Proceedings Paper:

Asi, AU, Chong, B, Zhang, L et al. (1 more author) (2020) A Single-Stage Z-source Inverter for Transformerless Grid Connection with a Proportional-Resonant Controller for DC Current Elimination. In: PEDG2020 Proceedings. IEEE 11th International Symposium on Power Electronics for Distributed Generation Systems, 28 Sep - 01 Oct 2020, Dubrovnik, Croatia. IEEE . ISBN 9781728169903

https://doi.org/10.1109/PEDG48541.2020.9244418

A Single-Stage Z-source Inverter for Transformer-less Grid Connection with a Proportional-Resonant Controller for DC Current Elimination

Asi, A U
School of Electronic and Electrical Engineering
University of Leeds
Leeds, United Kingdom
el15aoua@leeds.ac.uk

Chong, B
School of Electronic and Electrical Engineering
University of Leeds
Leeds, United Kingdom
b.chong@leeds.ac.uk

Zhang, L
School of Electronic and Electrical Engineering
University of Leeds
Leeds, United Kingdom
l.zhang@leeds.ac.uk

Nkanu, J
School of Electronic and Electrical Engineering
University of Leeds
Leeds, United Kingdom
eljen@leeds.ac.uk

Abstract— The ever-rising number of grid-connected inverters contributes to an increase of DC current injection into utility grid, resulting in the saturation of distribution transformers, metering errors and the corrosion of earthling conductors. A transformer-less single-stage Z-source inverter uses only two switching devices in its converter circuit to generate sinusoidal voltage as that of a full-bridge inverter. However, this inverter has the problem of having a DC offset in the AC waveform due to the presence of steady-state error when the modulation index is varied. The paper proposes a Proportional-Resonant (PR) control scheme to eliminate this DC offset. By comparing Z-source inverter output voltage with the sinusoidal reference voltage obtained from the sinusoidal control signal, an error signal is obtained which is fed into the PR controller. An infinite gain at the fundamental frequency is introduced by the PR controller, thus achieving zero steady-state error resulting in the elimination of DC current injection into the utility grid. This method does not depend on high-precision current measurement or the use of coupled inductors. Also, this method can be used to improve power quality by providing reactive power compensation to the load at the point of common coupling. Simulation results are presented to confirm that this simple, cost-effective method can be used to eliminate DC current injection for different values of modulation index without compromising the dynamic response of the current feedback loop

Keywords— transformer-less grid-connected inverter, DC offset injection, single-stage Z-source inverter, proportional resonant controller

I. INTRODUCTION

The application of renewable energy systems (RES) such as photovoltaic (PV) cell, wind turbine and fuel cells for distributed power generation in the utility grid have seen development of variety of converter topologies [1] [2]. Many of them are direct current to direct current (DC-DC) types since the RSGs generate DC voltages, however for supplying power to grid, direct current to alternating current (DC-AC) inverters are essential.

One way to classify inverters for grid-connected applications is by whether there is galvanic isolation. Those achieving galvanic isolation connect to the grid lines through low-frequency transformers at the output of the inverter, or a DC-DC converter (containing a high-frequency transformer) at the input [1] [2] [3]. The ones directly connected to the grid without transformers are called transformer-less inverters. Although the isolated inverters provide benefits of boosting capability and galvanic isolation, they have drawbacks in losses, size, high cost and complexity. Transformer-less inverters have become a mainstream market alternative, especially in low-voltage utilities, being cheaper, smaller, lighter and more efficient (about 4% better than transformer-based inverters) [1]. However, without galvanic isolation, problems of common-mode leakage current and DC current injection arise and can severely threaten normal operation of the utility grid.

Many novel topologies have been proposed to eliminate the common-mode leakage current, which solve concerns about safety and electromagnetic interference (EMI) arising from the resonant leakage current [4]-[10]. Among these, the impedance source (Z-source) inverter topologies [8]-[10] has received growing interest. One of them proposed in [10], the single-stage Z-source inverter, is particularly advantageous. With only two switching devices and unique LC network, this topology can produce a single-phase sinusoidal voltage with variable frequency and magnitude like a traditional voltage sourced four-switch full bridge (H-bridge) circuit. Using doubly grounded features, it can minimise the common-mode leakage current and so, improve system reliability and efficiency, and reduce cost.

However, using this inverter for grid-connection of RES allows unwanted DC current injection into the grid, which poses a significant concern [11]. This is caused by several reasons such as asymmetry in the switching of the semiconductor devices, quantization errors in digital systems, non-ideal semiconductor device characteristics, small DC bias in current reference signals and non-linearity and offset drift in Hall-effect transducers [12]-[14]. Deleterious effects may include saturation of distribution transformers with distortion of their magnetizing current, increase of iron losses, metering errors and corrosion of earthing conductors. A recently proposed solution [15] to DC current injection for Z-source inverters uses coupled inductors; however, the study of the required turns ratios and leakage inductance remains inconclusive.

