디지털 록인 앰프를 이용한 비정현 계통 전압 하에서 강인한 단상계통 연계 인버터용 고조파 보상법

칸 아마드 레이안, 아쉬라프 모하마드 노만, 최우진

A Robust Harmonic Compensation Technique using Digital Lock-in Amplifier under the Non-Sinusoidal Grid Voltage Conditions for the Single Phase Grid Connected Inverters

Reyyan Ahmad Khan, Muhammad Noman Ashraf and Woojin Choi
Department of Electrical Engineering, Soongsil University

ABSTRACT

The power quality of Single Phase Grid-Connected Inverters (GCIs) has received much attention with the increasing number of Distributed Generation (DG) systems. However, the performance of single phase GCIs get degraded due to several factors such as the grid voltage harmonics, the dead time effect, and the turn ON/OFF of the switches, which causes the harmonics at the output of GCIs. Therefore, it is not easy to satisfy the harmonic standards such as IEEE 519 and P1547 without the help of harmonic compensator. To meet the harmonic standards a certain kind of harmonic controller needs to be added to the current control loop to effectively mitigate the low order harmonics. In this paper, the harmonic compensation is performed using a novel robust harmonic compensation method based on Digital Lock-in Amplifier (DLA). In the proposed technique, DLAs are used to extract the amplitude and phase information of the harmonics from the output current and compensate it by using a simple PI controller in the feedforward manner. In order to show the superior performance of the proposed harmonic compensation technique, it is compared with those of conventional harmonic compensation methods in terms of the effectiveness of harmonic elimination, complexity, and implementation. The validity of the proposed harmonic compensation techniques for the single phase GCIs is verified through the experimental results with a 5kW single phase GCI.

Index Terms –Single Phase Grid Connected Inverter (SPGCI), Harmonic Compensation Method, Total Harmonic Distortion (THD) and Harmonic Standard.

1. INTRODUCTION

In Distributed Generations (DGs) systems the Grid Connected Inverter (GCI) plays a crucial role to transfer the surplus power into the utility grid. This high penetration of GCIs based DG systems can cause power quality issue due to the harmonics present in the grid voltage and other detrimental factors such as a dead band of PWM, device turn-on/turn-off delays, dc-offset and scaling error in the current and voltage sensing circuit, which in result lead to not satisfied the IEEE harmonic standards. Therefore the current control strategy in GCI is the key element. There are two well-known current control strategies: 1) Stationary Reference Frame (SRF) control using Proportional Resonant (PR) controllers, and 2) Rotating Reference Frame (RRF) control using Proportional Integral (PI) controllers.

Initially, the RRF current control is used to control the three-phase inverters. Thanks to its advantages this control method is also applied to control the Single Phase Grid Connected Inverters (SPGCIs) with the help of orthogonal signal generator (OSG). Though the OSG based control for SPGCIs works well under the sinusoidal grid condition, its output quality would be deteriorated when the grid is distorted with harmonics and DC offset. As well known the low order harmonics cause by many detrimental effects and it can hardly be eliminated completely by the RRF Current Controller, which in turn leads to an increased THD value of the output current. In order to improve the output quality of the GCI under distorted grid condition an advanced harmonic compensation method that can eliminate the low order harmonics needs to be employed.

One approach introduced in [1] employs a PR controller connected in parallel with a PI controller in d and q axis, respectively, to eliminate a certain harmonics. Another approach in [2] introduced a SOGI based harmonic compensator connected in parallel with a current regulator for each d and q axis, respectively. The other approach has introduced a method to detect the individual harmonic at its own frequency frame and to compensate it after converting it to a dc component. All of these conventional approaches are not able to eliminate the harmonic completely. Moreover, these approaches increase the complexity in the design of the current controller and hence the computational burden.

To overcome the aforementioned problems of the conventional harmonic compensation methods, a digital lock-in amplifier (DLA) based harmonic compensation method is proposed in this paper. In the proposed technique, a DLA capable of extracting the amplitude and phase information of harmonics components from output current is employed and the harmonics are compensated by using simple PI controllers in a feedforward manner. Since the DLA is robust in detecting the harmonic component from the output current and it can completely eliminate the harmonic to satisfy the harmonic standards all over the load range which is hard to achieve with previous harmonic compensation methods.

