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# Control Design for a Utility Interactive Inverter based on Time-delayed Estimator

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**Abstract**
This paper presents a control design method for a utility interactive inverter based on time-delayed estimator. The proposed control scheme is basically based on the predictive control. The primary control objective is to minimize the prediction error in order that the reference signal can be tracked rapidly without steady-state error. To overcome the well-known drawback of the predictive control due to the mismatch on system parameters, the time-delayed estimator will be introduced. Time-delayed estimator can effectively forecast the variations in system parameters as well as the disturbances in grid voltage by using the discrete-time model of system with nominal values. As a result, the proposed controller not only has the fast dynamic response but also provides a robust performance. Theoretical analyses and comparative simulation results are presented to demonstrate the effectiveness of the proposed control scheme.

**Keywords:** Distributed Generation, Harmonic Distortion, Robust Control, Time-delayed Estimator, Utility Interactive Inverter.

## Introduction

Recently, the ever increasing demand for electricity has drawn a lot of interest in small-scale renewable energies because they are not only inexhaustible but also clean for the environment [1]. Three of renewable energy resources mostly used are photovoltaic (PV), wind power, and hydroelectric systems. The small-scale renewable energy harvesting unit is typically composed of a primary energy converter and a power electronic converter. The primary energy converter such as wind turbine, PV panel, hydropower turbine harvests the primary renew-able energy into electrical energy. Consequently, the electronic power converter which is made of electronic devices converts the harvested electrical energies into the desired form in order to deliver a specified amount of active and reactive power to the grid, and (or) power the local load [2]. For instance, Fig. 1 shows a configuration of a utility interactive inverter for distributed generation (DG) system. In this figure, a permanent magnetic synchronous generator (PMSG) is employed as a primary energy converter in wind power system, which generates three phase alternating current (AC) electricity from the wind energy. As an electronic power converter, a back to back converter which includes a rectifier and a utility interactive inverter is used to convert variable three phase voltages from the PMSG output into gird level. The variable AC voltage from the PMSG output is rectified first to DC voltage, and then, the inverter converts the DC voltage to desired AC voltage with the fixed frequency and fixed voltage to deliver the power to the gird and local load.

A utility interactive inverter is considered as the most important element in DG systems since it is supposed to provide not only stable operation even in different grid conditions but also vital capabilities such as the voltage-sag mitigation and power quality enhancement [3]. Furthermore, the inverter should be able to supply critical local load autonomously during the absence of grid, and provide seamless transition between the islanded mode and gird-connected mode [4].

As the capability of renewable energy is growing rapidly, the improvement of power quality has become a very important issue in DG systems. The harmonic pollution caused by nonlinear loads in electrical networks brings about distorted grid voltage, power losses and heating in the electrical equipment. To limit the amount of harmonic current injected into utility grid to be below the specified values, the harmonic restriction standards such as IEEE-519 or IEC 61000-3-2 have been published.

The conventional PI control with the grid voltage feed-forward is commonly used for a current control scheme in utility interactive inverters in the synchronous reference frame because of its stability and simplicity in implementation. Nonetheless, the PI-based controller does not have the ability to attenuate the disturbances during the distorted grid voltage condition [5]. To overcome such a drawback, the proportional resonant (PR) controller has been proposed. The PR controller is developed on the basis of internal model principle and usually implemented in the stationary reference frame [6], where this controller theoretically introduces a high gain at the particular frequency. Because the PR controller has the main advantage that the specific harmonic components can be easily suppressed, this control scheme is often referred as a selective harmonic compensation method. Moreover, this control scheme can handle both positive and negative sequence at the same time, in contrast to the PI-based controller in the synchronous reference frame which only regulates positive sequence. However, the PR controller still has limitation such as the large computational load of main digital controller as it requires constructing separate resonant controllers for each harmonic component [7].