This paper presents a closed-loop control strategy which incorporates a proportional-resonant (PR) controller to monitor the inverter output voltage and introduces an infinite gain at the fundamental frequency to achieve zero steady-state error, resulting in the elimination of DC current injection into the AC network. The circuit operation, proposed closed-loop control method and simulation results are discussed below.

II. Operating Principle of the Transformer-less Single-Stage Impedance Source Inverter

The Z-source DC-DC converter with its doubly grounded feature is shown in Fig. 1 [10]. The continuous voltage gain curve of this converter is shown in Fig. 2 and is used to output the positive and negative voltage at the output. By changing the duty cycle of S1, D from 0 to 1 and providing proper modulation technique, this converter can be used as an inverter with $-V_g$ to V_g at the output just like the traditional full bridge inverter. Fig. 3 and 4 shows the transformer-less single-stage Z-source inverter and its duty cycle operation respectively. From Fig. 4, it can be seen that when D changes from (0 – 1/2), the inverter can output positive voltage while from (1/2 – 2/3) the output voltage is negative. When the duty cycle is equal to 1/2, the inverter outputs zero voltage [10].

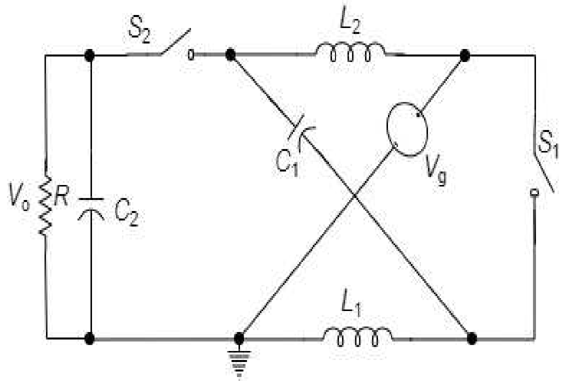

Fig. 1 Z-source DC-DC converter [10]

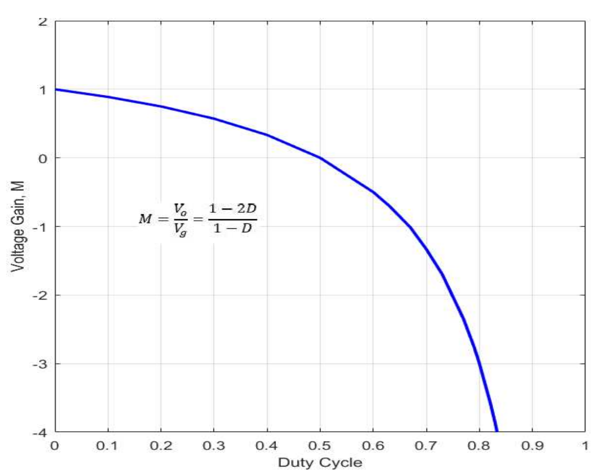

Fig. 2 Voltage gain curve [10]

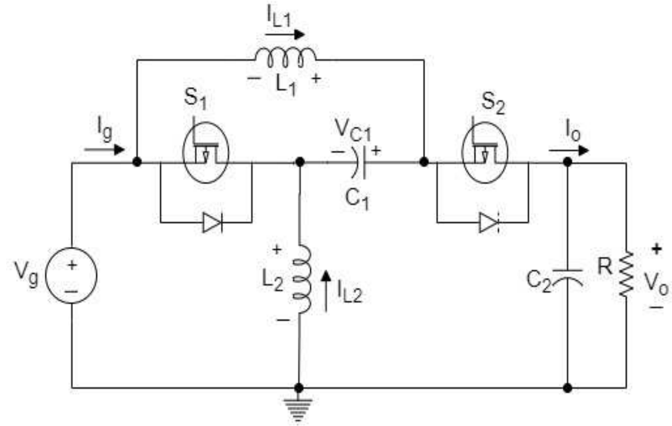

Fig. 3 Transformer-less single-stage Z-source inverter [9]

