TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.5, May 2014, pp. 3586 ~ 3594
DOI: http://dx.doi.org/10.11591/telkomnika.v12i5.4918

A Reference Compensation Current Control Strategy for Grid-Connected Inverter of Three-Phase Distributed Generators

Yunqing Zhang[1], Shaoru Zhang[1]*, Pingjun Wang[1], Lijun Wang[2], Ruiye Zhang[1], Xiaobo Liu[1], Lingling Liu[1], Yuanyuan Wu[1]
[1]Hebei Normal University,
[2]Shijiazhuang Management Department for Road and Bridge,
NO.20 Road East of 2nd Ring South, Shijiazhuang, 0311-80787300
*Corresponding author, e-mail: shaoruzhang@hotmail.com

Abstract

Renewable energy resources (RES) are being increasingly connected in distribution systems by utilizing power electronic converters. However, the extensive use of power electronics has resulted in a rise in power quality (PQ) concerns faced by the utility. A novel control strategy implementing reference compensation current was proposed in this paper. So that these grid-connected inverters can achieve maximum benefits when they were installed in 3-phase 4-wire distribution systems. The inverter is controlled to perform as a multi-function device by incorporating active power filter functionality. The inverter can thus be utilized as: 1) power converter to transfer active power from RES to the grid, and 2) load reactive power demand support; 3) current harmonics compensation at PCC; and 4) current unbalance and neutral current compensation in case of 3-phase 4-wire system. Moreover, with adequate control of grid-interfacing inverter, all the four objectives can be accomplished either individually or simultaneously. Simulation and experimental results show the validity and capability of the novel proposed control strategy.

Keywords: *grid-connected inverter, reference compensation current, power quality (PQ), active power filter (APF), distributed generators*

Copyright © 2014 Institute of Advanced Engineering and Science. All rights reserved.

1. Introduction

With the consumption of energy, air pollution, global warming concerns, it is necessary to exploit and utilize the renewable energy resources (RES), such as solar power, tidal power, and geothermal power and so on [1-3]. The market liberalization and government's incentives have further accelerated the renewable energy sector growth.

Renewable energy resource (RES) integrated at distribution level is termed as distributed generators (DG). The utility is concerned due to the high penetration level of intermittent RES in distribution systems as it may pose a threat to network in terms of stability, voltage regulation and power-quality (PQ) issues. Therefore, the DG systems are required to comply with strict technical and regulatory frameworks to ensure safe, reliable and efficient operation of overall network. With the advancement in power electronics and digital control technology, the DG systems can now be actively controlled to enhance the system operation with improved PQ at the point-of-common-coupling (PCC). However, the extensive use of power electronics based equipment and non-linear loads at PCC results in harmonic currents, unbalanced voltage, poor power factor, power losses and other power quality disturbances [1-2].

Generally, current controlled voltage source inverters are used to interface the intermittent RES in distributed system. Recently, a few control strategies for grid connected inverters incorporating PQ solution have been proposed. In [3] an inverter operates as active inductor at a certain frequency to absorb the harmonic current. But the exact calculation of network inductance in real-time is difficult and may deteriorate the control performance. A similar approach in which a shunt active filter acts as active conductance to damp out the harmonics in distribution network is proposed in [4].

Received October 24, 2013; Revised December 15, 2013; Accepted January 6, 2014

The non-linear load current harmonics may result in voltage harmonics and can create a serious PQ problem in the power system network. Active power filters (APF) are extensively used to compensate the load current harmonics and load unbalance at distribution level. This results in an additional hardware cost.

