A Modified Droop Control Method for Parallel-Connected Current Source Inverters

Wei, Baoze; Guerrero, Josep M.; Quintero, Juan Carlos Vasquez; Guo, Xiaoqiang

Published in:
Proceedings of IECON 2016: The 42nd Annual Conference of IEEE Industrial Electronics Society

DOI (link to publication from Publisher):
10.1109/IECON.2016.7793804

Publication date:
2016

Document Version
Early version, also known as pre-print

A Modified Droop Control Method for Parallel-Connected Current Source Inverters

Baoze Wei, Josep M. Guerrero, Juan C. Vásquez
Department of Energy Technology
Aalborg University
Aalborg, Denmark
bao@et.aau.dk, joz@et.aau.dk, juq@et.aau.dk
www.microgrids.et.aau.dk

Xiaoqiang Guo
Department of Electrical Engineering
Yanshan University
Qinhuangdao, China
gxq@ysu.edu.cn

***Abstract*—This paper proposes a novel control method for current source inverters under the grid-connected working mode. The control scheme is based on a modified droop control method, with an additional current reference signal that will be generated instead of the voltage reference. Hence, there is only a current control loop with droop control in the whole control scheme without voltage control loop. So it is very suitable for grid-connected current source inverter which will simplify the design of the control scheme and combine the advantage of droop control. The parallel configuration is widely used to acquire high power demand, but the circulating current problem is a key issue that should be considered. In this paper, a simulation based on parallel current source inverters using the proposed control scheme is provided. Simulation results showed that a good circulating current suppression capability of the proposed control scheme is obtained with a proper controller design.**

Keywords—droop control; current-source inverter; grid-connected; circulating current

I. INTRODUCTION

Distributed generation (DG) systems based on renewable energy sources, such as photovoltaic arrays, fuel cells, or small wind turbines, are attracting the market and research interest as a feasible choice in a sustainable development environment [1-3]. In this case, it is necessary to use intelligent power interfaces between the electrical generation sources and the grid. These interfaces have a common final stage consisting of dc/ac inverters. The performance of the inverters in a distributed generation system working as an interface between the utility grid and distributed power sources is a key issue that to be considered. And new control strategies and power architectures are needed to deal with high power demand. Increasing the system's capacity by connecting inverters in parallel is a well-known solution [4-8]. The power inverters are connected to a common AC line to feed power to the grid or supply the distributed loads.

The inverters can be classified into current-source inverters (CSIs) and voltage-source inverters (VSIs), and there is another type of inverter called impedance source inverter [9] which was proposed in the year 2002. But the VSI and CSI are still being used as the preferred topology in wide range of applications. The CSIs are commonly used to inject current to the grid directly. The current-source inverter (CSI) offers advantages over voltage source inverter (VSI) in terms of inherent boosting and short-circuit protection capabilities, direct output current controllability, and ac-side simpler filter structure [10], [11]. These features make it attractive in many applications [12], such as high speed elevators, high-power electric drives and distributed generation systems as an interface between the utility grid and distributed power sources [13]. The topology of CSI is shown in Fig.1. It consists of six IGBTs and six diodes to avoid current flowing from AC side to DC side. But with the rapid developments of the reverse-blocking IGBTs, the CSI may become a potentially predominant choice due to reduced conduction losses [14]. As the rating of switching devices is often limited or constrained by technical or economic considerations, parallel architecture is often adopted to increase the power rating. In a parallel system, one of the main problems is the circulating current [15-17].

A traditional current-sharing solution is the frequency and voltage droop method with the feature of wireless control among the parallel units [18-20]. There are many reviews on the control strategies in inverter-based applications. The role of the controller in parallel inverters is to have good current sharing while maintain the system stability. Also the controller must achieve synchronization, and to guarantee that the frequency and the voltage are within the allowed limits, the control strategies can be classified into centralized, master-slave, decentralized and distributed control strategies [21].