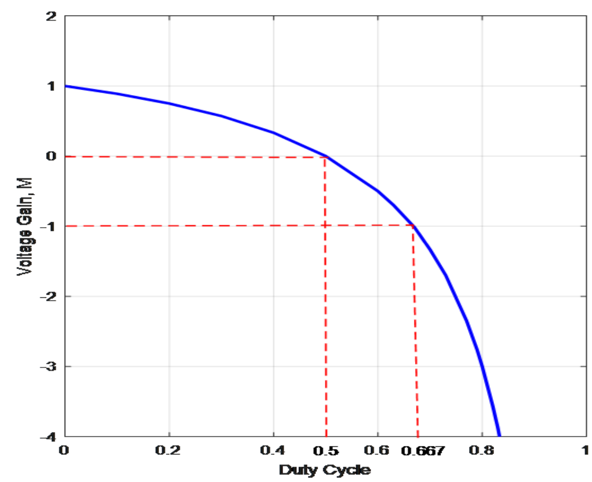

Fig. 4 Duty cycle operation of transformer-less single-stage Z-source inverter [10]

Fig. 5 and Fig. 6 shows two modes of operation. In mode 1: S1 is ON, the input DC source V_g charges the inductor L2 and capacitor C1 charges the inductor L1. In mode 2: S2 is ON, L2 charges C1 and C2 and L1 charges C1 and V_g.

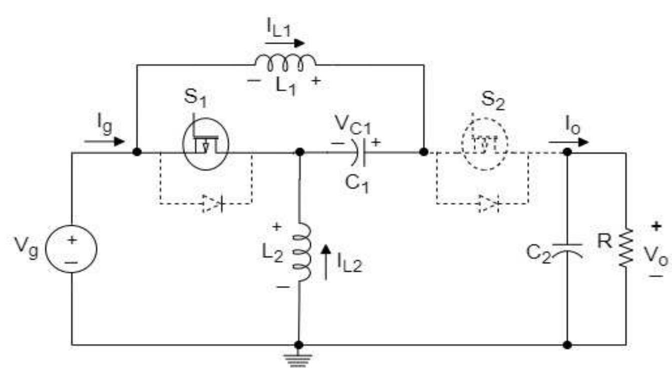

Fig. 5 Mode 1: S1 = ON, S2 = OFF [9]

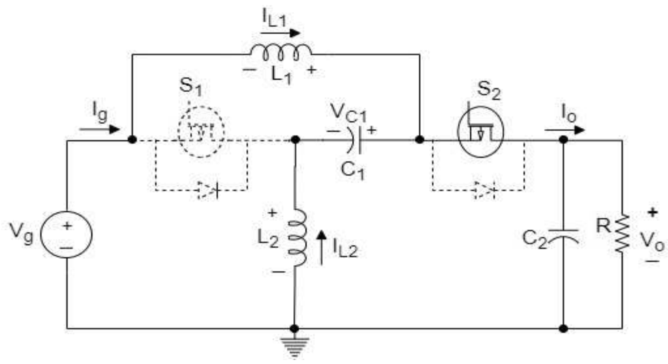

Fig. 6 Mode 2: S2 = ON, S1 = OFF [9]

Details of the DC operation modes of this circuit is shown in [9]. According to the inductor voltage-second and capacitor charge balance principle, the steady-state equations are derived as follows;

$$M = \frac{V_o}{V_g} = \frac{1-2D}{1-D} \quad (1)$$

$$V_{C1} = \frac{D}{1-D}(V_g - V_o) \quad (2)$$

$$I_{L1} = I_O \quad (3)$$

$$I_{L2} = \frac{D}{1-D} I_O \quad (4)$$

Assuming the inverter output voltage is represented as

$$V_O = \hat{V}_{ac} sin\omega t \quad (5)$$

Then, the modulation index can be represented as

$$M = \frac{\hat{V}_{ac}}{V_g} \quad (6)$$

The duty cycle, D of switch S1 is derived by combining (1), (5) and (6), to obtain

$$D = \frac{1 - Msin\omega t}{2 - Msin\omega t} \quad (7)$$

The duty cycle of switch S2 is defined as D' = 1−D represented in (8) as

$$D = \frac{1}{2 - Msin\omega t} \quad (8)$$

III. Control of Tranformer-less Single-stage Grid-connected Z-source Inverter with DC Current Elimination

The transformer-less single-stage grid-connected Z-source inverter is shown in Fig. 7. This paper improves on [10] by incorporating a closed-loop voltage oriented control (VOC) technique to enable the integration of a grid-connected PV system and elimination of the inherent DC current injection. The VOC technique is used transfer power from the single-stage Z-source inverter to the grid. This technique is based on independent control of active and reactive powers using the synchronous reference (dq) frame which rotates at angular speed ω [1]. The dq frame is synchronized with grid voltage vector through a phase locked loop (PLL) technique. An enhanced second order generalised integrator PLL (SOGI-PLL) has been used to achieve the grid synchronization. The controlled current source (CCS) at the input is used to model a solar PV panel. The DC voltage controller maintains the DC bus capacitor voltage (V_{DC}) at the required reference value and regulates active power flow at the output of the CCS. The current controller is used to regulate active and reactive power flow to the grid. The output of the current controller and SOGI-PLL are used to control the PWM switching of the single-stage Z-source inverter.

