단상 계통연계 인버터를 위한 새로운 고조파 보상법

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A Novel Harmonic Compensation Method for the Single Phase Grid Connected Inverters

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ABSTRACT

In order to meet the harmonics standards such as IEEE 519 and P1547 the output quality of a grid connected inverter should satisfy a certain level of Total Harmonic Distortion (THD) value. However, the output quality of an inverter gets degraded due to the grid voltage harmonics, the dead time effects and the nonlinearity of the switches, which all contributes to a higher THD value of the output. In order to meet the required THD value for the inverter output under the distorted grid condition the use of harmonic controller is essential. In this paper a novel feedforward harmonic compensation method is proposed in order to effectively eliminate the low order harmonics in the inverter current to the grid. In the proposed method, unlike the conventional harmonic control methods, the hamonic components are directly compensated by the feedforward terms generated by the PR controller with the grid current in the stationary frame. The proposed method is simple in implementation but powerful in eliminating the harmonics from the output. The effectiveness of proposed method is verified through the PSIM simulation and the experiments with a 5kW single phase grid connected inverter.

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

1. INTRODUCTION

The power quality of grid-connected inverters has received much attention with the increasing numbers of Distributed Generations (DGs). In a DG systems, the grid connected inverter plays a key role in transferring the energy from the source to the grid. In order to guarantee the power quality of the grid the THD value of the injected current by the inverter needs to be maintained within a certain value designated by the harmonic standards such as IEEE std. 519 and P1547. Therefore the current control of the grid connected inverter is very important. 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.

The RRF control, also called DQ frame control, is widely used for the control of the three phase inverters. In the RRF control varying ac variables can be transformed into equivalent dc quantities and eaily controlled by PI controllers. Thus, the design process is simple while exhibiting satisfactory performances in both dynamic and steady state conditions. In addition the control loop has no dependence on the fundamental frequecny and the active and rective power can be controlled dependently through the d and q axis current control, respectively.

The technique can be applied to control the single phase grid connected inverter with the help of orthogonal signal generator. Hence, all the advantages obtained with the DQ control of the three phase system become available in the signle phase system as well. However, it is only valid when the grid voltage is sinusoidal. As well known the harmonics are present in the grid voltage and hence the output current of the grid connected inverter is distorted by the low order harmonics which cannot be completely eliminated by the RRF Current Controller (CC). In addition the third harmonic caused by the dead time to prevent the shoot through fault of the inverter further deteriorates the output quality of the inverter, which in turn leads to an increased THD value of the output current.

In order to improve the output quality of the grid connected inverter under distorted grid condition an advanced control method that can eliminate the harmonics in the grid needs to be employed[1][2]. One approach introduced in Ref.[1] employs a PR controller connected in parallel with a PI controller in d and q axis, respectively, in order to eliminate a certain harmonic. Even though this control method is effective in harmonic rejection, the Harmonic Compensator (HC) for each d and q axis to mitigate a specific ac ripple is required. In addition, since a harmonic component in the SRF appears as two different components in the RRF, two harmonic compensators are required to eliminate a certain harmonic. This makes it very complex to design and to implement the harmonic controller. Another approach in Ref. [2] introduced a SOGI based HC connected in parallel with a current regulator for each d and q axis. This control method also provides desirable results in term of harmonic rejection. However, a low pass and a band pass filter included in the SOGI block makes the control method more complicated and increases the computational burden. The other approach is introduced a method to detect the individual harmonic at its own frequency frame and to compensate it after converting it to a dc component. The technique has two disadvantages that its computational burden is high due to the the use of multiple number of RRFs and its dynamic characteristics is not good enough due to the delay produced by the low pass filter.

In this paper, an advanced harmonic compensation technique is introduced to overcome the drawbacks of the conventional RRF techniques. In the proposed approach since the harmonic is compensated in the SRF the design process of the HC is simpler and the computational burden is lower as compared to the conventional approaches.

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

A general block diagram of a single phase grid connected inverter in DQ frame is shown in Fig.1, where the inverter is interfaced with the grid through a passive LCL filter. The grid voltage V_g and the output current I_g are fed back to the controller. The CC is responsible for injecting a sinusoidal current to the grid while meeting the IEEE harmonic standards.

Fig.2 shows the schematic diagram of the DQ frame CC. Here, 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. Therefore the loop gain for the whole system can be expressed by Eq. (1).

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

The output regulation performance can be improved by adding the cross coupling terms in a feedforward manner. While the performance of the CC is good enough only with fundamental frequency components, it becomes poor when the harmonics are present in the grid due to its limited bandwidth of the PI controller.

