Optimum Harmonic Reduction in the Multiple Parallel Grid-connected Inverters

Hussain Bierk, Ph.D.(lecturer) *

Abstract

the presence of low order harmonics in grid-connected renewable-energy inverter systems is undesirable and has many adverse impacts on the entire systems, so it is necessary to eliminate these harmonics to increase the system efficiency and stability. In this paper, the principle of power flow between the grid utility and the inverter(s) is reported and a single reference inverter is used employing conventional selective harmonic elimination pulse width modulation (SHEPWM) to eliminate the 5^{th} and 7^{th} harmonics. By adjusting a pre- calculated phase-shift angle between parallel inverters, it is also possible to eliminate other low order harmonics without any increase in the switching frequency. This approach has been applied for high power grid-connected voltage source inverter systems (VSI) supplied by renewable energy sources(such as wind energy, photovoltaic system,…etc) which are very sensitive to any increase in the switching frequency. Single, two, and four parallel VSI grid connected systems are investigated and simulated in PSPICE and MATLAB software.

Keyword: voltage source inverter (VSI), SHEPWM, 3-Phase PWM, high power inverters, low-order harmonics, grid-connected inverters.

*Al Iraqiya University

1. Introduction

The clean energy such as renewable energy sources which includes, but not limited to, wind turbines, geothermal energy, solar energy, and biomass energy has been attracting more attention in addition to its capability to connect to the AC supply grid-connected to voltage and/ or current source inverters. It is crystal clear that all inverters create some low-order harmonics which are harmful to the power system. Therefore, it is important to eliminate some of these low-order harmonics by available active and cost-effective control methods and then reduce the impacts of higher order harmonics using some traditional methods such as passive filters.

Selective harmonic elimination pulse width modulation (SHEPWM) is one of the most effective PWM approach and advance control to eliminate many of disruptive low-order harmonics [1]. Selective harmonic elimination is a type of programmed PWM and has been used broadly with the microprocessors. SHEPWM is one of the best strategies among the other control techniques using PWM such as space-vector modulation (SVM) and trapezoidal pulse-width modulation (TPWM) for low order harmonics elimination. One of the best characteristics of this method is that can be used as a control algorithm for deriving the gating signals for both current source inverters (CSI) and voltage source inverters(VSI) to reduce the undesirable impacts of low-order harmonics in high power low frequency applications [2]. Moreover SHEPWM, as with traditional 6-step inverter systems, has the ability to eliminate all triplen (multiples of three) harmonics in 3-phase inverter systems and thus can minimize the totalharmonic distortion (THD) in 3-phase inverter applications. In this paper the conventional SHEPWM technique has been used to control a single grid-connected inverter and also proposed a modified SHEPWM for grid connection of multiple parallel inverters.

Employing a three-level output voltage or current waveform SHEPWM technique is improved harmonic cancellation performance compared with the bi-level waveform [3]. Fig.1 depicts the conventional three-level SHEPWM waveform to eliminate two low-order harmonics in the output voltage waveform.

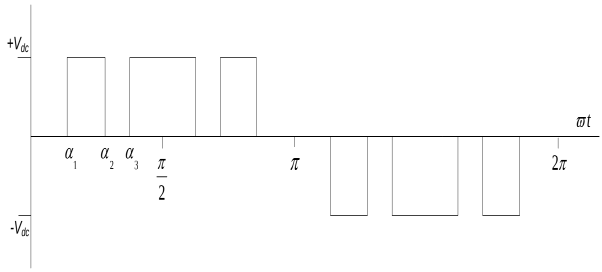

Fig.1 Three-level SHEPWM waveform

The above waveform can be analyzed by the Fourier series analysis as follows:

$$f(x) = \sum_{n=1}^{\infty} [a_n \sin nx + b_n \cos nx] \text{ ....(1)}$$

The Fourier series coefficients a_n and b_n are given as follows:

$$a_n = \begin{cases} \dfrac{4V_{dc}}{n\pi} \sum_{m=1}^{N} (-1)^{m+1} \cos(n\alpha_m) & n \text{ is odd} \\ 0 & n \text{ is even} \end{cases} \text{ ....(2)}$$

$b_n = 0$; where N is the number of the switching angles to be considered and V_{dc} is the inverter DC supply voltage.

