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PWM Inverter with 4-Phase Carrier for Grid Connection Via Combined LCL Filter

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Abstract. A PWM power conversion system connected to a grid through parallel-combined LCL filter is proposed in this paper. The system has four inverters paralleled and operates with PWM using 4-phase carrier for powering up and performance improvement. Four LCL filters have four separate filter inductors connected to individual inverters and one common LC filter which is composed of a filter capacitor and a grid inductor. The differential mode current circulates only through four inverters and four filter inductors. The differential mode current is completely eliminated from the filter capacitor and the connected power grid. Accordingly, performance improvement can be achieved since the current in the filter capacitor is reduced and the harmonic current into a grid is reduced. An 1.3kW single phase prototype system has been constructed and tested, and the proposed system has been verified.

Key words. Parallel Inverter, Combined LCL Filter, PWM with four phase carrier, Harmonic Reduction, Grid Connection.

1. Introduction

LCL filters are widely used for reduction of switching harmonics to a grid in AC/DC converters for DC loads and in DC/AC inverters for distributed renewable power system [1]-[12]. For up-powering, parallel systems are considered. Paralleling of switching devices themselves and paralleling of inverters through external circuits are possible [11]-[14]. The former can be called a direct paralleling and the latter an indirect paralleling. In the indirect paralleling, not only powering up but also performance enhancement can be achieved. In this paper, indirect paralleling of inverters with a combined parallel LCL filter is proposed, where four paralleled inverters have separate filter inductors and one set of a filter capacitor and a grid inductor in common. The switching harmonics in the currents to the filter capacitor and to the grid are greatly reduced due to the use of four-phase carrier in PWM (Pulse Width Modulation) processing, which is sometimes called interleaved PWM. Accordingly, performance improvement is achieved.

2. Filter system for grid connection

A. General Power Conversion System Tied to a Grid

Power systems such as wind power system and photovoltaic power system can be connected to a grid through filters as in Fig. 1. Filters supress harmonics flow into the grid. Simple L, LC or LCL filters can be used for these [1], [2]. The size of LCL filter can be greatly reduced compared to that of L filter under the condition of the same level of harmonics injected to the grid. The LCL filter per phase is shown in Fig. 2(a). If the switching frequency is sufficiently high and the current control is performed successfully, the circuit can be treated as if the inverter current is injected into L-C circuit [15]-[17]. The transfer function (current ratio) is given by the following:

$$\mathbf{H}_{\mathrm{o}}(s) = \frac{\mathbf{I}_{\mathrm{g}}}{\mathbf{I}_{\mathrm{i}}} = \frac{1}{C_{\mathrm{f}} L_g s^2 + 1} \quad (1)$$

From this, it is known that the system is inherently unstable because of the poles placed on the imaginary axis. The poles will move to the left half plane due to the small series resistances of the filter capacitor and grid inductor.

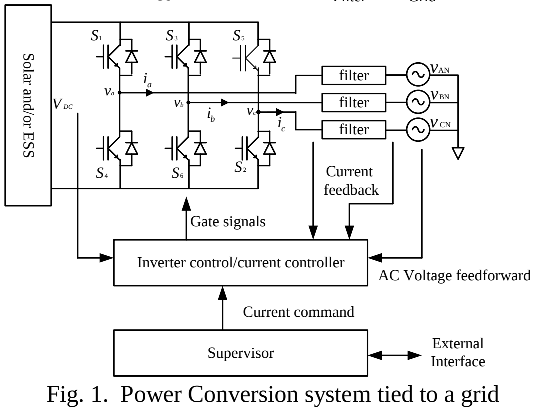

Fig. 1. Power Conversion system tied to a grid

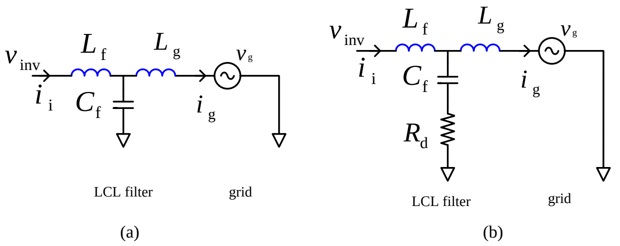

Fig. 2. LCL filters: (a) basic type, (b) augmented type (filter with damping resistor)