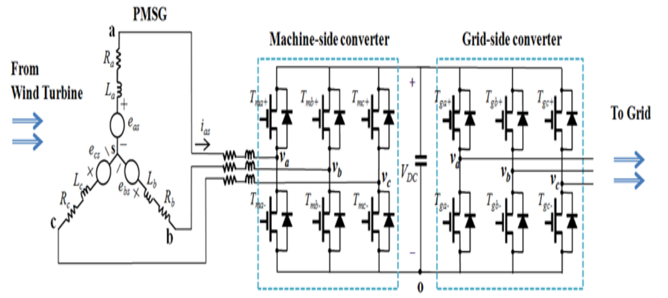


**Fig. 1. Configuration of a utility interactive inverter for distributed generation system**

As an alternative approach, several non-selective control methods such as sliding mode control (SMC) [8] and predictive control [9] have been presented to control the utility interactive inverter in the normal gird condition as well as during grid fault conditions. A SMC has successfully been applied in various electrical drive systems or electric power systems. Even though this control structure provides the good control performance against parameter variations over wide range of operating conditions, the SMC inherently suffers from chatting problem. On the contrast, the predictive control is designed to minimize the output error at next step. The control principle is to calculate the required reference voltages which force the inverter currents to follow their reference currents based on the system model and system states at the previous step. However, this controller is basically sensitive to model uncertainty and system parameter variations [10]. In spite of the addressed limitations, the predictive control has a fast transient response and simple structure, which makes the predictive control be an attractive solution to control a utility interactive inverter.

To improve the performance of DG system even in the presence of distorted grid condition and parameter variation, this paper presents a control design methodology for a utility interactive inverter based on time-delayed estimator. The control strategy is designed on the basic of the predictive control, which provides very fast dynamic response as well as good reference current tracking ability. In addition, the time-delayed estimator is employed to enhance the robustness of control scheme by estimating the disturbances caused by the abnormal grid condition and system parameter variations. The simulation results are given to validate the performance and the effectiveness of the proposed control scheme.

This paper is organized as follows. Section II presents the modeling of an L-filtered utility interactive inverter in both the continuous and discrete-time domain. Section III illustrates the proposed control scheme composed of the predictive controller as well as time-delay estimator. Simulation results are presented in section IV. Finally, the conclusions are given in Section V.

## Modeling of Utility Interactive Inverter

Fig. 2 shows the configuration of a utility interactive inverter with L-filter. Considering the utility grid and the output of a three-phase voltage source inverter as ideal voltage sources, the voltage equations of a utility interactive inverter in the synchronous reference frame can be written as follows:

$$v_{qs} = Ri_{qs} + L\frac{di_{qs}}{dt} + \omega L i_{ds} + e_{qs} \quad (1)$$

$$v_{ds} = Ri_{ds} + L\frac{di_{ds}}{dt} - \omega L i_{qs} + e_{ds} \quad (2)$$

where $v_{qs}$ and $v_{ds}$ are inverter output voltages in the $q$-axis and $d$-axis, respectively, $i_{qs}$ and $i_{ds}$ are inverter output currents in the $q$-axis and $d$-axis, respectively, $e_{qs}$ and $e_{ds}$ are grid voltages in the $q$-axis and $d$-axis, respectively, $\omega$ is grid angular frequency, $L$ is output filter inductance, and $R$ is filter resistance.

From (1) and (2), the discrete-time equations can be obtained as follows:

$$v_{qs}(k) = Ri_{qs}(k) + \frac{L}{T}\left[i_{qs}(k+1) - i_{qs}(k)\right] + \omega L i_{ds}(k)$$
$$+ e_{qs}(k) \quad (3)$$

$$v_{ds}(k) = Ri_{ds}(k) + \frac{L}{T}\left[i_{ds}(k+1) - i_{ds}(k)\right] - \omega L i_{qs}(k)$$
$$+ e_{ds}(k) \quad (4)$$

where $T$ is a sampling period, and $k$ is sampling instant. Using the nominal parameter, (3) and (4) can be rewritten as follows:

$$v_{qs}(k) = R_o i_{qs}(k) + \frac{L_o}{T}\left[i_{qs}(k+1) - i_{qs}(k)\right]$$
$$+ \omega L_o i_{ds}(k) + e_{qso}(k) + f_q(k) \quad (5)$$

$$v_{ds}(k) = R_o i_{ds}(k) + \frac{L_o}{T}\left[i_{ds}(k+1) - i_{ds}(k)\right]$$
$$- \omega L_o i_{qs}(k) + e_{dso}(k) + f_d(k) \quad (6)$$