As one of the decentralized control methods, droop control is suitable for modular design of distributed generation system. The main idea of the droop control is to regulate the voltage and the frequency by regulating the reactive and the active power respectively which can be sensed locally. The droop control method has many desirable features such as expandability, modularity, redundancy, and flexibility.

For a grid-connected inverter system, the main purpose is to inject current to the grid, and the grid voltage is uncontrollable, but the amplitude, frequency and phase information of the grid voltage can be used in the control loop. So the idea of this paper is to modify the traditional droop control to generate reference currents instead of voltage, then to simplify the control loops by using just one current control loop. By using the proposed modified method, it can combine the advantages of the droop control and the easy design of the controllers. And with proper design of the current controller, a good current sharing performance can be obtained.

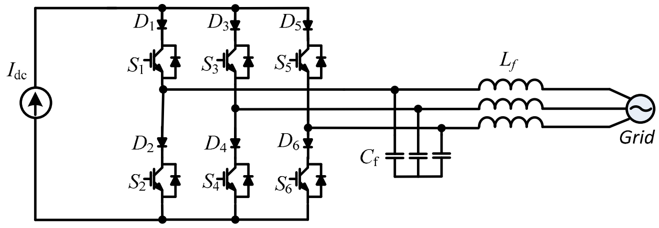

Fig. 1. Topology of the current source inverter.

This paper is organized as follows: In Section II, the concept of the traditional droop control is briefly introduced firstly, then the idea of the modified droop control is given and the circulating current analysis for paralleled current source inverters is discussed. In Section III, simulation results are implemented which verify the effectiveness of the presented idea. The conclusions are given in Section IV.

II. The Proposed Control Strategy

A. The concept of the traditional droop control

Fig. 2 shows the control scheme of the traditional droop control. With the objective to parallel connected inverters, the reference V_{ref} of the voltage control loop will be generated by the droop controller. The droop control is responsible to adjust the phase and the amplitude of the voltage reference according to the active and reactive powers (P and Q), for the case of power flow control. The droop control functions are defined as (1) and (2), and the power calculation can be realized by (3) and (4) [22]:

$$\phi = \phi^* - G_P(s)(P - P^*) \quad (1)$$

$$E = E^* - G_Q(s)(Q - Q^*) \quad (2)$$

$$p = v_{c\alpha} \cdot i_{o\alpha} + v_{c\beta} \cdot i_{o\beta} \quad (3)$$

$$q = v_{c\beta} \cdot i_{o\alpha} - v_{c\alpha} \cdot i_{o\beta} \quad (4)$$

where ϕ is the phase of V_{ref}, ϕ^* is the phase reference, P^* and Q^* are the active and reactive references, and $G_P(s)$ and $G_Q(s)$ are the compensator function, selected as:

$$G_P(s) = \frac{k_{pP}s + k_{iP}}{s} \quad (5)$$

$$G_Q(s) = \frac{k_{pQ}s + k_{iQ}}{s} \quad (6)$$

where p and q are the active and reactive power before filtering respectively, $v_{c\alpha\beta}$ and $i_{c\alpha\beta}$ are the capacitor voltage and the filter current.

In (5) and (6), k_{pP} and k_{pQ} are the droop coefficients. In order to eliminate p and q ripples, the following low pass filters are applied to obtain P and Q, being that ω_c is the cut-off frequency of the low-pass filters.

$$P = \frac{\omega_c}{s + \omega_c} p \quad (7)$$

$$Q = \frac{\omega_c}{s + \omega_c} q \quad (8)$$

Finally, the voltage reference can be obtained by using the following equation:

$$v_{ref} = E\sin(\phi) \quad (9)$$

The $\alpha\beta$-coordinates variables are obtained by using the well-known transformation:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \cdot \sqrt{2/3} \quad (10)$$

which has been used for currents and voltages from abc to $\alpha\beta$.