However, it is not sufficient and some harmonics can be amplified. It is advisable to insert a damping resistor in series with the filter capacitor, as in Fig. 2(b). Then the transfer function is changed to the following:

$$\mathbf{H}_{\mathrm{odp}}(s)=\frac{\mathbf{I}_{\mathrm{g}}}{\mathbf{I}_{\mathrm{i}}}=\frac{1+R_{\mathrm{d}}C_{\mathrm{f}}s}{C_{\mathrm{f}}L_{\mathrm{g}}s^{2}+R_{\mathrm{d}}C_{\mathrm{f}}s+1} \tag{2}$$

where damping ratio is given by

$$\zeta=\frac{R_{\mathrm{d}}}{2}\sqrt{\frac{C_{\mathrm{f}}}{L_{\mathrm{g}}}} \tag{3}$$

Damping can be inserted also by active damping technique, in which necessary damping is realized by feedback control [5]-[8].

B. The proposed system

The proposed system for a single phase is shown in Fig. 3. The four inverters (A1, A2, B1 and B2) are operating in parallel and drive the proposed combined LCL filter, which is composed of four separate filter inductors and one set of a filter capacitor and a grid inductor in common. The inverters use the same PWM technique but the carriers are slightly different, four-phase carriers are used as shown in Fig. 4. The PWM technique using multiple carriers is called an interleaved PWM and its benefit is studied in the next two sections. A1 and A2 are called group A, where carriers with 180 degrees of phase difference are used. Similarly, B1 and B2 are called group B, where carriers with 180 degrees of phase difference are used. The carriers in group A and B have 90 degrees of phase difference. When control is performed successfully, the fundamental components of four inverters are the same. So the four inverters operate as if in parallel. The inductance of the filter inductors in Fig. 3 is four times that of the inductors in Fig. 2, and the current rating is one quarter that in Fig. 2.

Assuming well balanced circuit, the differential signal between A1 and A2 causes the voltage at AB zero. Similarly, the differential signal between B1 and B2 causes the voltage at AB zero. The differential mode signals do not appear at the point AB. So differential voltages do not cause current into LC filter and accordingly to the grid. Only the common-mode voltage causes harmonics in the filter capacitor and the grid, and for the common mode signals the circuit in Fig. 2 can be used. Accordingly, harmonic currents in the filter capacitor and the grid can be reduced.