where $f_q(k)$ and $f_d(k)$ represent the disturbances in grid voltage or disturbances caused by parameter variations. These terms can be expressed as:

$$f_q(k) = \Delta R i_{qs}(k) + \frac{\Delta L}{T}\left[i_{qs}(k+1) - i_{qs}(k)\right]$$
$$+ \omega \Delta L i_{ds}(k) + \Delta e_{qs}(k) \quad (7)$$

$$f_d(k) = \Delta R i_{ds}(k) + \frac{\Delta L}{T}\left[i_{ds}(k+1) - i_{ds}(k)\right]$$
$$- \omega \Delta L i_{qs}(k) + \Delta e_{ds}(k) \quad (8)$$

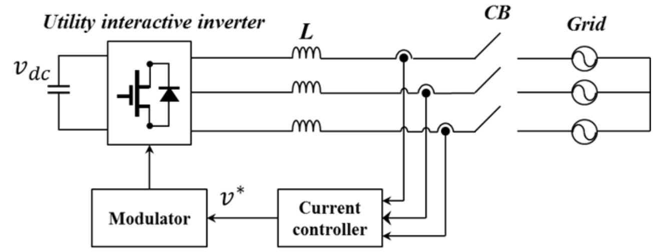


**Fig. 2. Block diagram of a typical configuration of three-phase utility interactive inverter**

where $\Delta R = R - R_o, \Delta L = L - L_o$ , $\Delta e_{qs} = e_{qs} - e_{qso}$ , $\Delta e_{ds} = e_{ds} - e_{dso}$, and subscript "o" denotes the nominal values. When the disturbances $f_q(k)$ and $f_d(k)$ do not exist, the predictive control is designed using the reference currents as follows:

$$v_{qs}^*(k) = R_o i_{qs}(k) + \frac{L_o}{T}\left[i_{qs}^*(k) - i_{qs}(k)\right] + \omega L_o i_{ds}(k) + e_{qso}(k) \quad (9)$$

$$v_{ds}^*(k) = R_o i_{ds}(k) + \frac{L_o}{T}\left[i_{ds}^*(k) - i_{ds}(k)\right] - \omega L_o i_{qs}(k) + e_{dso}(k) \quad (10)$$

where the symbol "*" denotes the reference quantities.

**Harmonic Compensation based on Time-Delayed Estimator**

Fig. 3 shows the proposed control scheme based on time-delayed estimator. To obtain an improved power quality of a utility interactive inverter even under distorted grid condition and parameter variations, the disturbances are estimated using the time-delayed estimator and they are used for feed-forward compensation.

Considering that the values of disturbances at the present time $t$ is very close to those at time $t - \tau$ in the past, the unknown disturbance terms of $f_q(t)$ and $f_d(t)$ in continuous-time domain can be written as follows:

$$f_q(t) \cong f_q(t - \tau) \quad (11)$$

$$f_d(t) \cong f_d(t - \tau) \quad (12)$$

In the discrete-time domain, (11) and (12) can be expressed as follows:

$$f_q(k) \cong f_q(k - L) \quad (13)$$

$$f_d(k) \cong f_d(k - L) \quad (14)$$

where $\tau = LT$ and $L$ is a positive integer. By approximating the disturbances at the time $k$ with those of $(k - L)$th time step and using (5) and (6), the estimating values of disturbances for one sampling period delay can be derived as follows [11]:

$$\begin{aligned}\widehat{f_q}(k) \cong f_q(k-1) &= v_{qs}(k-1) \\ &- \Big(R_o i_{qs}(k-1) \\ &+ \frac{L_o}{T}\left[i_{qs}(k) - i_{qs}(k-1)\right] \\ &+ \omega L_o i_{ds}(k-1) + e_{qso}(k-1)\Big)\end{aligned} \quad (15)$$

$$\begin{aligned}\widehat{f_d}(k) \cong f_d(k-1) &= v_{ds}(k-1) \\ &- \Big(R_o i_{ds}(k-1) \\ &+ \frac{L_o}{T}\left[i_{ds}(k) - i_{ds}(k-1)\right] \\ &- \omega L_o i_{qs}(k-1) + e_{dso}(k-1)\Big)\end{aligned} \quad (16)$$