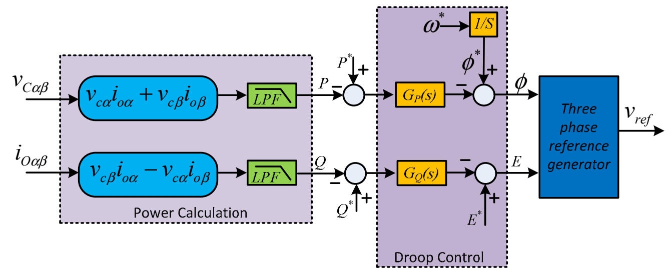

Fig. 2. The traditional droop control scheme.

B. The proposed modified droop control loop

Since in this paper, the parallel connected current source inverters are used to feed power to the grid, in order to simplify the control scheme, only a current control loop is needed. To implement this control concept with droop control, a small mofification is made in the control sheme.

Fig. 3 shows the block diagram of the modified droop control scheme for one of the parallel three-phase CSIs, the others will use the same control architectures. In the control architecture, the basic concept is to modify the droop control to generate the reference currents for the CSIs instead of the reference voltages. Equation (11) is used to calculate the reference currents, ϕ and E are from the traditional droop control loop, and E is the amplitude of the voltage, P^* represents the active power injected from one of the parallel inverters to the grid. In (11), "2/3" is used to calculate the amplitude of the reference currents for a single phase which is deduced from (12).

$$i_{ref} = \frac{P^*}{E} \cdot \sin(\phi) \cdot \frac{2}{3} \quad (11)$$

$$i_{ref} = \frac{P^*}{E/\sqrt{2}} \cdot \frac{1}{3} \cdot \sqrt{2} \cdot \sin(\phi) \quad (12)$$

A phase lock loop (PLL) is used to acquire the phase information of the grid voltage in order to synchronize the output currents with the grid voltage to gain a high power factor. Since there is no communication among the parallel CSIs, it is suitable for modular design of distributed generation system.