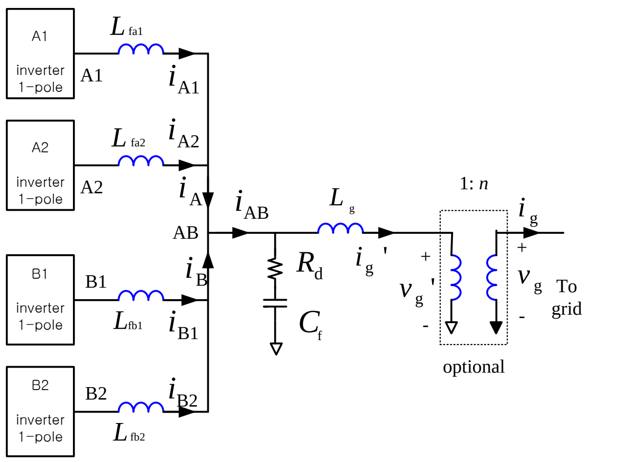

Fig. 3. The proposed system

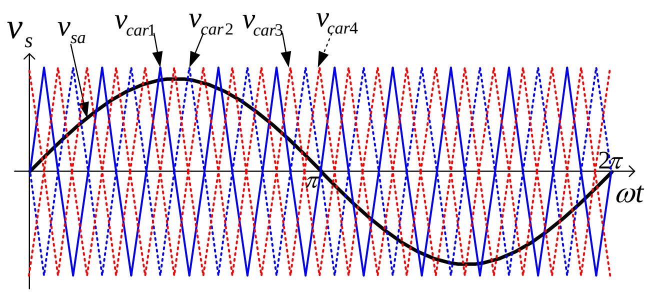

Fig. 4. The PWM processing with 4-phase carrier

C. *Current harmonics of the proposed system*

For the inverters, PWM (Pulse Width Modulation) with 4-phase carrier, namely interleaved PWM, is used as noted previously. The dramatic reduction of the ripple currents is shown graphically. In Fig. 5, the currents are shown when the time interval is short and the inverters supply the same average currents. The output currents of the inverter A1, A2, B1 and B2 are i_{A1}, i_{A2}, i_{B1} and i_{B2}, respectively. The currents i_{A1} and i_{A2} have a time difference of one half switching period. Their sum, i_A, has much smaller ripple current than i_{A1} or i_{A2}. The same is applied to i_{B1} and i_{B2}. The currents i_A and i_B have a time difference of a quarter switching period. Finally, the sum of i_A and i_B is i_{AB} and switching ripple is greatly eliminated from the resultant current i_{AB}.

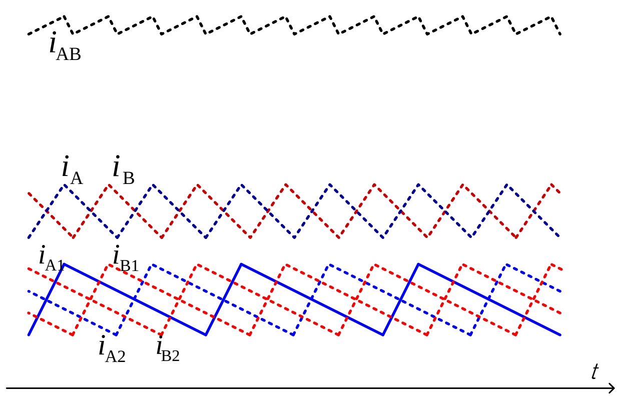

Fig. 5. The current waveforms under symmetric control

D. Detailed Harmonic Analysis by Computer Simulation

Nowadays, use of SiC FET is widespread. 25.2 kHz of the switching frequency is selected for our prototype system, which is designed based on SiC FETs. Although harmonic currents are reduced with the high switching frequency, the interleaved PWM shows dramatic effects on harmonics. Asynchronous PWM is adopted because a synchronous PWM is not easy and subharmonic is insignificant when the switching frequency is high compared to the fundamental frequency. Fig. 4 shows PWM for the inverters shown in Fig. 3. Four-phase triangular signals are carriers. The sinusoidal signal is modulating signal. According to the intersection of the carriers and the modulating signal, the inverters' switching operations occur. The carriers v_{car1}, v_{car2}, v_{car3} and v_{car4} are for the inverters A1, A2, B1 and B2, respectively. A numerical harmonic analysis has been done [18], [19]. The spectra of the output voltages of inverters A1 and A2 are shown in Fig. 6(a) where absolute magnitudes are displayed. The spectrum of the signal in common-mode among the output voltages of inverters A1 and A2 is shown in Fig. 6(b) where the first and third lobes are nearly disappeared. It is due to the fact that the switching harmonics of the inverters A1 and A2 are opposite in the first lobe, around the switching frequency. Fig. 7 is the same as Fig. 6 except that Fig. 7 is for inverters B1 and B2. The spectrum in Fig. 6(b) is called group A common mode voltage, and that in Fig. 7(b) group B common mode voltage. The spectrum of the common mode voltage between group A and group B is shown in Fig. 8. Only the fourth lobe is remaining. Voltage harmonics are greatly alleviated.