From the above equation, the switching angles α_1, α_2, α_3 in Fig.1 can be estimated by solving the following three non-linear equations using a numerical solver. In order to eliminate the 5th and 7th harmonics, the Fourier coefficient a_5, and a_7 shall be set to zero. The coefficient a_1 is equal to the peak of the fundamental which is equal to modulation index MI.

$$a_1 = \frac{\pi}{4} (\cos\alpha_1 - \cos\alpha_2 + \cos\alpha_3) = MI$$

$$\cos\alpha_1 - \cos\alpha_2 + \cos\alpha_3 = \frac{\pi}{4} * (MI) \text{ .... (3)}$$

$$a_5 = \cos 5\alpha_1 - \cos 5\alpha_2 + \cos 5\alpha_3 = 0 \text{ .... (4)}$$

$a_7 = \cos 7\alpha_1 - \cos 7\alpha_2 + \cos 7\alpha_3 = 0$ ………………….. (5)

Therefore, to eliminate two low- order harmonics, it is required to solve three non-linear equations and to eliminate more harmonics, the number of these transcendental equations increases and the computational process will be more complicated.

2. Typical Grid-Connected One Inverter

This reference system consists of a 3-phase dc/ac inverter fed from a renewable DC power supply. The inverter has six insulated-gate bipolar transistors (IGBT) which are gated with a SHEPWM gate drive circuit (g1-g6). As shown in Fig. 2, the inverter and grid are connected through smoothing reactors.

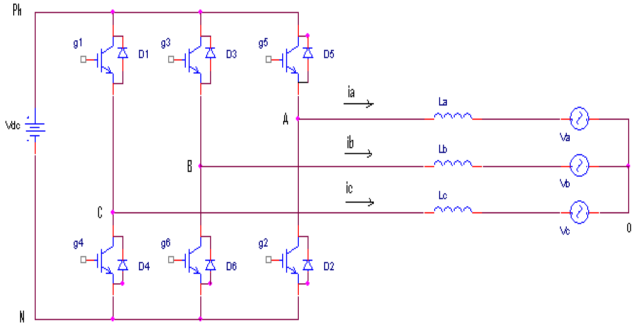

Fig.2 Schematic diagram of the grid connected VSI

To synchronize both inverter and utility grid, it is necessary to comply with these conditions:

1) The output voltage and frequency of the inverter(s) and utility grid should be equal. This is explained in detail in the following Sections.

2) The phase-sequence of all sources must be the same.

3. Principles Of Power Flow Between The Inverter(S) And The Utility Grid

The energy from the inverter to the utility grid will flow if the phase angle between both sources is shifted. If the inverter is represented by a single voltage source, then the equivalent diagram is as shown in Fig. 3.

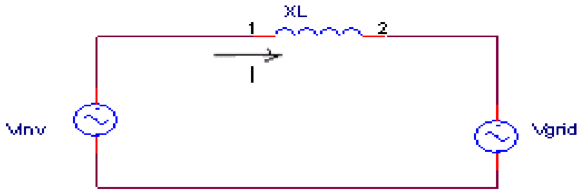

Fig.3 Equivalent circuit of inverter and the utility grid

Let V_{grid} and V_{inv} represent the RMS value of grid phase voltage and inverter phase voltage respectively, $\breve{E}_1$ is the instantaneous voltage of the inverter voltage, and $\breve{E}_2$ is the instantaneous grid voltage.

Hence

$$\breve{E}_1 = \sqrt{2}\ V \sin(\varpi t) \quad \text{.......................................(6)}$$

and

$$\breve{E}_2 = \sqrt{2}\ V \sin(\varpi t + \beta) \quad \text{................................ (7)}$$

; where β is the phase shift between inverter and the grid voltage and is referred to as load angle.