The DC current injection controller senses the DC component in the single-stage Z-source inverter output and set it to zero. A comparator at the input of the DC current injection continuously compares the inverter output voltage with the sinusoidal reference voltage obtained from the sinusoidal control signal control for steady-state errors, generated mainly due to variation of modulation index. The error signal is then fed to the PR controller which introduces an infinite gain at fundamental frequency, thus achieving zero steady-state error [16]. This results in the elimination of DC injection current in the AC network. The transfer function of the ideal PR controller is given by (9) [16].

$$G_{PR}(s) = K_p + \frac{2K_I s}{s^2 + \omega_o^2} \quad (9)$$

Where K_p and K_I are proportional and resonant gains respectively and ω_o is resonant frequency. The bandwidth, phase and magnitude of the controller is determined by K_p while K_I eliminates the steady-state error [16]. Optimal values of the PR's tuning parameters have been selected based on trial and error. For practical systems, the infinite gain associated with the ideal case causes stability problems [17]. Alternatively, a non-ideal PR controller with the transfer function in (10) can be used to obtain a finite gain in order to improve the performance of the controlled system.

$$G_{PR}(s) = K_p + \frac{2\omega_c K_I s}{s^2 + 2\omega_c s + \omega_o^2} \quad (10)$$

Where ω_c is the cutoff frequency introduced to reduce sensitivity towards variation of grid fundamental frequency and add more flexibility for selecting the bandwidth around the resonant frequency [17].

Conventional Z-source inverters generate sinusoidal voltage at its output using sinusoidal pulse width modulation (SPWM) with bipolar switching technique. That is, a sinusoidal voltage reference ($V_{control}$) at the desired inverter output frequency (f_m) is compared with a triangular waveform (V_{tri}) at a higher constant switching frequency (f_s), which then produces gating signals for the switches. However, the transformer-less single-stage Z-source inverter has a non-linear relationship between the voltage gain and duty cycle. Thus, a modified non-linear sinusoidal voltage reference defined in (7) and (8) is used generate switching pulses for S1 and S2 respectively. When these modified reference signals are greater than the triangular carrier signal, the switches are turn on and vice versa as shown in Fig. 8.

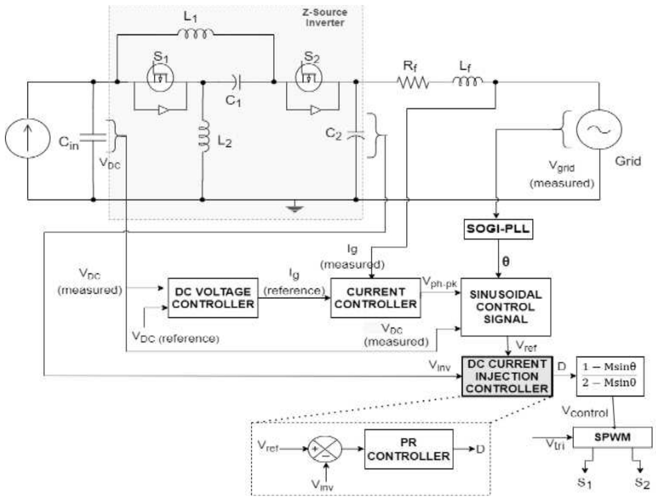

Fig. 7 Transformer-less single-stage Z-source inverter with proposed modified control signal

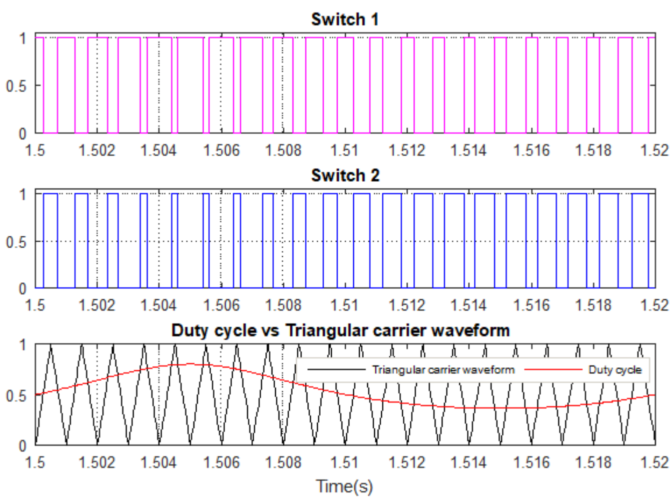

Fig. 8 Modified SPWM technique for transformer-less single-stage Z-source inverter