3. Experimental Results

To verify the proposal, a prototype of 1.3kW has been constructed. SiC FET NTHL020N120 from Onsemi is used for switching devices. The switching frequency is 25.2 kHz. TI's TMS320F28377 DSP is adopted as the controller for performing control and generating PWM waveforms. Circuit parameters are shown in Table I. Experimental setup is shown in Fig. 9. Fig. 10 shows the currents in group A. It shows harmonics are greatly eliminated in the current i_A due to the elimination of differential-mode current. Fig. 11 is a time-expanded version of Fig. 10, where the reduction of ripple current is clearly shown. Fig. 12 shows i_A, i_B and i_{AB}. The i_A and i_B are summed up to the final combined current i_{AB}. Harmonics are again reduced in the processing of summed up. The LCL filter operation is shown in Fig. 13. The combined current i_{AB} is injected into the L-C filter. Harmonics are once more eliminated, and the resultant current is fed to the grid. Fig. 14 shows the grid voltage and current. Very clean current is obtained. A tie transformer with turns ration of 1:3 is used to bridge the filter and the grid.

Harmonic reduction property of the interleaved PWM will remain as long as stability is ensured whether passive damping is used or active damping is used.

(a)

(b)

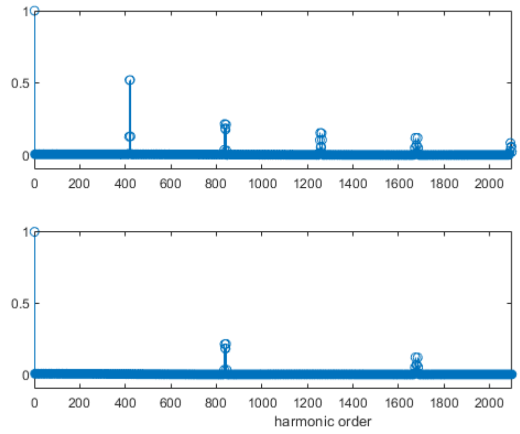

Fig. 6. Harmonics of the group A:
(a) individual voltage, (b) common mode voltage

(a)

(b)

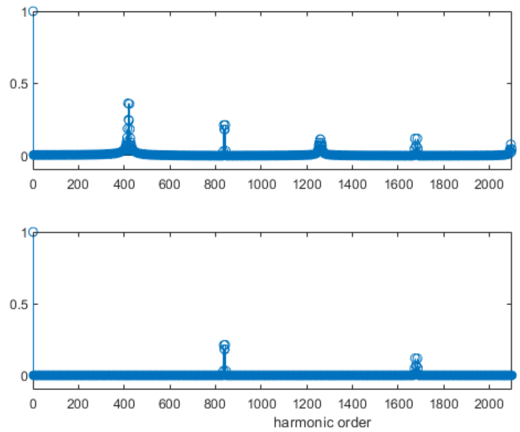

Fig. 7. Harmonics of the group B:
(a) individual voltage, (b) common mode voltage

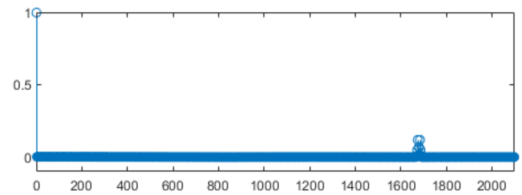

Fig. 8. Overall Harmonics (overall common mode voltage)

Table I. – Circuit Parameters

Name		Symbol	Value
DC voltage		V_{DC}	510 [V]
Grid voltage		V_g	200 [V]
Turns ratio of tie Trans.		1 : n	1 : 3
Filter parameters	filter inductor	L_{fxx}	3.9 [mH]
	filter capacitor	C_f	6 [μF]
	grid inductor	L_g	870 [μH]
	damping resistor	R_d	8.8 [Ω]