The features of APF was incorporated in the conventional inverter interfacing renewable with the grid, without any additional hardware cost in this paper. And a novel control strategy implementing reference compensation current was proposed. Here, the main idea is the maximum utilization of inverter rating which is most of the time underutilized due to intermittent nature of RES. It is shown in this paper that the grid-connected inverter can effectively be utilized to perform following important functions: 1) as a power converter to transfer active power from RES to the grid, and 2) as a shunt APF to compensate current unbalance, load current harmonics, load reactive power demand and load neutral current. All of these functions may be accomplished either individually or simultaneously. With such a control, the combination of grid- connected inverter and the 3-phase 4-wire linear/non-linear unbalanced load at PCC appears as balanced linear load to the grid. The simulation and experimental results confirmed the validity and capability of the novel proposed control strategy for grid- connected inverter when they installed in 3-phase 4-wire distributed generators.

2. Research Method

2.1. System Description

The proposed system consists of RES interfaced to the dc-link of a grid-connected inverter as shown in Figure 1. A set of 3-phase and 1-phase loads are connected to the grid. The voltage source inverter is a key element of a DG system as it interfaces the renewable energy source to the grid and, it delivers the generated power by DG system to the grid. The grid-connected inverter is connected to the grid at PCC via filter inductor, which can reduce switching frequency ripple of the inverter currents. The RES may be a DC source or an AC source with rectifier coupled to dc-link. Usually, the fuel cell and photovoltaic energy sources generate power at variable low dc voltage, while the variable speed wind turbines generate power at variable ac voltage. Thus, the power generated from these renewable sources needs power conditioning (i.e., dc/dc or ac/dc) before connecting on dc-link [5-7]. The dc-capacitor decouples the RES from grid and also allows independent control of inverters on either side of dc-link.

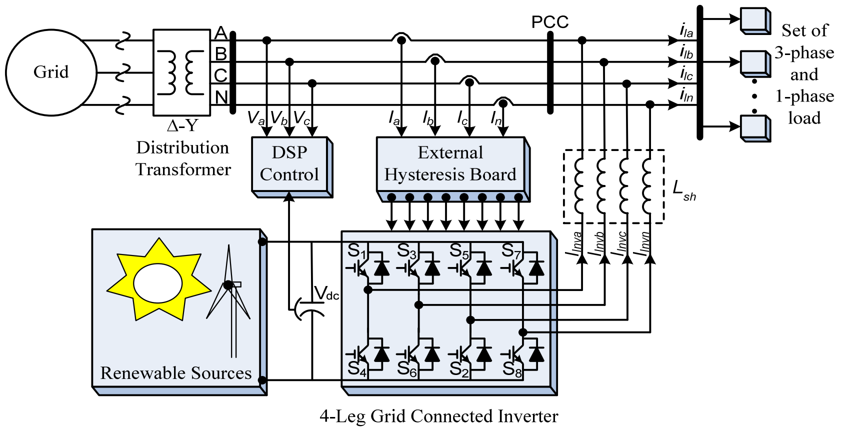


Figure 1. Schematic of Proposed Renewable Based Distributed Generation System

2.2. Proposed Control Arithmetic

2.2.1. DC-Link Voltage and Power Control Operation

Due to the intermittent nature of RES, the generated power is of variable nature. The dc-link plays an important role in transferring this variable power from renewable energy source to the grid. RES are represented as current sources connected to the dc-link of a grid-interfacing inverter. Figure 2 shows the systematic representation of power transfer from the renewable energy resources to the grid via the dc-link. The current injected by renewable energy resources into dc-link at voltage level can be given as:

$$I_{dc1} = \frac{P_{RES}}{V_{dc}} \tag{1}$$

Where P_{RES} is the power generated from RES.

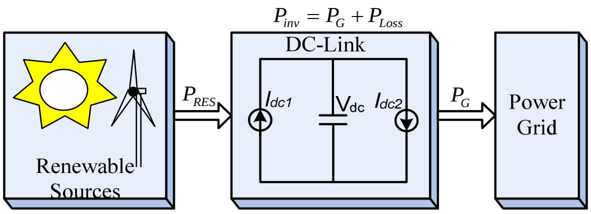


Figure 1. DC-Link Equivalent Diagram

The current flow on the other side of dc-link can be represented as:

$$I_{dc2} = \frac{P_{inv}}{V_{dc}} = \frac{P_G + P_{Loss}}{V_{dc}} \tag{2}$$

Where P_{inv} , P_G and P_{Loss} are total power available at grid-interfacing inverter side, active power supplied to the grid and inverter losses, respectively. If inverter losses are negligible, then $P_{RES} = P_G$.