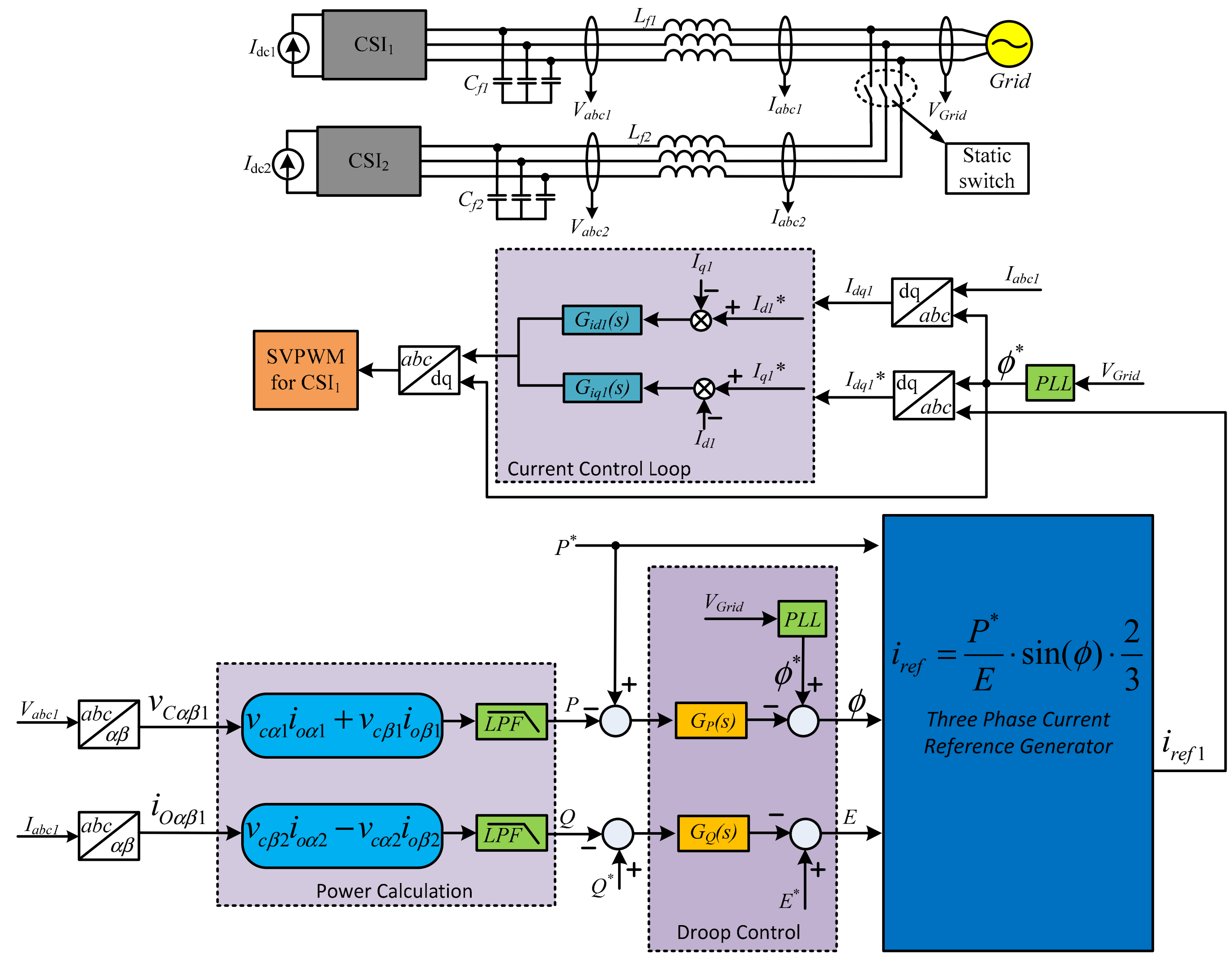

Fig. 3. The control architecture of CSI_1.

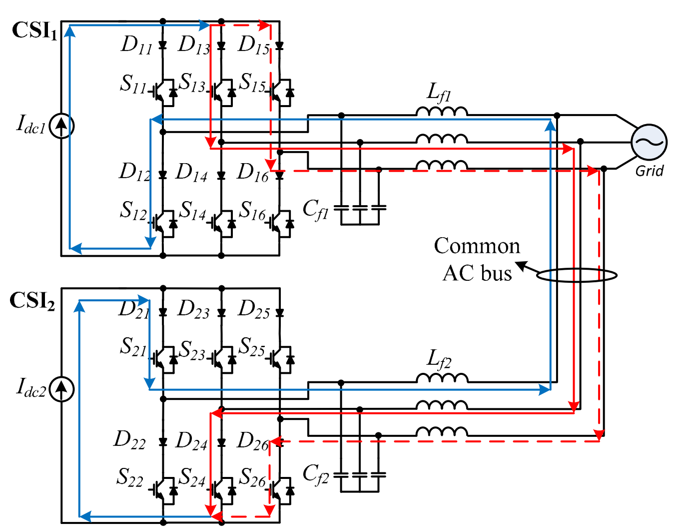

Fig. 4. The circulating current path in two parallel connected CSIs.

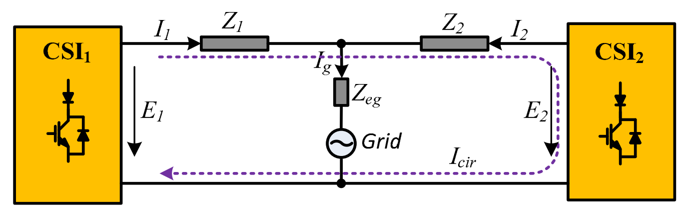

Fig. 5. Equivalent circuit of two parallel CSIs.