Hence, the instantaneous current $\breve{I}$ is:

$$\breve{I} = \frac{\breve{E}_1 - \breve{E}_2}{XL} \quad \text{..........................(8)}$$

Therefore, the total power flow from inverter to the power grid is:

$$P = \frac{V^2}{XL} \sin\beta \quad \text{.. (9)}$$

Let us consider the complex power =Z

then

$$Z = P + j\,Q \quad \text{...................................... (10)}$$

Let $\alpha = V_{inv} / V_{grid}$

β = the phase angle between V_{inv} and V_{grid}

$Z = 3\ V_{grid} \times I^*$ where I^* is a complex quantity of the current I.

Assume

V_1 = Grid line to line voltage = $\sqrt{3}\ V_{grid}$

V_2 = Inverter line to line voltage = $\sqrt{3}\ V_{inv}$

And $X_L = \omega L$

$$Z = V_1 * \frac{\alpha * V_1 \sin\beta}{XL} - jV_1 * \frac{V_1(1-\alpha\cos\beta)}{XL} \quad \text{.......................(11)}$$

The control of the power flow is totally depends on the reference value of P and Q and their actual values and for any differences between these values, both α and β will be adjusted.

4. Schematic Diagram Of Grid- Connected One Inverter System

The schematic-line diagram for the system is

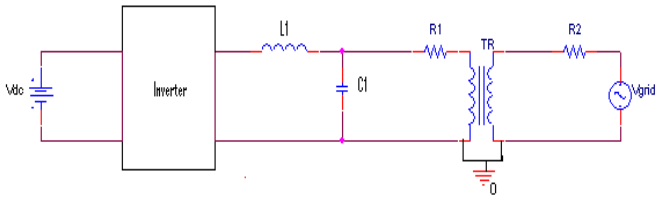

Fig.4 Schematic diagram of a grid-connected one inverter

With this topology, we have exploited the conventional SHEPWM technique to eliminate the 5th and 7th harmonics. It is worthy to know that all even harmonics and all triplen harmonics are eliminated completely. Note that these harmonics can not be eliminated 100% because of the discretization of the switching instances in simulation. The inverter is designed to deliver an output voltage of 4.16 kV and is boosted through transformer to the grid voltage which is 7.2 KV. The total harmonic distortion (THD) is a function of many parameters including the angle β, LC filter, resistors R1,R2, and modulation index (MI) and these values have been selected precisely to get optimum values of THD. In this paper the THD is calculated for different values of loading angle β and specific value of MI. The parameters for this topology are selected as shown in Table 1.

Table 1 Elements of the grid-connected single inverter

MI	L1	C1	R1	R2
0.8	2.00 mH	150 uF	8.00 Ω	0.3Ω

The output low-order current harmonics as a percentage of the fundamental frequency with $\beta = 5^{O}$ are shown in Table 2.

Table 2 The output current harmonics contents (in percent) with $\beta = 5^{O}$

Harmonic No.	PSpice	MATLAB
3rd	1.02	0.95
5th	1.85	1.78
7th	0.84	0.78
9th	0.38	0.36
11th	2.19	2.11
13th	14.89	14.78
15th	0.24	0.21
17th	6.88	6.80
19th	3.68	3.58
21st	0.18	0.16

The THD for 21 harmonics is = 6.95%
The THD for 200 harmonics is =11.02%

From this Table, It is obvious that there are differences in harmonics calculation between MATLAB software and PSpice. These differences are due to that fact that the MATLAB calculations are based on ideal assumptions but the PSpice is dealing with actual values.

Table (3) shows THD (200 harmonics) for different β using the parameters in Table 1.

Table 3 THD (in percent) for grid-connected one Inverter for different values of β (in degrees)

Angle(β)	PSpice	MATLAB
0.50	6.10	6.04
8.00	16.21	15.94
10.00	20.83	20.11
20.00	31.80	31.10

Generally as β increases, the THD also increases.
Fig.5 demonstrates the Fourier component magnitudes for all harmonics up to the 21th for this topology.