In additional, based on the energy conservation law, as for as the whole system in Figure 1 is concerned, (3) must hold:

$$P_{RES} + P_s - P_{Loss} - P_L = 0 \tag{3}$$

Where P_s and P_L are total power available at PCC by grid generated, and total power consumed by load, respectively.

2.2.2. Proposed Control Arithmetic

a) The grid-connected inverter performs the function as a shunt APF

The proposed controller is based on the requirement that the source currents need to be balanced, undistorted, and in phase with the source voltages. The functions of the grid-connected inverter are: 1) to unitize supply power factor; 2) to minimize average real power consumed or supplied by the grid-connected inverter; 3) to compensate harmonics and reactive currents. To carry out the functions, the desired three-phase source currents of (4) must be in phase with the source voltages of (5):

$$\begin{cases} i_{sa} = I_m \sin(\omega t + \phi) \\ i_{sb} = I_m \sin(\omega t + \phi - 120°) \\ i_{sc} = I_m \sin(\omega t + \phi + 120°) \end{cases} \tag{4}$$

$$\begin{cases} v_{sa} = V_m \sin(\omega t + \phi) \\ v_{sb} = V_m \sin(\omega t + \phi - 120°) \\ v_{sc} = V_m \sin(\omega t + \phi + 120°) \end{cases} \tag{5}$$

Where V_m and ϕ are the voltage magnitude and the phase angle of the source voltages respectively. Under the conditions that the load active power is supplied by the source and the grid-connected inverter does not provide or consume any real power, it is required to determine the current magnitude Im from the sequential instantaneous voltage and real power components supplied to the load. According to the symmetrical-component transformation for the three-phase root mean square (rms) currents at each harmonic order, the three-phase instantaneous load currents can be expressed by:

$$i_{lk} = \sum_{n=1}^{\infty} i_{lkn}^{+} + \sum_{n=1}^{\infty} i_{lkn}^{-} + \sum_{n=1}^{\infty} i_{lkn}^{0}, k \in K \tag{6}$$

In (6), K = {a, b, c}; 0, +, and - stand for zero-, positive-, and negative-sequence components, respectively, and n represents the fundamental (i.e., n = 1) and the harmonic components. Since the average real power consumed by the load over one period of time T must be supplied by the source and it requires that the grid-connected inverter consumes or supplies null average real power, (7)–(11) must hold:

$$p_s = p_l + p_f \tag{7}$$

$$\overline{p_s} = \frac{1}{T}\int_0^T \sum_{k \in K} v_{sk} i_{sk} dt \tag{8}$$

$$\overline{p_l} = \frac{1}{T}\int_0^T \sum_{k \in K} v_{sk} i_{lk} dt \tag{9}$$

$$\overline{p_f} = 0 \tag{10}$$

$$\overline{p_s} = \overline{p_l} \tag{11}$$

Substituting (6) into (9) yields the sum of the fundamental and the harmonic power terms at the three sequential components, as given in (12):

$$\overline{p_l} = \overline{p}_{l1}^{+} + \overline{p}_{l1}^{-} + \overline{p}_{l1}^{0} + \overline{p}_{lh}^{+} + \overline{p}_{lh}^{-} + \overline{p}_{lh}^{0} \tag{12}$$

Where:

$$\overline{p}_{l1}^{+} = \frac{1}{T}\int_0^T \sum_{k \in K} v_{sk} i_{lk1}^{+} dt = \frac{1}{T}\int_0^T \sum_{k \in K} v_{sk} i_{sk} dt = \frac{3V_m I_m}{2} \tag{13}$$