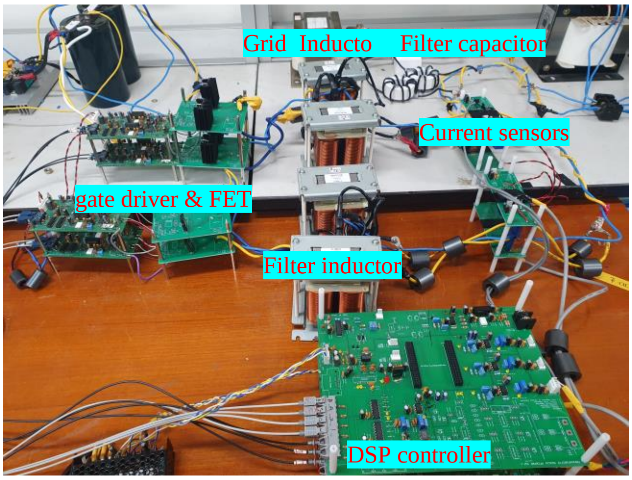

Fig. 9. Experimental Setup

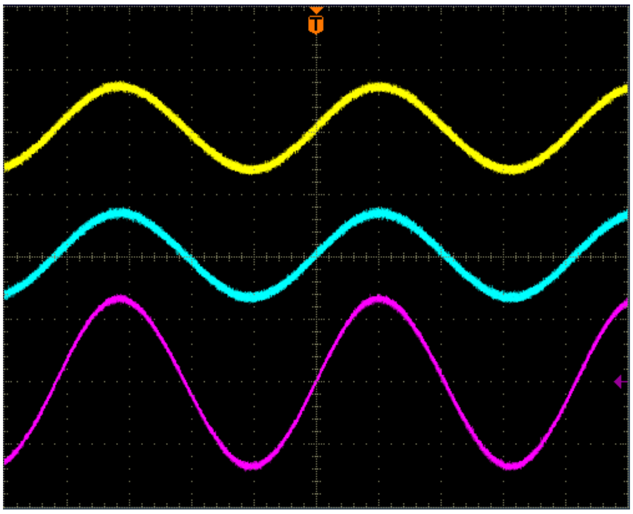

Fig. 10. Currents in group A:
Upper: i_{A1} (10 [A/div]), middle: i_{A2} (10 [A/div]),
lower: i_A (10 [A/div]), time base: 4 [msec/div]

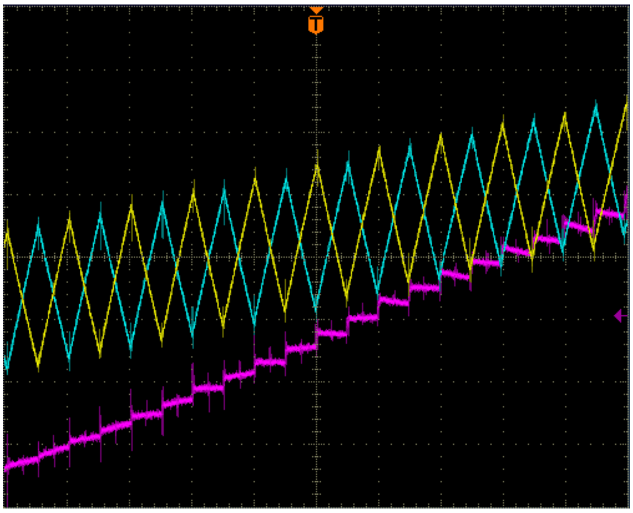

Fig. 11. Currents in group A (expanded):
Yellow: i_{A1} (0.5 [A/div]), Blue: i_{A2} (0.5 [A/div]),
pink: i_A (0.5 [A/div]), time base: 40 [μsec/div]

