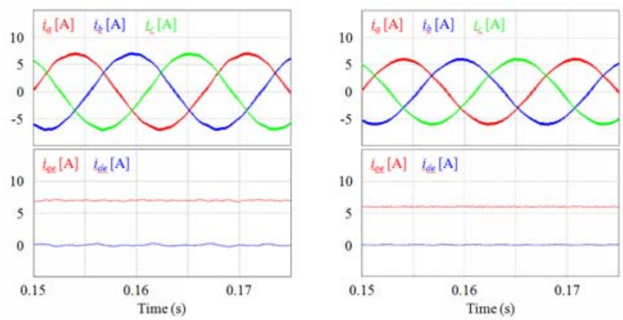
It is observed from these figures that the *q*-axis and *d*-axis currents as well as the three-phase currents are controlled to their reference values precisely without a significant harmonic distortion. Fig. 6(b) represents the results of the proposed DOB based controller, where the current waveforms are very similar to those in Fig. 6(a).

Fig. 7 shows simulation results under unbalanced grid voltages as in Fig. 5(b) for the conventional scheme and the proposed scheme. In the conventional scheme, the three-phase currents are slightly distorted as shown in Fig. 7(a). In addition, the *q*-axis and *d*-axis currents are not well regulated to constant reference values, and show small fluctuations. On the other



(a) (b)

Fig. 7. Simulation results for grid connected inverter under the unbalanced grid voltages, (a) with the conventional PI controller, (b) with the proposed DOB based controller.



(a) (b)

Fig. 8. Simulation results for grid connected inverter under the harmonic distorted grid voltages, (a) with the conventional PI controller, (b) with the proposed DOB based controller.

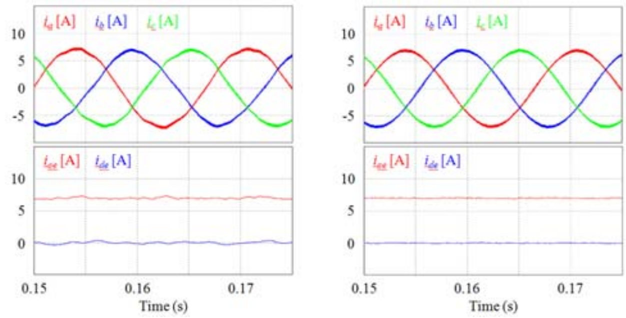
hand, the proposed scheme shows a good regulation property of the *q*-axis and *d*-axis currents without a harmonic distortion in the phase currents due to the proposed DOB based disturbance rejection capability.

Fig. 8 represents simulation results when the grid voltages have harmonic distortion as shown in Fig. 5(c). Whereas the conventional scheme shows harmonic distorted phase currents and some fluctuations in the *q*-axis and *d*-axis currents, the inverter output currents of the proposed DOB based current controller are effectively controlled without showing harmonic distortion as in Fig. 8(a).

Fig. 9 represents simulation results when the grid voltages are unbalanced and harmonic distorted at the same time as in Fig. 5(d). As expected, the waveforms in Fig. 9(a) and Fig. 9(b) show good agreement with the previous results and the proposed scheme shows good control performance.

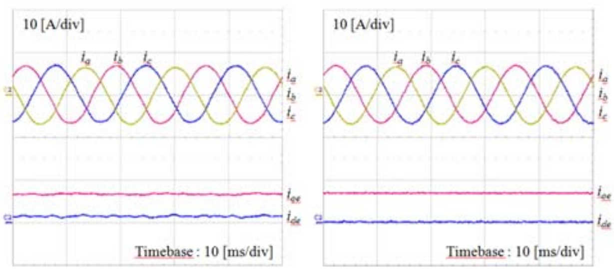
In view of Fig. 6 through Fig. 9, the conventional PI decoupling control cannot effectively regulate the inverter output currents, leading to harmonic distortion or fluctuations in the currents. On the other hand, the proposed DOB based scheme shows good control performance despite the fact that the grid voltages are perturbed by external disturbances caused by harmonics and imbalance.

For the sake of showing the comparative performance of the proposed scheme and the conventional one, experiments are



(a) (b)

Fig. 9. Simulation results for grid connected inverter under the unbalanced and harmonic distorted grid voltages. (a) with the conventional PI controller, (b) with the proposed DOB based controller.



(a) (b)

Fig. 10. Experimental results for grid connected inverter under the ideal grid voltages. (a) with the conventional PI controller, (b) with the proposed DOB based controller.

carried out using the equipments depicted in Fig. 4. In these experiments, the three-phase programmable AC power source generates the same grid voltages used in the simulation as shown in Fig. 5.

Fig. 10 shows experimental results under ideal grid voltages. All of the experimental conditions, including the current references, are the same as those in the simulations. Since there are no disturbances in the grid voltages, both of the control schemes regulate the inverter output currents successfully, which shows good agreement with the simulation results shown in Fig. 6.