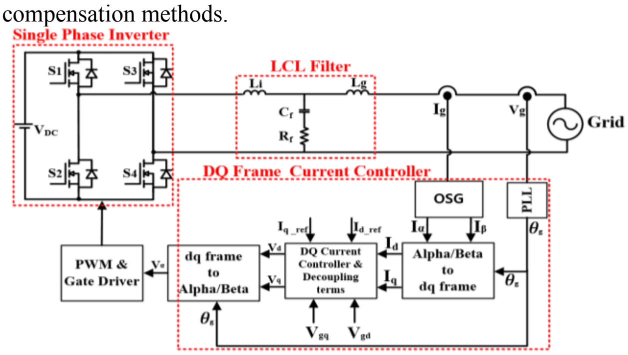


Fig. 1 Block diagram of a typical single phase grid connected inverter.

2. CONVENTIONAL CURRENT CONTROLLER FOR A SINGLE PHASE INVERTER IN RRF FRAME

A single phase grid connected inverter in RRF frame is shown in Fig.1, where the GCI is interfaced with the grid through a passive LCL filter. For the sake of simplification, the LCL filter can be modeled below its resonant frequency as an L filter. From Fig.1 the loop gain of the system can be expressed by Eq. (1) where the $G_P(s)=1/((L_i+L_g)+(r_i+r_g))$ is the transfer function of the LCL filter and $G_{PWM}(s)$ is the PWM unit which represents a computation delay, a sampler, and a zero-order holder.

$$G_{ol}(s) = G_i(s) * G_{PWM}(s) * G_P(s) \quad (1)$$

The output regulation performance can be improved by adding the cross coupling terms in a feedforward manner. Hence, the performance of the current controller is good enough only with fundamental frequency components. In the presence of detrimental factors, the current controller regulation performance becomes poor due to PI controller limited bandwidth.

3. HARMONIC COMPENSATION METHODS FOR A SINGLE PHASE INVERTER

3.1. CONVENTIONAL HARMONIC COMPENSATION METHODS IN RRF FRAME

Since the PI controller has a limited capability in regulating the ac components, it is difficult to meet the harmonic standard without the help of additional harmonic controllers. There are two well-known methods to eliminate the harmonics in the inverter current by the RRF frame current controller. One is the PR controllers connected in parallel with the current controller (PI) at each harmonic frequency of the output current as shown in Fig.2. Each PR controller acts as a harmonic compensator, which is able to extract the harmonic information from the error command and adds it to the output of the current regulator. Then the harmonics are compensated by the closed loop with negative feedback.

From Fig.3 the current controller transfer function can be expressed by Eq. (2).

$$G_i(s) = K_p + \frac{K_i}{s} + \sum_{h=1,2,3....} \frac{K_{rh} s}{s^2 + (h\omega_f)^2} \quad (2)$$

Where the K_p and K_i is the proportional and integral gain of the PI controller, respectively, and K_{rh} is the resonant gain of the resonant controllers.

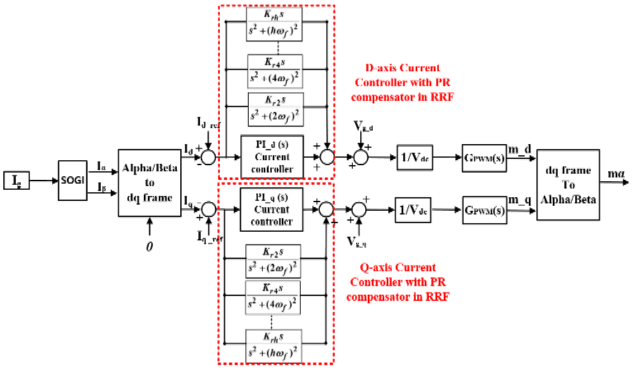


Fig. 2 Block diagram of the conventional harmonic inverter method in RRF frame current controller.

Though this method is effective in harmonic compensation, it is disadvantageous in that it requires many harmonic controllers for each D and Q axis. As well known a harmonic component in SRF appears as two different harmonic components in the RRF as shown by Eq. (3)-Eq. (5). The grid current can be expressed as Eq. (3) when the 3rd and 5th harmonics are present in it.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_g\left(\cos\theta_g + \cos 3\theta_g + \cos 5\theta_g\right) \\ i_g\left(\sin\theta_g + \sin 3\theta_g + \sin 5\theta_g\right) \end{bmatrix} \quad (3)$$

Then the park transformation is applied to transform the orthogonal components of the grid current in the SRF into those in the RRF as shown in Eq. (4).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta_g & \sin\theta_g \\ -\sin\theta_g & \cos\theta_g \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (4)$$

It can be found from Eq. (5) that odd harmonic in the SRF appears as n±1 even harmonics in the RRF.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} i_g\left(1 + (\cos 2\theta_g) + (\cos 4\theta_g) + (\cos 6\theta_g)\right) \\ i_g\left((\sin 2\theta_g) + (\sin 4\theta_g) + (\sin 6\theta_g)\right) \end{bmatrix} \quad (5)$$

To verify the Eq. (5), the FFT analysis of the 3rd and 5th harmonics in SRF and RRF is shown in Fig.4. It is confirmed from the Fig. 3, the 3rd and 5th harmonics in SRF appear as 2nd, 4th and 6th harmonics in RRF. In results, in order to compensate the 3rd and 5th harmonics in SRF, three harmonic controllers are required at 2nd, 4th and 6th of the fundamental frequency at each D and Q axis, respectively. Therefore, it would increase the complexity in the design of the current controller and hence the computational burden. In addition, since the PR controller is not able to extract the harmonic information completely, the perfect elimination of the harmonics can be hardly achieved.