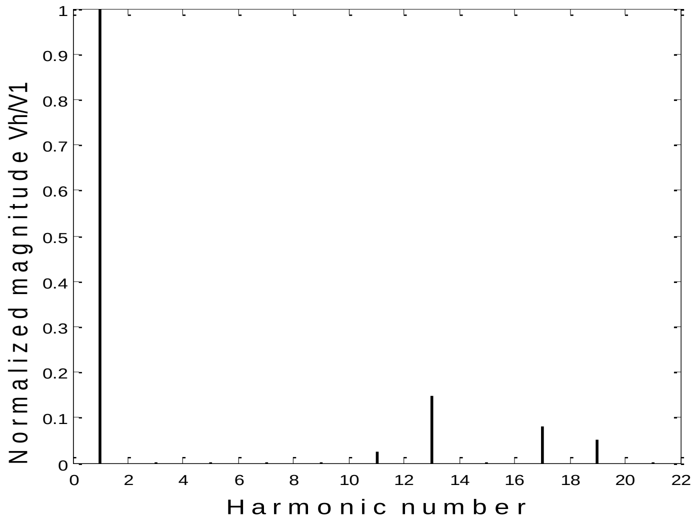

Fig.5 MATLAB simulation Fourier component magnitudes for the single VSI

5. Topology Of Grid-Connected 2-Parallel Inverters

Generally, in the case of grid-connected parallel-inverters, there are two essential issues to be considered:

1. The danger of improper current sharing among all units of the system.
2. The circulation current among the phases of the grid-connected parallel inverters.

There are many methods developed to solve the first issue [4, 5] but the simple and best one is a master and follower control strategy. While the circulating current issue is controlled by using inductors or reactors between the parallel inverters [6, 7].

The schematic diagram for the grid-connected two parallel inverters topology is depicted in Fig. 6.

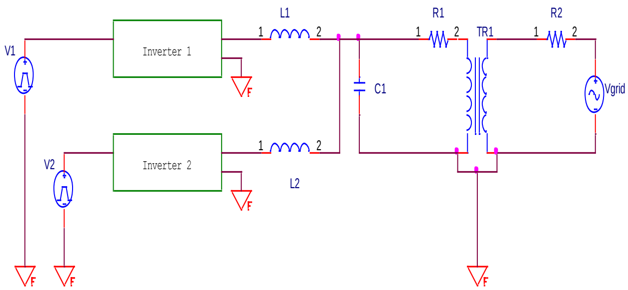

Fig.6 Schematic diagram of grid-connected two parallel inverters

In this scheme, we use a traditional SHEPWM to drive the first inverter to eliminate 5^{th} and 7^{th} harmonics, while the second inverter is gated with pre-calculated phase-shift angle (the phase-shift in this case is calculated to be equal to T/(2*11), where T is the period of the sine wave) to eliminate the 11^{th} harmonics. This technique is called the modified SHEPWM and therefore we can eliminate 5^{th}, 7^{th}, and 11^{th} harmonics by this method. Once again, the inverter output voltage delivered to the grid is 7.2KV pure sinusoidal waveform. The parameters of this arrangement are shown in Table 4.

Table 4 Elements of the grid-connected 2-parallel inverters

MI	L1	L2	C1	R1	R2
0.8	3.00 mH	3.00 mH	200uF	18.00Ω	0.26Ω

The output low-order current harmonics as a percentage of fundamental frequency with $\beta=5^{O}$ are shown in Table 5.

Table 5 The output current harmonics contents (in percent) with $\beta=5^{O}$

Harmonic No.	PSpice	MATLAB
3^{rd}	1.12	1.03

5th	1.12	0.98
7th	1.11	1.08
9th	0.30	0.22
11th	0.45	0.40
13th	0.64	0.58
15th	0.62	0.56
17th	2.49	2.41
19th	2.45	2.43
21th	0.55	0.52

The THD for 21 harmonics is = 3.25%
The THD for 200 harmonics is = 4.52%

Table (6) shows THD (200 harmonics) for different β using the parameters in Table 4.

Table 6. THD (in percent) for two grid-connected inverters for different values of β (in degrees).

Angle (β)	PSpice	MATLAB
0.5	2.62	2.38
8.00	8.12	8.05
10.00	10.89	10.13
20.00	19.35	19.08

It is clear that as β increases, the THD increases as well.