IV. Simulation Results

Simulation parameters used for this system are listed in Table 1. Fig. 9(a), 12(a) and 15(a) shows the grid current, grid voltage, inverter output voltage and modulation index without the PR controller while Fig. 9(b), 12(b) and 15(b) are with the PR controller. Fig. 10, 13 and 16 shows the fast Fourier Transform (FFT) analysis without the PR controller while Fig. 11, 14 and 17 are with the PR controller. The DC current injection causes an offset in the grid current as shown in Fig. 9(a), 12(a) and 15(a). This offset is the difference between the vertical (Y-axis) maxima and minima. A current of 7A, 2.6A and 0.25A was set for the CCS resulting in a modulation index of 0.6, 4.2 and 0.24 respectively. The grid current of Fig. 9(a) shows a DC current injection of 3.7% above the fundamental current amplitude. The total harmonic distortion is 12.09% as shown in Fig. 10. Incorporating the PR controller with K_p = 0.0016 and K_I = 0.75, the DC current injection is eliminated and the THD of the grid current is reduced as shown in Fig. 9(b) and 11 respectively.

Table 1 Simulation parameters

Parameter	Description	Values
V_{DC}	Input DC voltage	500 V
Vgrid	Grid voltage	110 Vrms
f_{nom}	Nominal frequency	50 Hz
f_s	Switching frequency	20 kHz
Cin	Input Capacitance	6000 μF
L1, L2	Z-source network inductance	3 mH
C1, C2	Z-source network capacitance	10 μF
Lf	Filter inductance	2 mH
Rf	Filter resistance	5 Ω
K_p	Proportional gain	0.0016
K_I	Resonant gain	0.5

The grid current of Fig. 12(a) shows a DC current injection of about 8.4% above the fundamental current amplitude when the modulation index is changed to 0.42. The THD is 9.64% as shown in Fig. 13. Integrating a PR controller with K_p = 0.0016 and K_I = 0.75, the DC current injection is eliminated and the THD of the grid current is reduced as shown in Fig. 12(b) and 14 respectively.

When the modulation index is changed to 0.24, the grid current of Fig. 15(a) shows a DC current injection of about 16.61% above the fundamental current amplitude. The THD is 8.69% as shown in Fig. 16. Integrating a PR controller with K_p = 0.0013 and K_I = 0.5, the DC current injection is eliminated and the THD of the grid current is reduced as shown in Fig. 15(b) and 17 respectively. The results presented below show that DC current injection increases with lower values of modulation index.

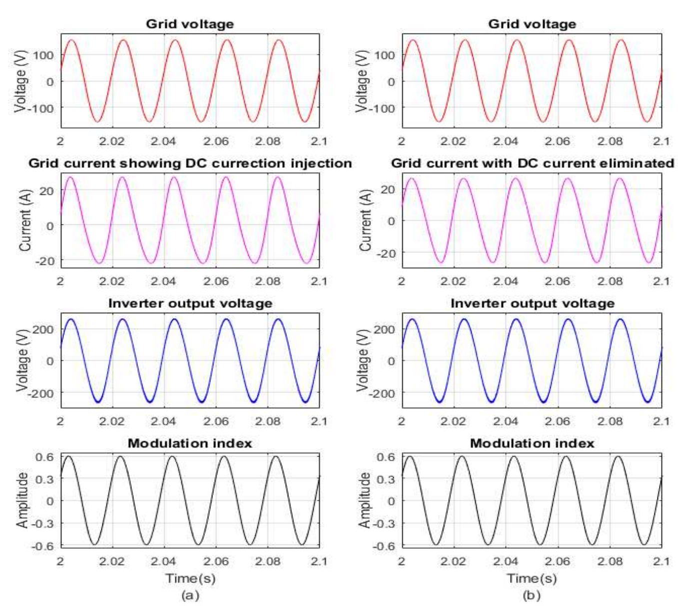

Fig. 9 Grid voltage, grid current, inverter output voltage and modulation index set at 0.6 (a) without PR controller (b) with PR controller