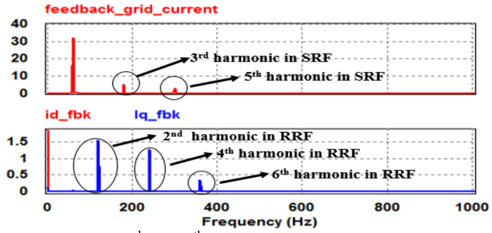


Fig. 3 FFT analysis of 3rd and 5th harmonics in SRF and RRF.

The other approach is the technique to employ the multiple numbers of RRFs as shown in Fig.4. In this method, the individual harmonic is detected at its own frequency frame and it is compensated after converting it to a dc component. This method is advantageous in that the harmonic can be regulated by a simple PI controller.

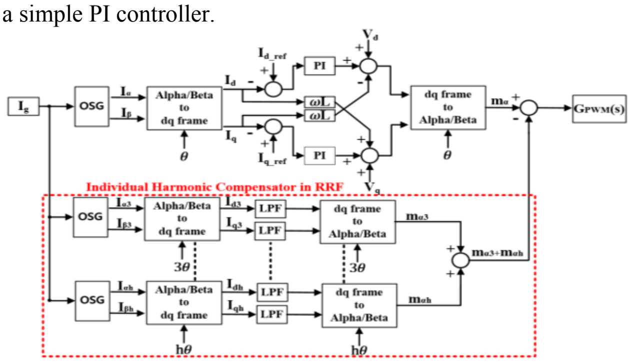


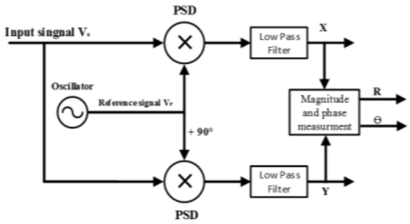
Fig. 4 Block diagram of selective harmonic compensation method in RRF

However, this technique has several disadvantages that its computational burden is quite high and its dynamic performance is not good enough due to the delay produced by the OSG block at each RRF and the park transformation to transform the AC components to DC variables. In the case of asymmetric generation of OSG, the harmonic compensation can hardly be performed perfectly, resulting in a steady state error. Furthermore, since the SOGI utilizes two second order low pass filters, it also attenuates the harmonics, which makes it difficult to eliminate the harmonics completely.

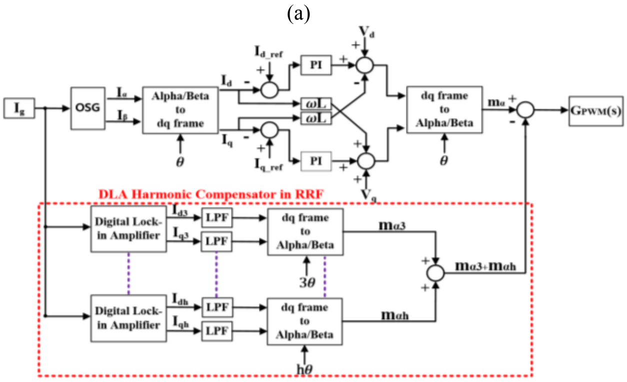
3.2. PROPOSED HARMONIC COMPENSATION METHOD

To overcome the aforementioned problems associated with the conventional harmonic compensation, a digital lock-in amplifier (DLA) harmonic compensation method is proposed, the schematic diagram of DLA is shown in Fig. 5 (a). In this proposed technique, DLAs are employed to extract the amplitude and phase information of the harmonics from the output current. Hence, the harmonics are compensated by the current controllers (PI) in a feedforward manner after the inverse park transformation as shown in Fig. 5 (b).

The advantages of the proposed method over the conventional methods include the simplicity in the implementation of the controller. Since the proposed method does not require OSG block and park transformation block for the harmonic compensation, it has lower computational burden and complexity of the current control than those of others. Furthermore, the DLA is robust in detecting the harmonic component from the output current and hence it can almost completely eliminate the harmonic currents to satisfy the harmonic standards all over the load range which is hard to achieve with conventional harmonic compensation methods.