Fig.7 depicts the Fourier component magnitudes for all harmonics up to the 21th for this scheme.

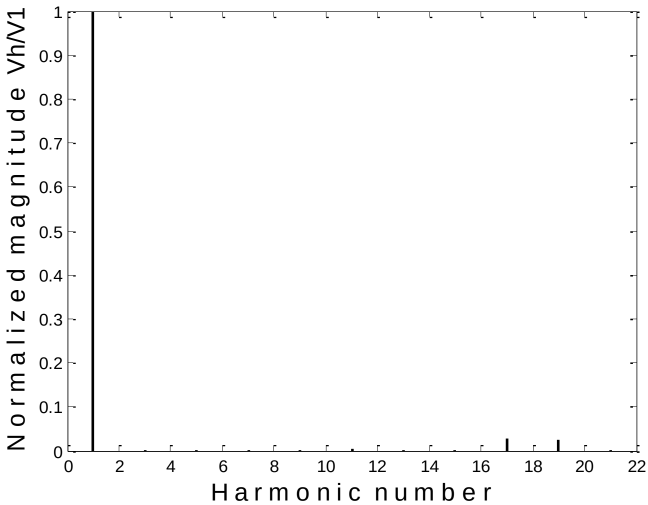

Fig.7 Simulation Fourier component magnitudes for the two parallel VSI

It is worthy to know that the output current harmonics and output voltage harmonics are equal because the harmonics have been measured across the resistor part of the inductive load.

6. Grid-Connected 4-Parallel Inverter System

The schematic diagram of the four parallel inverter topology is depicted in Fig.8.

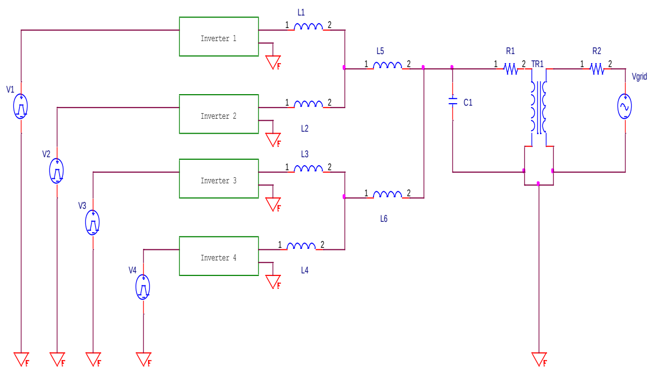

Fig.8 Schematic diagram of grid-connected 4-parallel inverters

For this approach, we use a modified SHEPWM technique to eliminate 5th, 7th , 11th with first two parallel inverters (as previously described) while second two parallel inverters is used to eliminate the 13th low order harmonics. So, this method is relevant to eliminate 5th, 7th, 11th, and 13th harmonics. The parameters of this arrangement are shown in Table 7

Table 7 Elements of the grid-connected 4-parallel inverters

MI	L1=L2	L3=L4	L5=L6	C1	R1	R2
0.8	3.00 mH	3.00mH	0.1mH	300uF	18.00 Ω	0.20 Ω

The output low-order current harmonics for this arrangement as a percentage of fundamental frequency with $\beta = 5^{O}$ are shown in Table 8

Table 8 The output current harmonics contents (in percent) with $\beta = 5^{O}$

Harmonic No.	PSpice	MATLAB
3rd	1.20	1.08
5th	0.50	0.45
7th	0.43	0.41
9th	0.30	0.27
11th	0.20	0.15
13th	0.21	0.18
15th	0.19	0.14
17th	0.16	0.12
19th	0.17	0.16
21st	0.13	0.10

The THD for 21 harmonics is = 2.50%
The THD for 200 harmonics is = 3.70%

Table (9) shows THD (200 harmonics) for different β using the parameters in Table 7.

Table 9 THD (in percent) for grid-connected 4-parallel inverters as a function of β (in degrees)

Angle (β)	PSpice	MATLAB
0.5	1.40	1.34
8.00	5.34	5.06
10.00	8.04	7.78
20.00	14.34	14.05

It is clear that as the number of parallel inverters is increased the THD decreases significantly.