C. Analysis of the circulating current

This paper takes a system of two parallel-connected CSIs for an example to analyze the circulating current. The circulating current will flow from one inverter to another through the common AC bus. Fig. 4 shows the probably circulating current path when IGBTs S_{12} and S_{21} are turned on. The circulating current will flow through the blue line, then across the solid red line or dotted red line based on the IGBTs which are in ON state. The parallel three-phase inverters considering the output impedances can be simplified as Fig. 5 because of the similar principle of three-phase and single-phase inverters. In Fig. 5, Z_1 and Z_2 are the output impedances of the two parallel inverters respectively, Z_{eg} is the equivalent grid impedance, E_1 and E_2 are the outputs voltage of the two inverters, I_1 and I_2 are the output currents, I_g is the grid current. According to literature [16], the circulating current I_{cir} can be defined as:

$$I_{cir} = (I_1 - I_2)/2 \quad (13)$$

Assuming that the output impedances of the parallel inverters are equal to each other, Z_1=Z_2=Z, then based on Fig. 5, the circulating current can be calculated as:

$$I_{cir} = (E_1 - E_2)/2Z \quad (14)$$

In a practical system, Z_1 and Z_2 will be different because of the different parameters of filters and line impedances or stray parameters. So that virtual impedance can be used to modify the output impedance of the parallel inverters which will be discussed in future literatures.

III. Simulation Results

In order to verify the effectiveness of the proposed control strategy, a simulation model consists of two parallel-connected CSIs was built in Matlab/Simulink, using the modified droop control method. The whole active power of the system is about 29 kW, and the RMS value of the grid voltage is 230V, so the amplitude of single phase current for one CSI is 30A. The simulation results are shown in Fig. 6 to Fig. 15.

Figs. 6 and 7 are the phase *A* reference currents of the parallel connected CSIs generated by the modified droop control loop, sinewave reference currents were obtained. As can be seen from Fig. 8 and Fig. 9, the circulating current among the parallel inverters is very small. As shown in Fig. 11 to Fig.13, the current injected by the system is synchronized

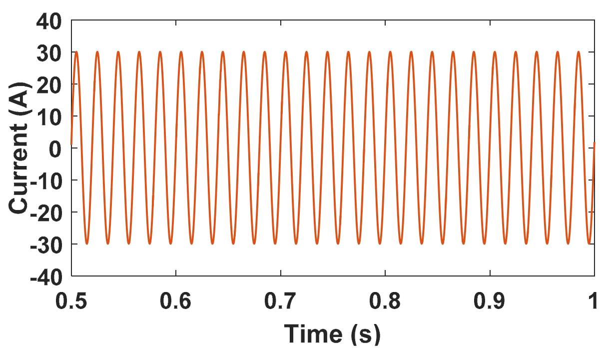

Fig. 6. The phase *A* reference current of CSI_1 from the modified droop control loop.

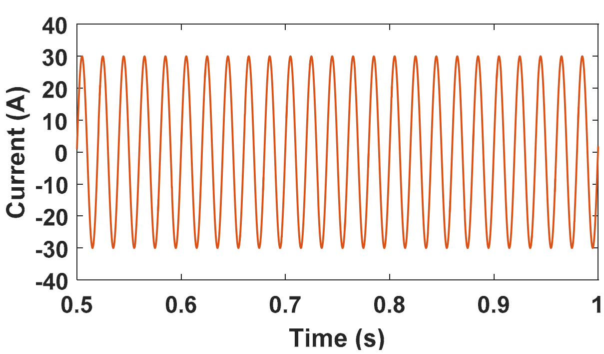

Fig. 7. The phase *A* reference current of CSI_2 from the modified droop control loop.

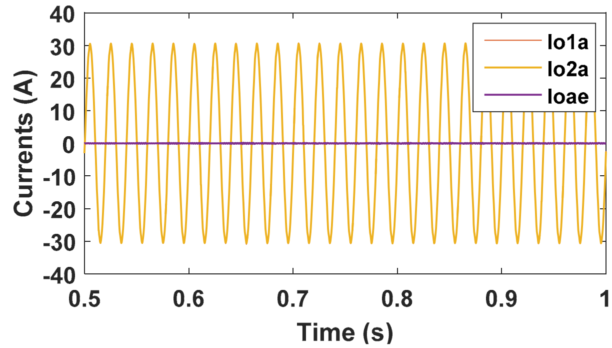

Fig. 8. The phase *A* output currents of the two parallel CSIs and the circulating current among them.