where "^" denotes estimated quantities. In order to reduce high frequency noise caused by the numerical differentiation in estimated disturbances, a low pass filter is used. A simple first-order low pass filter $G(s) = \frac{a}{s+a}$ with the cut-off frequency $a$ is discretized using the bilinear transform method where the Laplace operator $s$ is replaced as follows:

$$s = \frac{2}{T}\frac{1-z^{-1}}{1+z^{-1}} \quad (17)$$

Using (17), the discrete-time transfer function of the low pass filter can be obtained as follows:

$$G(z) = \frac{\hat{f}_{qf}(z)}{\hat{f}_q(z)} = \frac{aT\,(1+z^{-1})}{(2+aT)-(2-aT)z^{-1}}. \quad (18)$$

Using the filtered values for the estimated disturbances $\widehat{f_{qf}}(k)$ and $\widehat{f_{df}}(k)$ by a feedforward control, the reference voltages in the proposed control scheme can be calculated as follows:

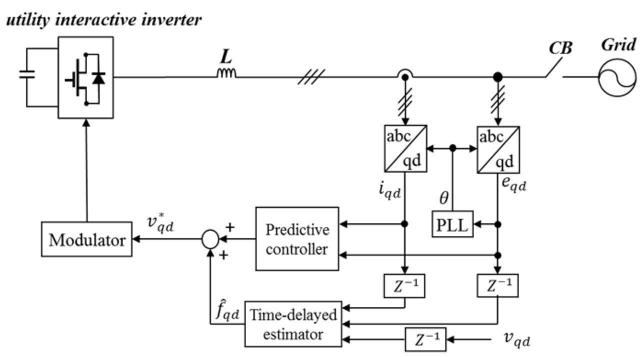


**Fig. 3. Block diagram of the proposed control scheme for a utility interactive inverter**

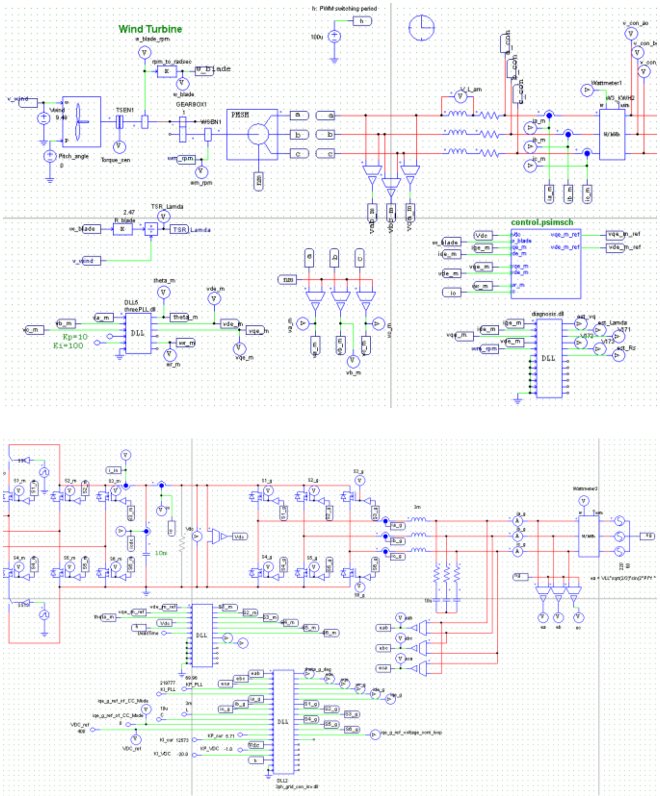


**Fig. 4. Simulation configuration for the utility interactive inverter**

$$v_{qs}^{*}(k) = R_o i_{qs}(k) + \frac{L_o}{T}\left[i_{qs}^{*}(k) - i_{qs}(k)\right] + \omega L_o i_{ds}(k)$$

$$+e_{qso}(k) + \widehat{f_{qf}}(k) \qquad (19)$$

$$v_{ds}^{*}(k) = R_o i_{ds}(k) + \frac{L_o}{T}\left[i_{ds}^{*}(k) - i_{ds}(k)\right] - \omega L_o i_{qs}(k)$$

$$+e_{dso}(k) + \widehat{f_{df}}(k) \qquad (20)$$

**Simulation Results**

The whole wind power system including a utility interactive inverter and control system is implemented in PSIM software as shown in Fig. 4, where the inverter output filter parameters are $R$ = 0.5 (Ohms), and $L$ = 7 (mH).