7. Conclusions

A modified SHEPWM technique to drive multi parallel combinations of grid-connected voltage source inverters VSI is proposed to eliminate a critical low order harmonics namely, the 5^{th}, 7^{th} , 11^{th}, and 13^{th} and this results to improve the harmonic profile of the system. The selection of optimum phase shifting between parallel inverters driven by SHEPWM strategy, and a proper load angle β contributes to reduce the THD of the grid-connected VSIs and consequently to obtain a better quality of power and hence a clean energy.

The proposed novel SHEPWM methodology to eliminate low-order harmonics has proved to be an effective strategy in terms of reduction of mathematical complicity and long computational process through employing a minimum number of nonlinear transcendental and trigonometric equations required to eliminate such low order harmonics. Finally, the THD of the system is decrease significantly with increasing the number of parallel inverters.

References

[1] F. Zhang, and Y Yan "Selective Harmonic Elimination PWM Control Scheme on a Three-Phase Four-Leg Voltage Source Inverter" *IEEE Trans.*On Power *Electron.*vol. 24, no. 7, pp. 1682 – 1689, Jul. 2009.

[2] J. R. Espinoza, G. Joos, J. I. Guzman, L. Moran, and "Selective harmonic elimination and current/voltagecontrolin current/voltage source topologies: An unifiedapproach,"*IEEE Transactions Industrial Electronics,*

[3] H. Bierk, "Characterization of distortion reduction forsingle-phase multipleinverter operation," MSc thesis, University of Calgary, Canada, 2006.

[4] J. Reed and N. Sharma, "Large Parallel UPS Systems Utilizing PWM Technology" *INTELEC-84*, pp. 282- 289, Nov.1984.

[5] W. Lee, T. Lee, S. Lee, K. Kim, D. Hyun, and I. Suh, "A master and slave control strategy for parallel operation of three-phase UPS systems with different ratings," in*Proc. IEEE APEC*, Anaheim, CA, Feb. 2004, vol. 1, pp. 456–462.

[6] Y. Zhang. S. Duan, Y. Kang, and J. Chen," The restrain of harmonic circulating currents between inverters"*IEEE 5th International Power Electronics and Motion Control Conference (IPEMC*), vol. 2, pp.1-5, Aug. 2006.

[7] Z. Ye, D. Boroyevich, J. Choi, and F. C. Lee,"Controlof circulating currentin two parallel Three-phase boost rectifiers," *IEEE Trans. PowerElectron.*, vol.17, no. 5, pp. 609–615, Sept. 2002.

الطريقة المثالية لتخفيض التوافقيات في المحولات ذات ربط متعدد التوازي واالمرتبطة بالشبكة الكهربائية الرئيسية

م.د.حسين مصطفى بيرك*

المستخلص

وجود التوافقيات ذات الترتيب العددي المنخفض في انظمة محولات الكترونيات القدرة للطاقة المتجددة المتصلة بالشبكة الكهربائية الرئيسية غير مرغوب فيه وله العديد من الآثار السلبية على النظم، لذلك فمن الضروري ازالة هذه التوافقيات لزيادة كفاءة النظام والاستقرار.في هذا البحث تم شرح فكرة انتقال القدرة بين المحول والشبكة للكهربائيةويستعمل محول واحد كاساس مستخدماالطريقة التقليدية لتعديل العرضي للنبض لازالة التوافقياتالخامسة والسابعة. وعند ربط المحولات على التوازي وبوجود فرق في الطور الزاوي بين كل مجموعة واخرى نتمكن من ازالة التوافقات الاخرى بدون زيادة تردد التبديل. وتم تطبيقهذه الفكرة على محولاتمصدر الفولتية(VSI) والمغذى بواسطة مصادر الطاقة البديلة والتي تكون حساسة لاي زيادة في تردد التبديل . في هذا البحث تم استخدام منظومة احادية ومنظومتين متوازيتين وكذلك اربعة منظومات متوازيه لغرض التحقيق من صحة تطبيق الفكرة المذكورة وتم اجراءالتجربة والفحص بواسطة البرامج PSPICE و MATLAB

*الجامعة العراقية