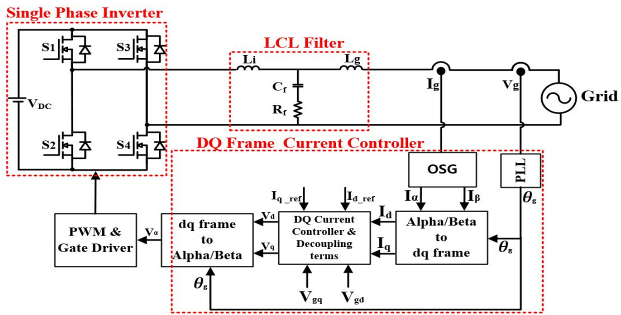

Fig. 1 Block diagram of a typical single phase grid connected inverter

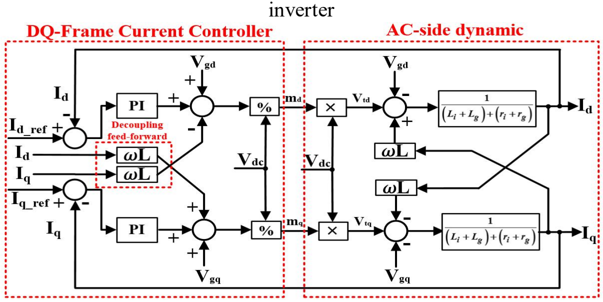

Fig. 2 Block Diagram of the DQ Frame CC in an Inverter.

Fig.3 shows the simulation results of typical DQ frame CC under the conditions of 2nd, 3rd and 5th harmonic with 0.1%, 0.4% and 0.1% in the grid voltage, respectively, and its THD is about 0.5% and the dead time is 0.5µs. The inverter output current shows a higher THD value when the harmonics are present in the grid. Therefore, additional controllers for the harmonics need to be added to ensure the quality of the inverter output under non-sinusoidal grid condition, which will be discussed in detail in the following section.

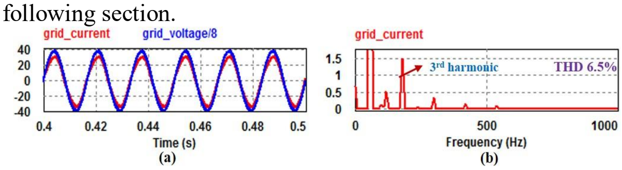

Fig. 3 Simulation results of typical DQ frame CC with non-sinusoidal grid condition

3. HARMONIC COMPENSATION METHODS FOR A SINGLE PHASE INVERTER

3.1. CONVENTIONAL HARMONIC COMPENSATION METHODS IN DQ FRAME

Since the PI controllers have 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 DQ frame CC. 1) Using PR controllers connected in parallel with the current regulator to detect the harmonics and compensating it by the negative feedback 2) Using multiple number of RRFs for each harmonic to regulate it after converting it as a dc component and compensating it by a feedforward manner.

The former approach with PR controllers is shown in Fig.4 and its open loop 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.

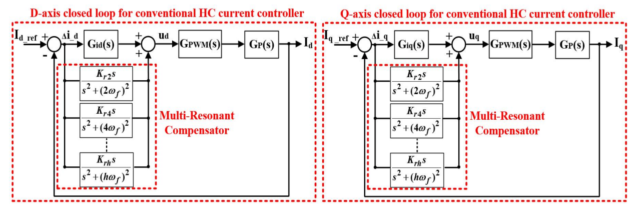

Fig. 4 Block diagram of the conventional HC method in DQ frame CC

As already mentioned a harmonic component in the SRF appears as two different 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 an odd harmonic in the SRF appears as two different even harmonics in the RRF.

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

Therefore, it is difficult to compensate for the harmonics in the RRF since the compensators for the two different harmonics should be implemented. In addition, this technique requires a harmonic controller for each d and q axis, respectively, and it would further increase the complexity in the design of controllers and hence the computational burden.

The later approach with multiple number of RRFs is shown in Fig.5. In this method the output current is measured and fed back to each RRF with different frequency such as 180Hz, 300Hz and 420Hz. Each harmonic component appears as a DC term in its own frequency frame. This method is advantageous in that the hamonic can be regulated by a simple PI controller.

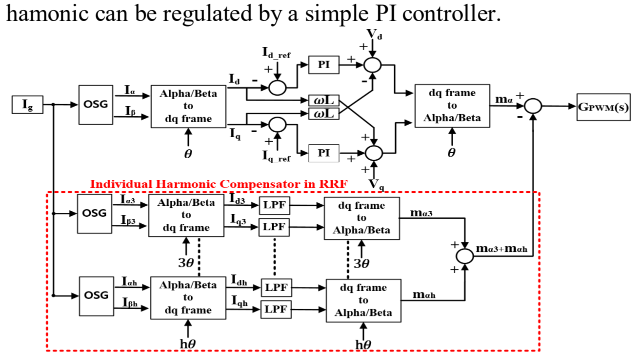

Fig. 5 Block diagram of selective HC method in RRF

However, the main disadvantage of the method is that the dynamic characteristics of the harmonic compensation is not good enough because of the delay produced by the low pass filter.

Moreover, the use of multiple number of RRFs and the associated computation blocks such as the low pass filters and frame transformation blocks result in a quite high complexity and computational burden.

3.2. PROPOSED HARMONIC COMPENSATION METHOD FOR DQ FRAME

In order to solve the aforementioned problems in the conventional HC methods a novel harmonic control method for a single phase grid connected inverter is proposed. In this proposed method the harmonic is detected by a PR controller in the SRF and is directly added to the PWM voltage command to compensate for a certain harmonic as shown in Fig.6.