Fig. 5 shows the distorted grid voltages to validate performance of the proposed control scheme. These grid voltages include the fifth, seventh, eleven, and thirtieth harmonic components, resulting in the total harmonic distortion (TDH) of 13%.

Fig. 6 shows the inverter output currents in which only the conventional PI decoupling controller is employed to regulate the inverter current. It is easily noticed that the inverter output currents are highly distorted due to the grid voltage harmonics, as a result of the inability of the PI-based controller to suppress periodic disturbance.

Fig. 7 shows the inverter output currents of the proposed control scheme. In contrast to Fig. 6, a robust behavior of inverter output currents are observed even under the distorted grid voltages. Harmonic components in inverter currents are noticeably suppressed as compared with the case of the conventional PI controller.

As stated in former sections, the PI-based controller exhibits a low quality performance in disturbance rejection under the distorted grid voltage, which is illustrated in Fig. 8 and Fig. 9. These figures show the $q$-axis and $d$-axis inverter current responses, respectively. As is observed in Fig. 8, the $q$-axis current response has a high overshoot of above 20% in step current response as well as long settling time. Also, the $d$-axis inverter current exhibits a high oscillatory behavior due to harmonics in grid voltage. On the contrary, Fig. 10 and Fig. 11 show the $q$-axis and $d$-axis inverter current responses of the proposed control scheme, respectively. In these waveforms, it is clearly seen that the overshoot as well as the settling time in the $q$-axis current is significantly reduced. Moreover, the fluctuation in the $d$-axis inverter current is relatively small as compared with the waveform in Fig. 9 due to an effective harmonic compensation by adopting the timed-delayed disturbance estimator, which indicates the robustness of the proposed control scheme.