And,

$$\overline{p}_{l1}^{-} = \overline{p}_{l1}^{0} = \overline{p}_{lh}^{+} = \overline{p}_{lh}^{-} = \overline{p}_{lh}^{0} = 0 \tag{14}$$

Each power term in (14) is determined based on the orthogonal theorem for a periodic sinusoidal function. Then, (9) becomes:

$$\overline{p_s} = \overline{p_l} = \overline{p_{l1}^{+}} = \frac{1}{T}\int_0^T \sum_{k \in K} v_{sk} i_{sk} dt \tag{15}$$

By (11), (13), and (15), the desired source current magnitude at each phase is determined to be:

$$I_m = \frac{2\overline{p_l}}{3V_m} = \frac{2\int_0^T \sum_{k\in K} v_{sk} i_{lk} dt}{3TV_m} \tag{16}$$

and the source currents of (4) can be expressed by:

$$i_{sk} = I_m \frac{v_{sk}}{V_m} = \frac{2\overline{p_l}}{3(V_m)^2} v_{sk}, k \in K \tag{17}$$

The required current compensation at each phase by the grid-connected inverter is then obtained by subtracting the desired source current from the load current as given in (18):

$$i_{fk}^* = i_{lk} - i_{sk} = i_{lk} - \frac{2\overline{p_l}}{3(V_m)^2} v_{sk}, k \in K \tag{18}$$

The average real power consumed or supplied by the grid-connected inverter is expressed as:

$$\overline{p_f} = \frac{1}{T}\int_0^T \sum_{k\in K} v_{sk} i_{fk} dt \tag{19}$$

Substituting (18) into (19) yields:

$$\overline{p_f} = \frac{1}{T}\int_0^T \sum_{k\in K} v_{sk} i_{lk} dt - \frac{2\overline{p_l}}{3(V_m)^2}\frac{1}{T}\int_0^T \sum_{k\in K} v_{sk}{}^2 dt = \overline{p_l} - \frac{2\overline{p_l}}{3(V_m)^2}\frac{3(V_m)^2}{2} = \overline{p_l} - \overline{p_l} = 0 \tag{20}$$

Therefore, the grid-connected inverter does not consume or supply average real power when it performs the function as a shunt APF.

b) the grid-connected inverter performs the function as a power converter to transfer active power from RES to the grid.

When the generated power by RES is not equal to zero, the inverter will start injecting active power from RES. And when the generated power is more than the load power demand, the additional power will feed back to the grid. The active power supplied by the inverter is determined by the dc bus voltage. The difference of the actual dc-link voltage and reference dc-link voltage is given to a PI controller to maintain a constant dc-link voltage under varying generation and load conditions. The PI controller then generates the reference current magnitude corresponding to the output active power of RES.

2.2.3. Average Models of Four-Leg Voltage-Source Inverter

The average model of 4-leg inverter can be obtained by the following state space equations:

$$\frac{di_{Inva}}{dt} = \frac{v_{Inva} - v_{sa}}{L_{sh}} \tag{21}$$

$$\frac{di_{Invb}}{dt} = \frac{v_{Invb} - v_{sb}}{L_{sh}} \tag{22}$$

$$\frac{di_{Invc}}{dt} = \frac{v_{Invc} - v_{sc}}{L_{sh}} \tag{23}$$

$$\frac{di_{Invn}}{dt} = \frac{v_{Invn} - v_{sn}}{L_{sh}} \tag{24}$$

$$\frac{dV_{dc}}{dt} = \frac{i_{Invad} + i_{Invbd} + i_{Invcd} + i_{Invnd}}{C_{dc}} \quad (25)$$