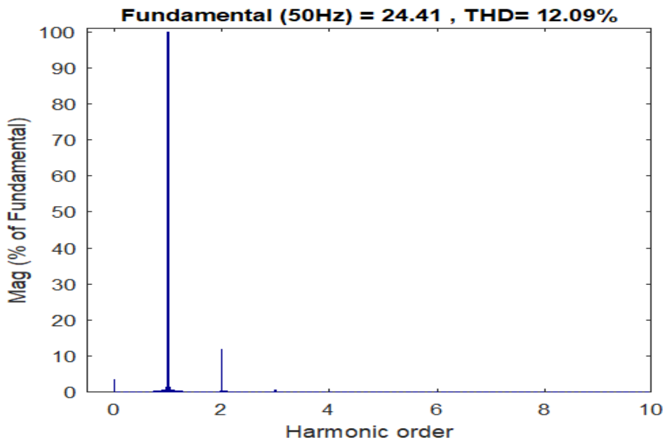

Fig. 10 FFT analysis of grid current without PR controller and M = 0.6

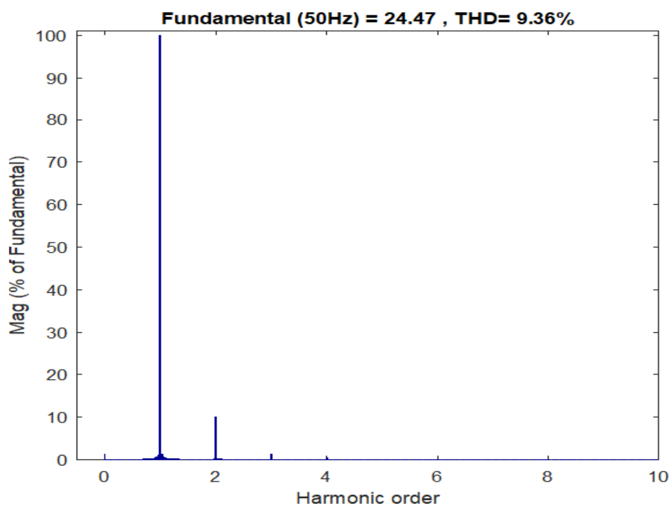

Fig. 11 FFT analysis of grid current with PR controller and M = 0.6

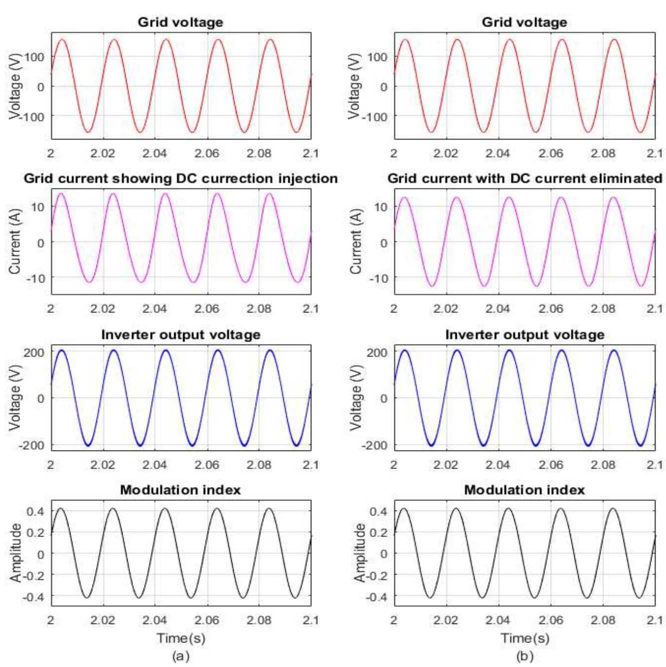

Fig. 12 Grid voltage, grid current, inverter output voltage and modulation index set at 0.42 (a) without PR controller (b) with PR controller