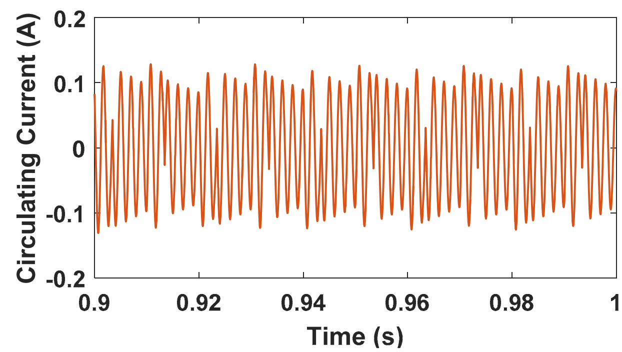

Fig. 9. The zoomed-in circulating current among the parallel CSIs.

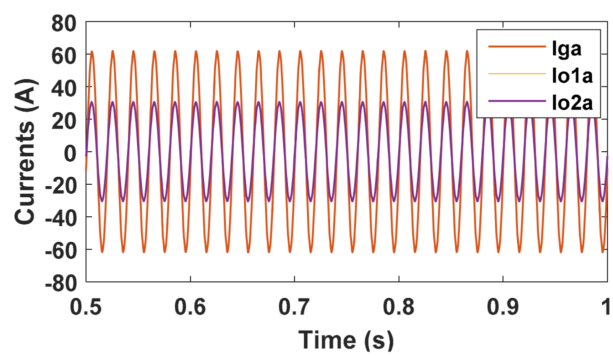

Fig. 10. The phase *A* output currents of the two parallel CSIs and the phase *A* grid current.

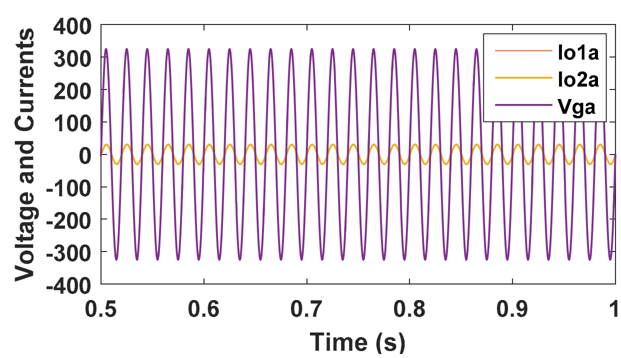

Fig. 11. The phase *A* output currents of the two parallel CSIs and the phase *A* grid voltage.

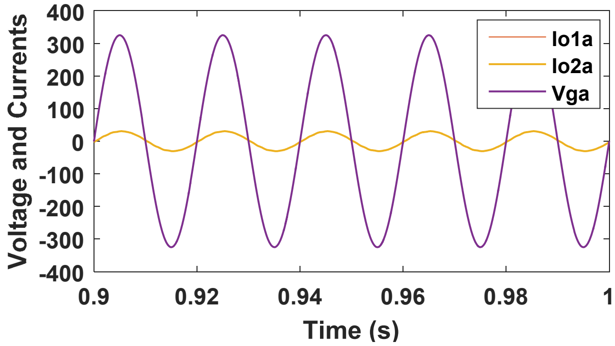

Fig. 12. The zoomed-in phase *A* output currents of the two parallel CSIs and the phase A grid voltage.

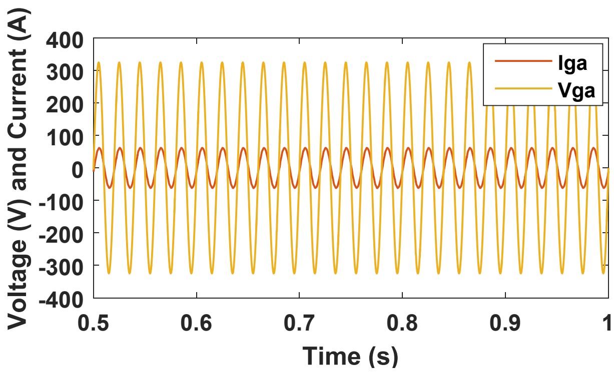

Fig. 13. The phase *A* grid voltage and grid current.