Where v_{Inva} , v_{Invb} , v_{Invc} and v_{Invn} are the three-phase ac switching voltages generated on the output terminal of inverter. These inverter output voltages can be modeled in terms of instantaneous dc bus voltage and switching pulses of the inverter as:

$$v_{Inva} = \frac{P_1 - P_4}{2} V_{dc} \quad (26)$$

$$v_{Invb} = \frac{P_3 - P_6}{2} V_{dc} \quad (27)$$

$$v_{Invc} = \frac{P_5 - P_2}{2} V_{dc} \quad (28)$$

$$v_{Invn} = \frac{P_7 - P_8}{2} V_{dc} \quad (29)$$

Similarly the charging currents i_{Invad} , i_{Invbd} , i_{Invcd} , and i_{Invnd} on dc bus due to the each leg of inverter can be expressed as:

$$i_{Invad} = i_{Inva}(P_1 - P_4) \quad (30)$$

$$i_{Invbd} = i_{Invb}(P_3 - P_6) \quad (31)$$

$$i_{Invcd} = i_{Invc}(P_5 - P_2) \quad (32)$$

$$i_{Invnd} = i_{Invn}(P_7 - P_8) \quad (33)$$

The switching pattern of each IGBT inside inverter can be formulated on the basis of error between actual and reference current of inverter, which can be explained as:

If $i_{Inva} < \left(i^*_{Inva} - h_b\right)$, then S_1 upper switch will be OFF ($P_1 = 0$) and lower switch S_4 will be ON (P4 = 1) in the phase “a” leg of inverter.

If $i_{Inva} > \left(i^*_{Inva} - h_b\right)$, then S_1 upper switch will be ON ($P_1 = 1$) and lower switch S_4 will be OFF (P4 = 0) in the phase “a” leg of inverter.

Where h_b is the width of hysteresis band. On the same principle, the switching pulses for the other remaining three legs can be derived.

4. Results and Discussion

4.1. Block Diagram of the Proposed Controller

Figure 3 depicts the block diagram of the control circuit based on the proposed approach to fulfill the function of the reference compensation current calculator. The source voltages are input to a phase-locked-loop (PLL), where the peak voltage magnitude V_m, the unity voltages (i.e., v_{sk}/V_m) and the period T are generated. The average real power of the load consumed is calculated by using the Equation (15) and is input to a divider to obtain the desired source current amplitude I_m in (16). DI denotes the calculation of definite integral (DI). The desired source currents in (17) and reference compensation currents of the grid-connected inverter in (18) are computed by using the voltage magnitude and the unity voltages (because of the power loss and the power generated by RES, the actual source current magnitude should be equal to $I''_m + I_m$). These reference compensation currents are given to HCC. The hysteresis controller then generates the switching pulses (P_1 to P_8) for the gate drives of the bidirectional switches.

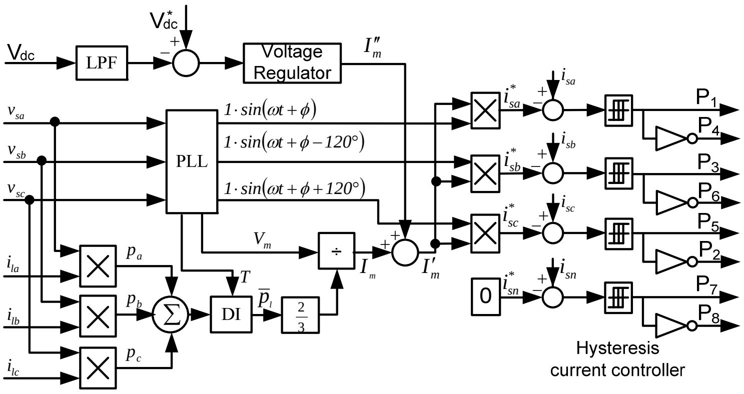
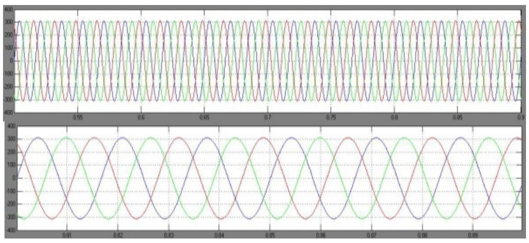