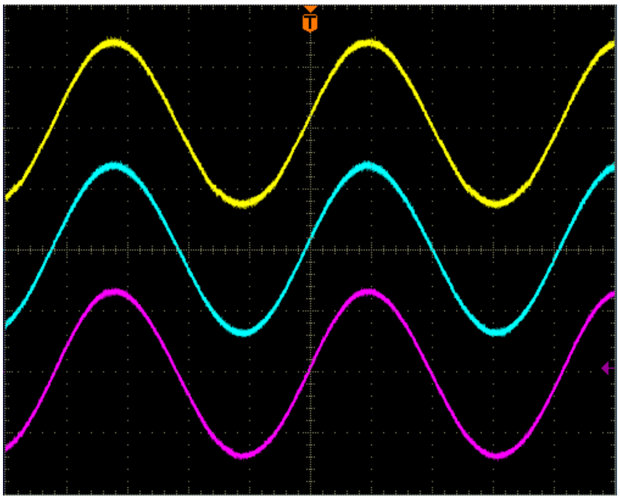

Fig. 12. Combined current:
Upper: i_A (10 [A/div]), middle: i_B (10 [A/div]),
lower: i_{AB} (20 [A/div]), time base: 4 [msec/div]

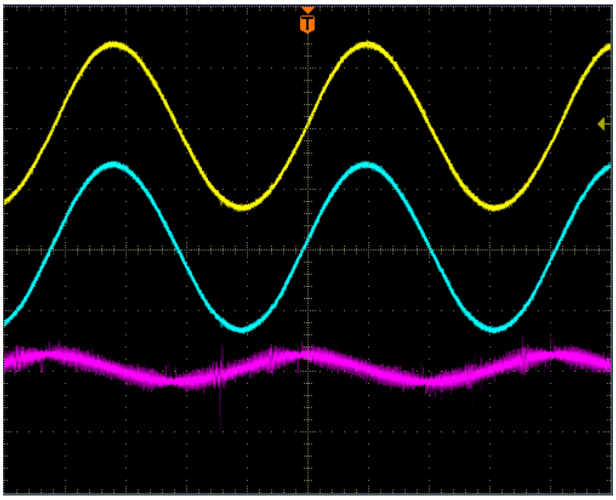

Fig. 13. Filter operation:
Upper: i_{AB} (20 [A/div]), middle: $i_{g'}$ (20 [A/div]),
lower: i_{Cf} (1 [A/div]), time base: 4 [msec/div]

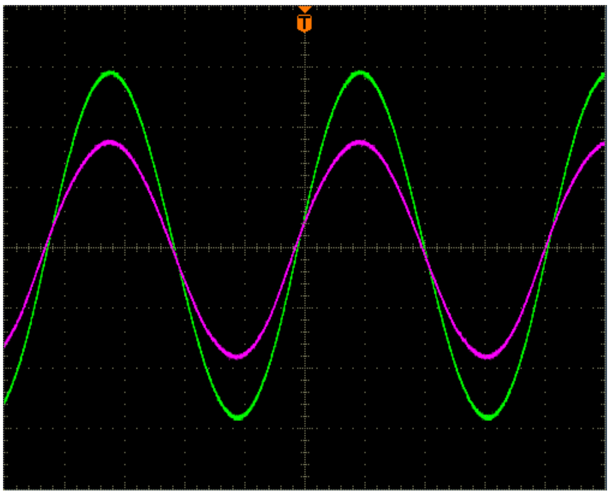

Fig. 14. Grid voltage and current:
Green: voltage v_g(100 [V/div]), pink: current i_g(5 [A/div]), time base: 4 [msec/div]

4. Conclusion

In this paper, the inverter system tied to a grid has been studied. The connecting filter size is minimized by using SiC FETs as switching devices. Four-phase carrier-based interleaved PWM is applied to the inverter system. Harmonic currents into the filter capacitor and the grid are greatly reduced. The proposal is verified through prototype system. We expect that this study contributes to grid connection systems.

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