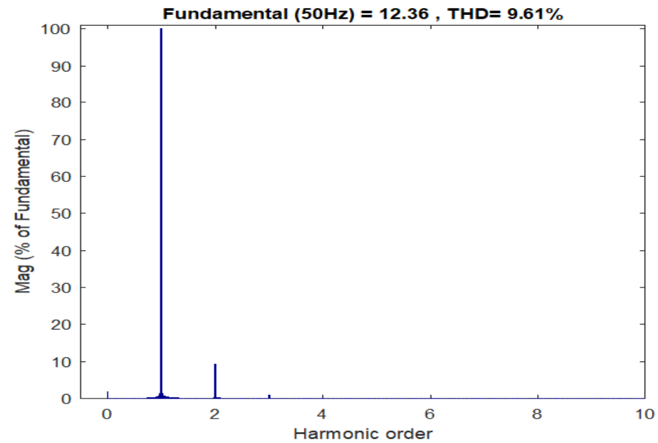

Fig. 13 FFT analysis of grid current without PR controller and M = 0.42

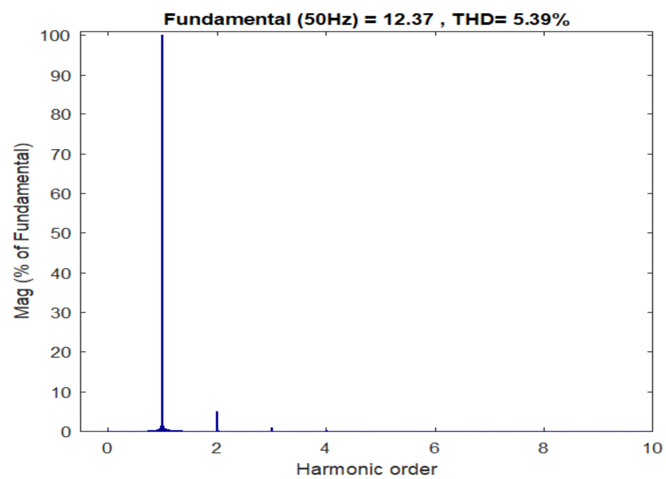

Fig. 14 FFT analysis of grid current with PR controller and M = 0.42

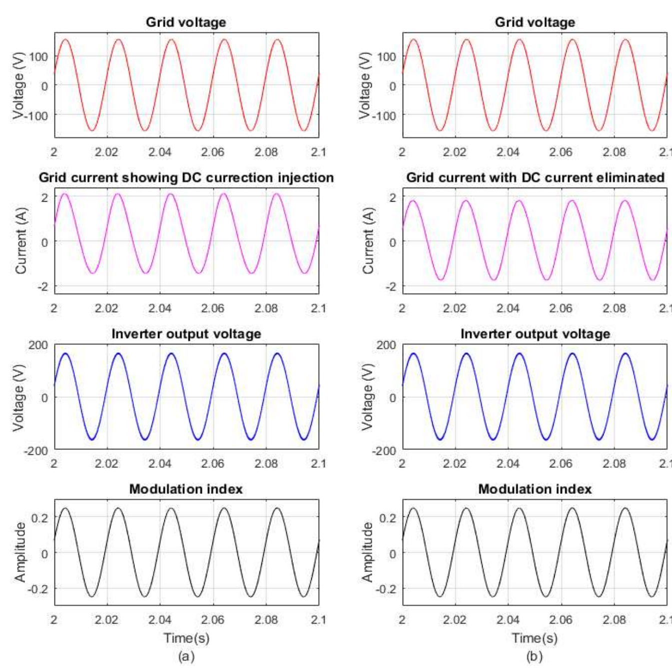

Fig. 15 Grid voltage, grid current, inverter output voltage and modulation index set at 0.24 (a) without PR controller (b) with PR controller

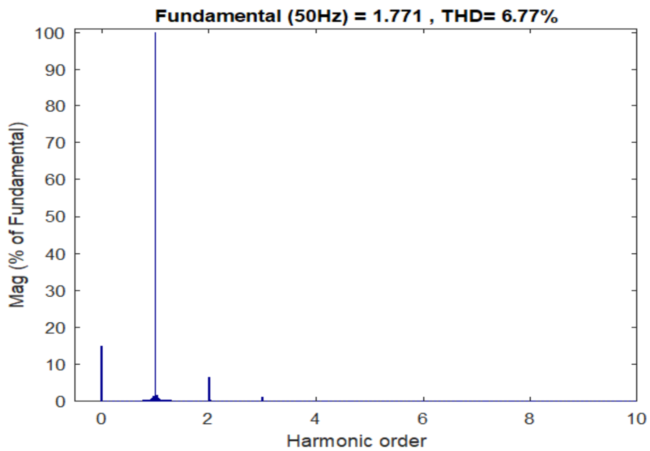

Fig. 16 FFT analysis of grid current without PR controller and M = 0.24

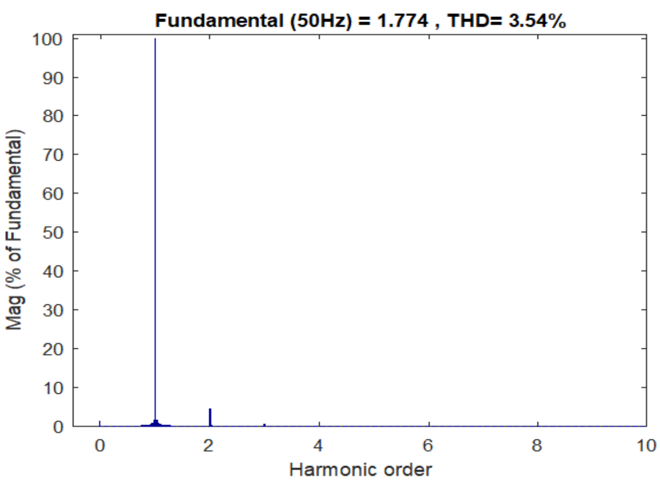

Fig. 17 FFT analysis of grid current with PR controller and M = 0.24

V. CONCLUSION

This paper improves on the Z-source inverter in [10] by incorporating a closed-loop VOC mechanism to enable the integration of a grid-connected PV system and elimination of the inherent DC current injection using a PR controller. The PR controller monitors the inverter output voltage and introduces an infinite gain at the fundamental frequency to achieve zero steady-state error, resulting in the elimination of DC current injection into the AC network. Simulations results confirm that this simple, cost-effective method can eliminate DC current injection for varying modulation index without compromising the dynamic response of the current feedback loop as well as a reduction in the THD of the grid current.