Fig. 11 shows comparative experimental results under unbalanced grid voltages. The current responses in Fig. 11(a) and Fig. 11(b) are very similar to Fig. 7. The conventional PI decoupling control shows distinct fluctuations in the *q*-axis and *d*-axis currents. Meanwhile, the proposed scheme demonstrates good regulation. Fig. 11(c) and Fig. 11(d) clearly shows this difference based on the frequency response. Note that the *q*-axis and *d*-axis currents should have only pure DC quantities at the synchronous reference frame. Whereas the *q*-axis and *d*-axis currents have larger second-order and sixth-order harmonics in the conventional scheme, shown in Fig. 11(c), these harmonics are noticeably reduced in the proposed scheme as shown in Fig. 11(d).

Fig. 12 shows comparative experimental results under harmonic distortion in the grid voltages. It can be observed in

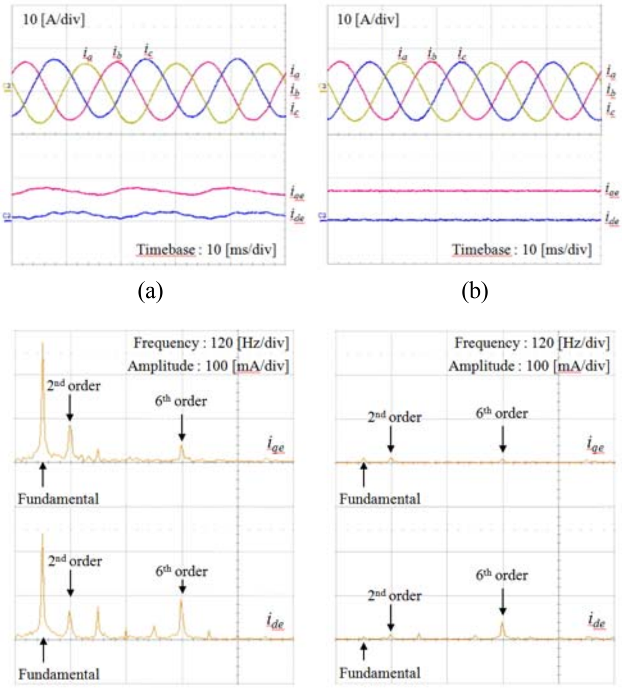


Fig. 11. Experimental results for grid connected inverter under the unbalanced grid voltages. (a) with the conventional PI controller, (b) with the proposed DOB based controller, (c) FFT results of *q*-axis and *d*-axis currents in (a), (d) FFT results of q-axis and d-axis currents in (b).

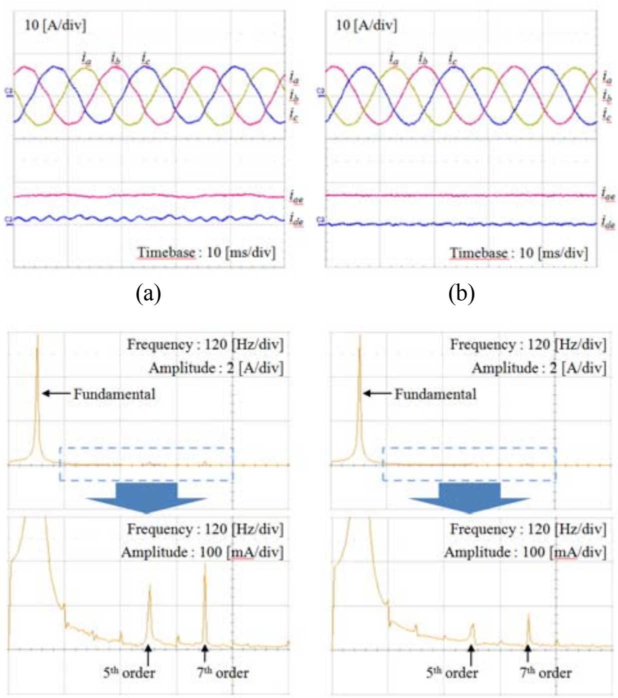


Fig. 12. Experimental results for grid connected inverter under the harmonic distorted grid voltages. (a) with the conventional PI controller, (b) with the proposed DOB based controller, (c) FFT results of i_q in (a), (d) FFT results of i_q in (b).