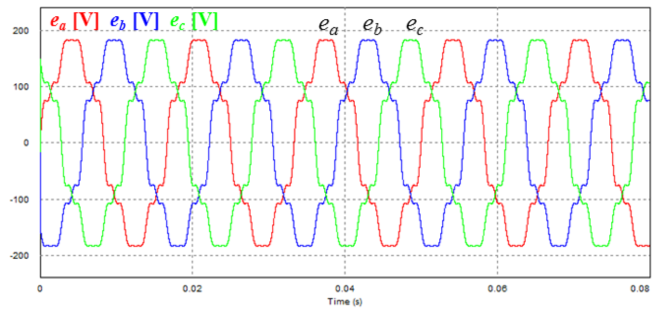


**Fig. 5. Three-phased distorted grid voltages**

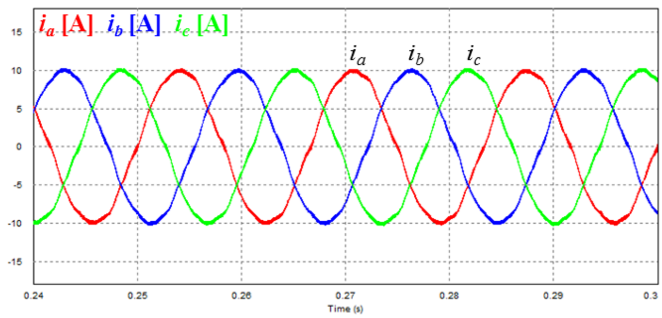


**Fig. 6. Three phase inverter output currents with the conventional PI decoupling controller**

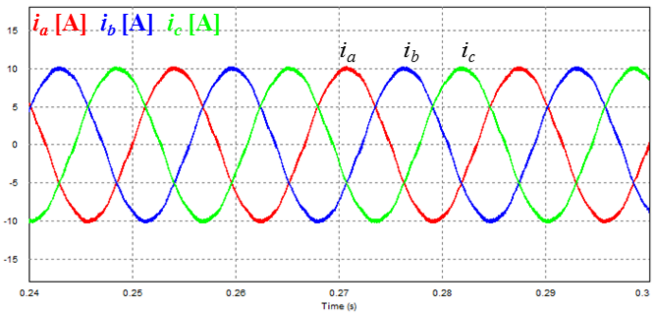


**Fig. 7. Three-phase inverter output currents with the proposed control scheme**

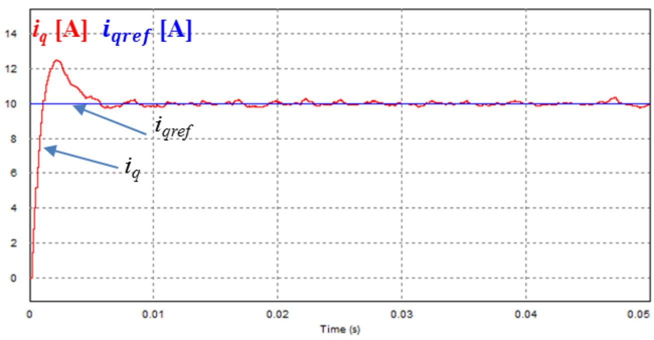


**Fig. 8. *q*-axis current response of the conventional PI decoupling control**

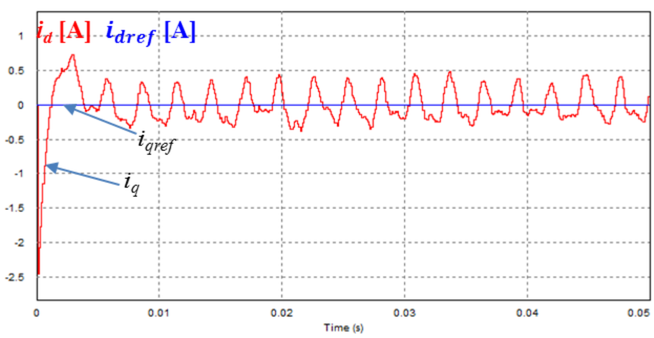


**Fig. 9. *d*-axis current response of the conventional PI decoupling control**

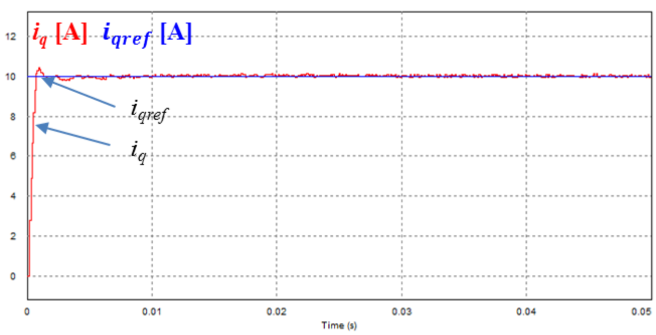


**Fig. 10. *q*-axis current response of the proposed control scheme**

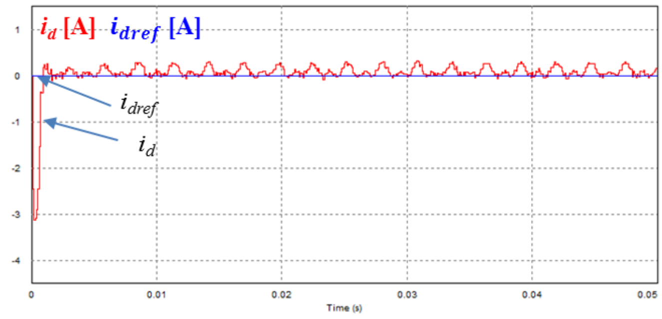


**Fig. 11. *d*-axis current response of the proposed control scheme**

Finally, the FFT result of an inverter phase current is given in Fig. 12 to corroborate the effectiveness of the proposed control scheme. The FFT result shows a significant low harmonics with the THD of 2.33% even under such highly distorted grid voltages. As a result, it has been verified through the comparative simulation results that the proposed control scheme can not only improve the dynamic response of the utility interactive inverter but also provide the ability to compensate the model uncertainties due to the parameter variations and distorted grid conditions.