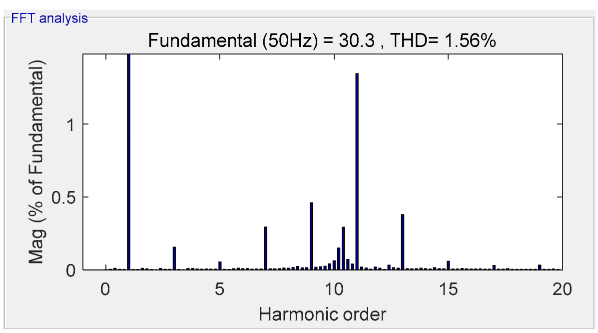

Fig. 14. The total harmonic distortion (THD) of phase *A* output current of CSI_1.

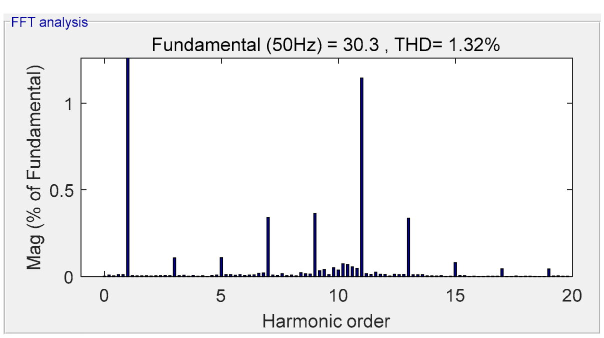

Fig. 15. The THD of phase *A* output current of CSI_2.

with the grid voltage, it means that a high power factor is obtained. Figs. 14 and 15 show the THD of the output currents, both of them are much smaller than 5% which is in the limitation of the harmonic standard.

IV. CONCLUSION

Parallel inverters are widely used in industrial applications for high power demand, and the average current-sharing scheme is necessary. A modified droop control method was proposed in this paper for grid-connected working mode current source inverters. It simplifies the control scheme by just using one current control loop compared with the traditional droop control which consists of one voltage loop and one current loop. Simulation has been done with two parallel-connected inverters feeding power to the grid. The simulation results demonstrate that, sinewave reference currents are obtained with the modified droop control loop, and with proper design of the current controller, the circulating current among the parallel CSIs can be effectively suppressed, and the average current-sharing is realized.

REFERENCES

[1] J. Sun, “Impedance-Based Stability Criterion for Grid-Connected Inverters,” IEEE Trans. Power Electron., vol. 26, no. 11, pp. 3075-3078, Nov. 2011.

[2] R. Turner, S. Walton, and R. Duke, “Stability and Bandwidth Implications of Digitally Controlled Grid-Connected Parallel Inverters,” IEEE Trans. Ind. Electron., vol. 57, no. 11, pp. 3685-3694, Nov. 2010.

[3] J. L. Agorreta, M. Borrega, J. L´opez, and L. Marroyo, “Modeling and Control of N -Paralleled Grid-Connected Inverters With LCL Filter Coupled Due to Grid Impedance in PV Plants,” IEEE Trans. Power Electron., vol. 26, no. 3, pp. 770 - 785, Mar. 2011.

[4] J. S. Siva Prasad and G. Narayanan, “Minimization of grid current distortion in parallel-connected converters through carrier interleaving,” IEEE Trans. Ind. Electron., vol. 61, no. 1, pp. 76–91, Jan. 2014.

[5] D. Zhang, F. Wang, R. Burgos, and D. Boroyevich, “Common-mode circulating current control of paralleled interleaved three-phase two-level voltage-source converters with discontinuous space vector modulation,” IEEE Trans. Power Electron., vol. 26, no. 12, pp. 3925–3935, Dec. 2011.

[6] H. Inaba, K. Kishine, and Y. Igura, “An electric power conversion system composed of two parallel-connected converters providing different output currents,” in Proc. 15th Int. Conf. ICEMS, 2012, pp. 1-4.