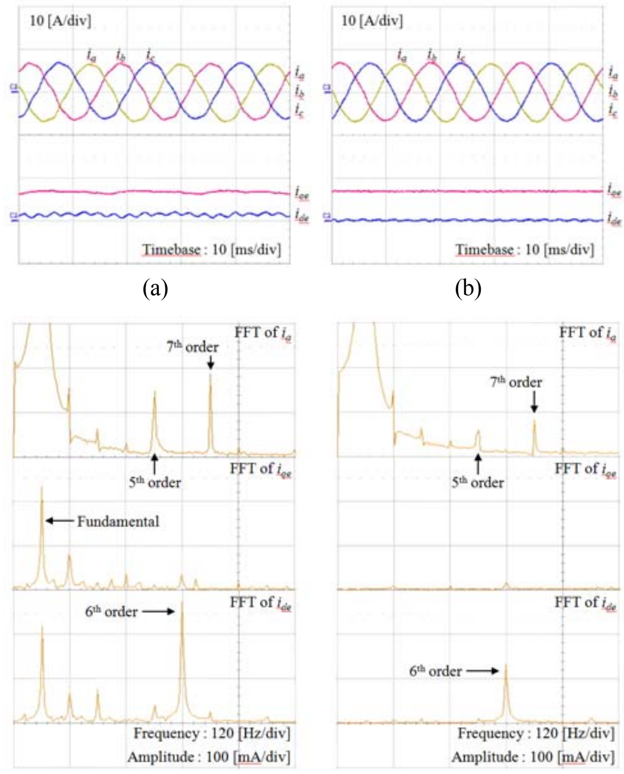


Fig. 13. Experimental results for grid connected inverter under the unbalanced and harmonic distorted grid voltages. (a) with the conventional PI controller, (b) with the proposed DOB based controller, (c) FFT results of i_q, i_{qe} and i_{de} in (a), (d) FFT results of i_q, i_{qe} and i_{de} in (b).

these figures that the current control can be significantly improved by the proposed scheme due to effective compensation of the disturbances caused by harmonic distorted grid voltages. This is well illustrated by the FFT results of the phase current as can be seen in Fig. 12(c) and Fig. 12(d), where the dominant harmonic components in the fifth and seventh order are quite attenuated in the proposed scheme.

Fig. 13 shows comparative experimental results when the grid voltages are unbalanced and harmonic distorted at the same time. All of the waveforms in Fig. 13 are well matched with the previous simulations and experimental results with good regulation characteristics and reduced harmonics in the proposed scheme.

VI. Conclusions

To improve the power quality in DG systems, even in the presence of disturbances in the grid voltages such as harmonic distortion and three-phase imbalance, a robust DOB based current control scheme for grid connected inverters has been presented. Disturbances in the grid voltages are stochastic in nature and have a direct influence on current control performance, and eventually, on the power quality of DG systems. For the purpose of controller design, the system model is first transformed into a new model in terms of new control inputs. Based on this mathematical model, the proposed DOB based current control scheme is designed for robust tracking. The design procedure is simple and straightforward in the sense that system uncertainty can be effectively canceled out using the estimated disturbance by the DOB. Through comparative simulations and experimental results under various grid conditions, the effectiveness of the proposed control scheme has been demonstrated. As a result, the proposed scheme can effectively suppress harmonic currents thanks to the good disturbance rejection capability of the DOB even when the grid voltages are distorted by harmonics or imbalance.

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Hyun-Sou Kim was born in Korea, in 1989. He received his B.S. degree in Electrical and Information Engineering from the Seoul National University of Science and Technology, Seoul, Korea, in 2014; where he is presently working towards his M.S. degree in Department of Electrical and Information Engineering. His current research interests include three-phase utility interactive inverters, observer based control, power quality improvement of the grid connected inverters, AC machine drives, and power electronics. He is Student Member of the Korean Institute of Power Electronics (KIPE) and IEEE.

Jung-Su Kim received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Korea University, Seoul, Korea, in 1998, 2000, and 2005, respectively. He was a post-doctoral fellow at the CDSL, Seoul National University, Seoul, Korea, in 2005; at the IST, University of Stuttgart, Stuttgart, Germany, from 2006 to 2007; and the Systems Biology Laboratory, University of Leicester, Leicester, England, UK, in 2008. Since 2009, he has been with Department of Electrical and Information Engineering, Seoul National University of Science and Technology, Seoul, Korea. His current research interest includes MPC (Model Predictive Control) and its application to energy systems.

Kyeong-Hwa Kim was born in Seoul, Korea, in 1969. He received his B.S. degree from Hanyang University, Seoul, Korea, in 1991; and his M.S. and Ph.D. degrees from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 1993 and 1998, respectively, all in Electrical Engineering. From 1998 to 2000, he was a Research Engineer with Samsung Electronics Company, Korea, where he was engaged in the research and development of AC machine drive systems. From 2000 to 2002, he was a Research Professor with KAIST. From August 2010 to August 2011, he was a Visiting Scholar with the Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA, USA. Since August 2002, he has been with the Seoul National University of Science and Technology, Seoul, Korea, where he is presently working as a Professor. His current research interests include AC machine drives, the control and diagnosis of power systems, power electronics, renewable energy, and DSP-based control applications. Processor Kim is a Member of the Korean Institute of Power Electronics (KIPE) and IEEE.