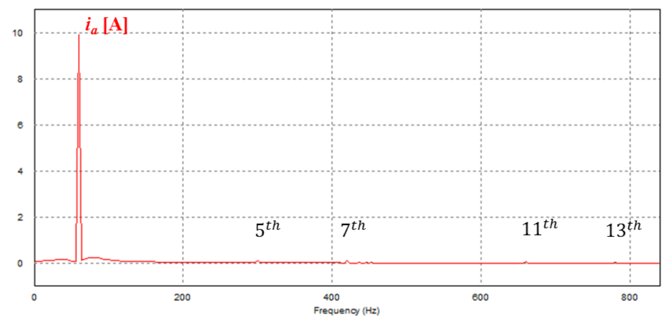


**Fig. 12. FFT result of *a*-phase current of the proposed control scheme**

## Conclusion

In this paper, a control design methodology for a utility interactive inverter based on time-delayed estimator has been proposed to improve the performance of DG system even in the presence of distorted grid condition. For a current control of a utility interactive inverter, the predictive control approach is employed. This control scheme calculates the required voltage which forces the inverter currents to follow their references by predicting the present system behavior through the previous system states. The mismatch in system parameters and disturbances due to the harmonics in distorted grid voltage can effectively be compensated by a time-delayed estimator. The proposed control scheme has been developed in the discrete-time domain in order that it can be implemented directly in digital signal controllers. Simulation results have been shown to illustrate a good performance of the proposed control scheme.

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**References**

[1] G. Chicco, and P. Mancarella, "Distributed multi-generation: A comprehensive view," Renewable and Sustainable Energy Reviews, vol. 13, no. 3, pp. 535-551, 2009.
[2] A. M. Bouzid, J. M. Guerrero, A. Cheriti, and M. Bouhamida, "A survey on control of electronic power distributed generation systems for microgrid applications," Renewable and Sustainable Energy Re-views, vol. 44, pp. 751-766, 2015.
[3] J. C. Vasquez, R. A. Masrtromauro, J. M. Guerrero, and M. Liserre, "Voltage support provided by a droop-controlled multifunctional inverter," IEEE trans. on Power Electronic, vol. 56, no. 11, pp. 4510-4519, 2009.
[4] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization," IEEE trans. on Power Electronic, vol. 58, no. 1, pp. 158-172, 2011.
[5] R. Teodorescu, M. Liserre, and P. Rodriguez, "Grid converters for photovoltaic and wind power system," A John Willey and Sons, Ltd, Chap. 12, 2011.
[6] R. Teodorescu, F. Blaabjerg, M. Liserre, and P. C. Loh, "Proportional-resonant controllers and filters for grid-connected voltage-source converters," IEE Proceedings Electric Power Applications, vol. 153, no. 5, pp. 750-762, 2006.
[7] M. Liserre, R. Teodorescu, and F. Blaabjerg, "Multiple harmonics control for three-phase grid converter systems with the use of PI-RES current controller in a rotating frame," IEEE trans. on Power Electronic, vol. 21, no. 3, pp. 836-841, 2006.
[8] S. L. Jung, and Y. Y. Tzou, "Discrete sliding-mode control of a PWM inverter for sinusoidal output waveform synthesis with optimal sliding curve," IEEE trans. on Power Electronic, vol. 11, no. 4, pp. 567-577, 1996.
[9] J. M. Espi, J. Castello, R. García-Gil, and G. Garcera, "An adaptive robust predictive current control for three-phase grid-connected inverters," IEEE trans. on Power Electronic, vol. 58, no. 8, pp. 3537-3546, 2011.
[10] K. H. Kim, and M. J. Youn, "A simple and robust digital current control technique of a PM synchronous motor using time delay control approach," IEEE trans. on Power Electronic, vol. 16, no. 1, pp. 72-82, 2001.
[11] Y. T. Karmal, and O. Ito, "A time delay controller for systems with unknown dynamics," ASME Journal of Dynamic Systems, Measurement, and Control, vol. 112, no. 2, pp. 133-142, 1990.