[7] T. B. Lazzarin, G. A. T. Bauer and I. Barbi, “A control strategy for parallel operation of single-phase voltage source inverters: analysis, design and experimental result,” IEEE Trans. Ind. Electron., vol. 60, no. 6, pp. 2194-2204, Jun. 2013.

[8] M. Narimani, and G. Moschopoulos, G, “Improved method for paralleling reduced switch VSI modules: harmonic content and circulating current,” IEEE Trans. Power. Electron., vol. 29, no. 7, pp. 3308-3317, Sep. 2013.

[9] Z Peng, “Z-source inverter”, IEEE transactions on Industry Applications, Vol.39, No.2, pp.504-510, Mar/Apr 2003.

[10] Z. Bai, X. Ruan, and Z. Zhang, “A Generic Six-Step Direct PWM (SS-DPWM) Scheme for Current Source Converter,” IEEE Trans. Power Electron., vol. 25, no. 3, pp. 659 - 666, Mar. 2010.

[11] R.Guedouani, B.Fiala, E.M. Berkouk, and M.S. Boucherit, “Modeling and control of multilevel three-phase PWM current source inverter,” in Proc. IEEE ACEMP 2011, Sep. 8–10, pp. 455 - 460.

[12] D. C. Pham, S. Huang, and K. Huang, “Modeling and Simulation of Current Source Inverters with Space Vector Modulation,” in Proc. IEEE ICEMS 2010, Oct. 10–13, pp. 320 - 325.

[13] Z. Bai, Z. Zhang, and X. Ruan, “A Natural Soft-Commutation PWM Scheme for Current Source Converter and Its Logic Implementation,” IEEE Trans. Ind. Electron., vol. 58, no. 7, pp. 2772 - 2779, Jul. 2011.

[14] C. Klumpner, “A new single-stage current source inverter for photovoltaic and fuel cell applications using reverse blocking IGBTs,” in Proc. IEEE PESC 2007, Jun. 17–21, pp. 1683–1689.

[15] T. B. Lazzarin, G. A. T. Bauer, and I. Barbi, “A control strategy for parallel operation of single-phase voltage source inverters: Analysis,

design and experimental result," IEEE Trans. Ind. Electron., vol. 60, no. 6, pp. 2194–2204, Jun. 2013.

[16] F. Wang, Y. Wang, Q. Gao, C. wang, and Y. liu, "A Control Strategy for Suppressing Circulating Currents in Parallel-Connected PMSM Drives With Individual DC Links," IEEE Trans. Power Electron., vol. 31, no. 2, pp. 1680-1691, Feb. 2016.

[17] H. Cai, R. Zhao, and H. Yang, "Study on Ideal Operation Status of Parallel Inverters," IEEE Trans. Power Electron., vol. 23, no. 6, pp. 2964–2969, Nov. 2008.

[18] J. M. Guerrero, J. Matas, L. G. Vicuna, M. Castilla, and J. Miret, "Wireless-control strategy for parallel operation of distributed-generation inverters," IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1461–1470, Oct. 2006.

[19] Y. Zhang, M. Yu, F. Liu, and Y. Kang, "Instantaneous Current-Sharing Control Strategy for Parallel Operation of UPS Modules Using Virtual Impedance," IEEE Trans. Power Electron., vol. 28, no. 1, pp. 432-440, Jan. 2013.

[20] J. M. Guerrero, L. G. Vicuna, J. Matas, M. Castilla, and J. Miret, "Output impedance design of parallel-connected UPS inverters with wireless load-sharing control," IEEE Trans. Ind. Electron., vol. 52, no. 4, pp. 1126–1135, Aug. 2005.

[21] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, "Review of Power Sharing Control Strategies for Islanding Operation of AC Microgrids," IEEE Trans. Smart Grid, vol. 7, no. 1, pp. 200–215, Jan. 2016.

[22] E. Hoff and T. Skjellnes, "Paralleled three-phase inverters," Proc. NORPIE'2004 Conf.