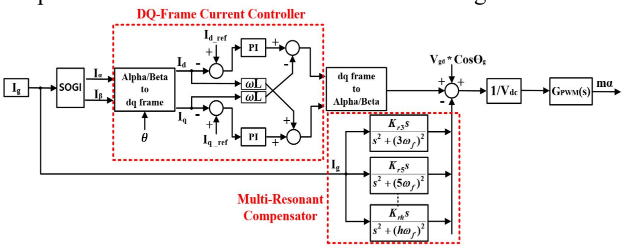

Fig. 6 Block Diagram of the proposed harmonic compensation method

The advantages of the propose method over the conventional methods includes the simplicity in the implementation of the controller. Since the harmonic compensation is implemented in SRF there is no need for the transformation for the harmonic compensation. In addition only one controller needs to be implemented to compensate for a certain harmonic and the computational burden can be further reduced as compared to the conventional methods.

The open loop gain $G_{ol}(s)$ can be derived from Fig.6 under the assumption that the decoupling control is perfect such that there is a negligible effect on the performance of the controller. The open loop gain of the proposed control method can be expressed as follows:

$$G_{ol}(s)=\left(G_i(s)+HC(s)\right)G_p(s)*G_{PWM}(s) \tag{7}$$

4. SIMULATION RESULTS

In order to show the superior performance of the proposed method with respect to the conventional methods simulations are conducted using PSIM software. The simulation is carried out under the conditions of 2[nd], 3[rd] and 5[th] harmonics with 0.1%, 0.4% and 0.1% in the grid voltage, respectively, and its THD is about 0.5% and the dead time is 0.5μs.

The performance of typical DQ frame CC is shown in Fig.3. In order to compare the performances of the proposed method and the conventional HC methods both methods are implemented and simulated as shown in Fig.10 and 11, respectively. It can be noticed that the proposed method shows a superior performance as compared to that of the conventional HC.

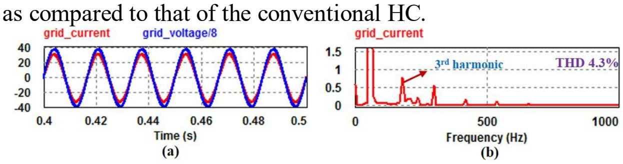

Fig 3 Simulation result of a conventional HC method at 5kW

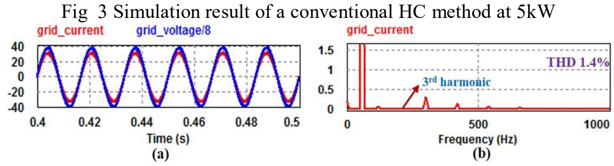

Fig 4 Simulation result of a proposed HC method at 5kW

5. 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.12 the experimental results with a typical DQ frame CC without HC is shown and the THD of the inverter current is 7.75%.

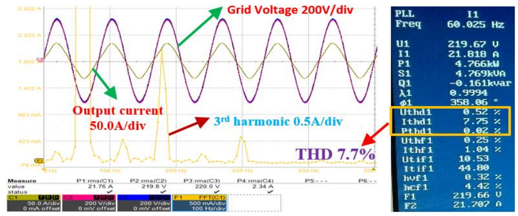

Fig. 5 Experimental result with a typical DQ frame CC (5kW)

Fig. 13 shows the performance of the conventional HC implemented to compensate for the 3[rd] harmonic and the THD of the inverter current is reduced from 7.7% to 6.4%. Fig. 14 shows the performance of the proposed method and the THD of the inverter current is reduced significantly from 7.7% to 2.4%. It can be confirmed with the experimental results that the harmonic attenuation performance of the proposed method is better than that of the conventional methods with even less computation burden.

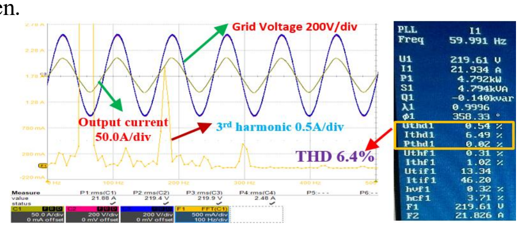

Fig. 6 Experimental result of the conventional HC (5kW)

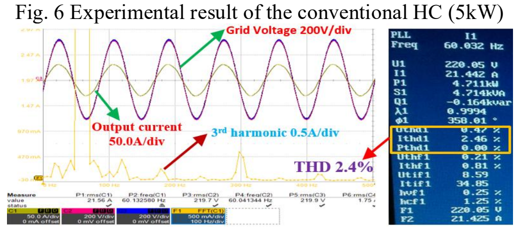

Fig. 7 Experimental result of the proposed HC method (5kW)

6. Conclusion

In this paper, a method to improve the THD of the single phase grid connected inverter using novel feedforward harmonic controller has been proposed and its effectiveness has been verified through simulation and experiments. The proposed method exhibits a superior performance over that of the conventional method with even less computational burden.

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