(a)



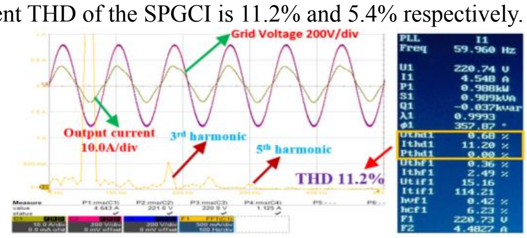
(b)

Fig. 5 (a) Block Diagram of Digital Lock-in Amplifier (DLA) (b) Block diagram of the proposed harmonic compensation in RRF.

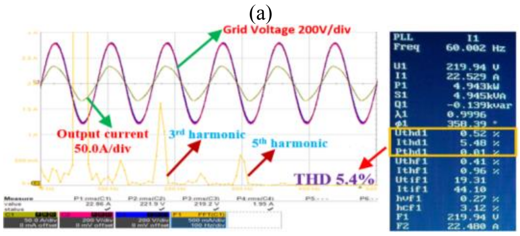
4. Experimental Results

In order to verify the superior performance of the proposed method by the experiments a 5kW single phase grid connected inverter was built. The system was tested in the following conditions: V_{dc} (400V), V_g (220V_{rms}) with THD (0.5%), fundamental frequency f_g (60Hz), switching frequency 10kHz and the dead time (0.5µs). A TMS320F28335 DSP is used to control the inverter. All the controllers are implemented by discretizing it with bi-linear transformation.

In Fig. 6 (a) and (b) shows the experimental results with conventional RRF current controller at 1kW and 5kW and the current THD of the SPGCI is 11.2% and 5.4% respectively.



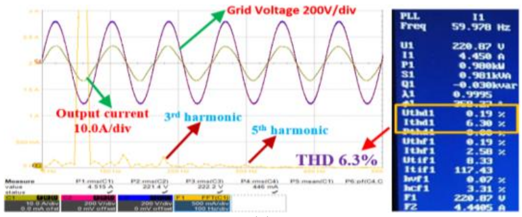
(a)



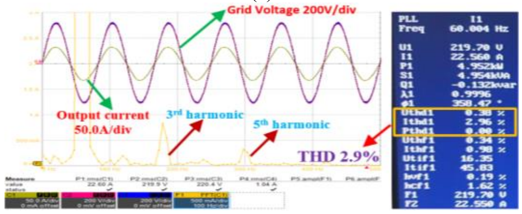
(b)

Fig. 6 Experimental results of conventional RRF current controller (a) at 1kW power (b) at 5kW power.

Fig. 7 (a) and (b) shows the performance of the conventional harmonic compensation method implemented to compensate for the 3rd and 5th harmonics. The THD of the inverter output current is reduced from 11.2% to 6.3% at 1kW and from 5.4% to 2.9% at 5kW, respectively, when the harmonic compensation method is applied. Fig. 8 (a) and (b) show the performance of the proposed method. The THD of the inverter current is reduced significantly from 11.2% to 4.2% at 1kW and from 5.4% to 1.72% at 5kW, respectively. It can be confirmed with the experimental results that the harmonic attenuation performance of the proposed method is better than those of the conventional methods.

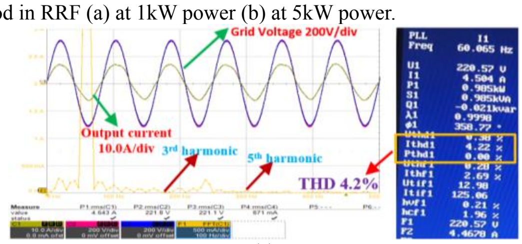


(a)

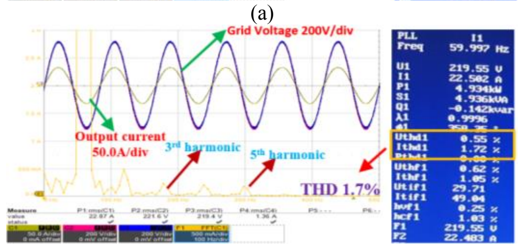


(b)

Fig. 7 Experimental results of conventional harmonic compensation method in RRF (a) at 1kW power (b) at 5kW power.



(a)



(b)

Fig. 8 Experimental results of proposed harmonic compensation method in RRF (a) at 1kW power (b) at 5kW power

5. Conclusion

In this paper, a method to improve the THD of the SPGCI using a novel DLA based harmonic controller has been proposed and its effectiveness has been verified through experimental results. The proposed method exhibits a superior performance over those of the conventional methods in terms of harmonic rejection.

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