REFERENCES

[1] R. Teodorescu, M. Liserre and P. Rodríguez, “Photovoltaic Inverter Structures.” in: Grid Converters for Photovoltaic and Wind Power Systems. Chichester: John Wiley, 2011

[2] M. Calais, J. Myrzik, T. Spooner, and V. G. Agelidis, “Inverters for single-phase grid connected photovoltaic systems—An overview,” in Proc. IEEE PESC’02, vol. 2, 2002, pp. 1995–2000.

[3] S.B Kjaer, J. K. Pederson and F. Blaabjerg. “A review of single-phase grid-connected inverters for photovoltaic modules,” IEEE Trans Ind Appl, vol 48, no. 5, pp. 1292-1306, 2005.

[4] E. Koutroulis and F. Blaabjerg, "Design optimization of transformerless grid-connected PV inverters including reliability," IEEE Transactions on Power Electronics, vol. 28, no. 1, pp. 325-335, 2013.

[5] O. Lopez, F. D. Freijedo, A. G. Yepes and P. Fernández-Comesaña, "Eliminating ground current in a transformerless photovoltaic application," IEEE Transactions on Energy Conversion, vol. 25, no. 1, pp. 140-147, 2010.

[6] B. Yang, W. Li, Y. Gu, W. Cui, and X. He, "Improved transformerless inverter with common-mode leakage current elimination for a photovoltaic grid-connected power system," IEEE Transactions on Power Electronics, vol. 27, no. 2, pp. 752-762, 2012.

[7] L. Zhang, K. Sun, Y. Xing, and M. Xing, "H6 Transformerless full-bridge PV grid-tied Inverters," IEEE Transactions on Power Electronics, vol. 29, no. 3, pp. 1229–1238, Mar. 2014.

[8] F. Z. Peng, "Z-source inverter," Conference Record of the 2002 IEEE Industry Applications Conference. 37th IAS Annual Meeting (Cat. No.02CH37344), Pittsburgh, PA, USA , Vol.2, pp. 775-781, 2002

[9] D. Cao and F. Z. Peng, "A Family of Z-source and Quasi-Z-source DC-DC Converters," Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition, Washington, DC, pp. 1097-1101, 2009.

[10] D. Cao, S. Jiang, X, Yu and F. Z. Peng, “Low-cost semi-Z-source inverter for single-phase photovoltaic systems,” IEEE Trans. Power Electronic, vol. 26 no. 12, pp. 3514-2523, 2011.

[11] L. Gertmar, P. Karlsson, and O. Samuelsson, "On DC injection to AC grids from distributed generation," Proceedings of European Conference on Power Electronics and Applications, pp. 1-10, 2005.

[12] Q. Yan, X. Wu, X. Yuan, Y. Geng, and Q. Zhang, "Minimization of the DC component in transformerless three-phase grid-connected photovoltaic inverters," IEEE Transactions on Power Electronics, vol. 30, pp. 3984-3997, 2015

[13] M. Armstrong, D. J. Atkinson, C. M. Johnson, and T. D. Abeyasekera, "Auto-calibrating DC link current sensing technique for transformerless, grid connected, H-bridge inverter systems," IEEE Transactions on Power Electronics, vol. 21, pp. 1385-1393, 2006

[14] G. Buticchi, E. Lorenzani, and G. Franceschini, "A DC offset current compensation strategy in transformerless grid-connected power converters," IEEE Transactions on Power Delivery, vol. 26, pp. 2743-2751, 2011.

[15] A. Tofael and F. Mekhilef. Semi-Z-source inverter topology for grid-connected photovoltaic system. IET Power Electron, vol. 8, no. 1, pp. 63-75, 2015.

[16] R. Teodorescu and F. Blaabjerg. “Proportional-resonant controllers. A new breed of controllers suitable for grid-connected voltage-source converters,” IEEE Proceedings, vol. 3, pp. 9-14, 2004.

[17] D. N. Zmood and D. G. Holmes. “Statonary frame current regualator for PWM inverters with zero steady-state error,” in IEEE Transactions on Power Electronics, vol. 18, no. 3, pp. 814-822, 2003.