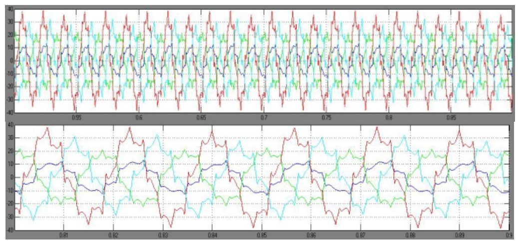
Figure 3. The Proposed Control Strategy

4.2. Simulation Results

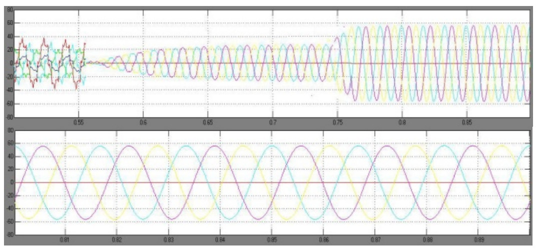
In order to verify the proposed control approach to achieve multi-objectives for grid interfaced DG systems connected to a 3-phase 4-wire network, an extensive simulation study is carried out using MATLAB/SIMULINK. A 4-leg current controlled voltage source inverter is actively controlled to achieve balanced sinusoidal grid currents at unity power factor (UPF) despite of highly unbalanced nonlinear load at PCC under varying renewable generating conditions. A RES with variable output power is connected on the dc-link of grid-interfacing inverter. An unbalanced 3-phase 4-wire nonlinear load, whose unbalance, harmonics, and reactive power need to be compensated, is connected at PCC. The waveforms of grid voltage (v_{sa}, v_{sb}, and v_{sc}), unbalanced load currents(i_{la}, i_{lb}, and i_{lc}), grid currents (i_{sa}, i_{sb}, and i_{sc}) and inverter currents (i_{Inva}, i_{Invb}, and i_{Invc}) are shown in Figure 4.



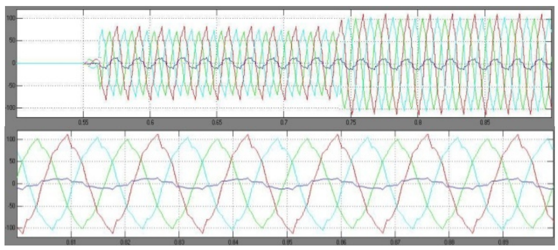
(a) grid voltage



(b) unbalanced load currents



(c) grid currents



(d) inverter currents

Figure 4. Simulation Results

Initially, the grid-connected inverter is not connected to the network (i.e., the load power demand is totally supplied by the grid alone). Therefore, before time 0.56s, the grid current profile in Figure 4(c) is identical to the load current profile of Figure 4(b). At t = 0.56s, the grid-connected inverter is connected to the network. At this instant the inverter starts injecting the current in such a way that the profile of grid current starts changing from unbalanced non linear to balanced sinusoidal current as shown in Figure 4(c). As the inverter also supplies the load neutral current demand, the grid neutral current becomes zero after 0.56s.

At t = 0.56s, the inverter starts injecting active power generated from RES. Since the generated power is more than the load power demand, the additional power is fed back to the grid. Moreover, the grid-interfacing inverter also supplies the load reactive power demand locally. Thus, once the inverter is in operation, the grid only supplies/receives fundamental active power.

At t = 0.73s, the active power from RES is increased to evaluate the performance of system under variable power generation from RES. This results in increased magnitude of inverter current. As the load power demand is considered as constant, this additional power generated from RES flows towards grid, which can be noticed from the increased magnitude of grid current as indicated by its profile.

Thus from the simulation results, it is evident that the grid- connected inverter can be effectively used to compensate the load reactive power, current unbalance and current harmonics in addition to active power injection from RES. This enables the grid to supply/ receive sinusoidal and balanced power at UPF.

4.3. Experimental Results

To demonstrate the fast dynamic response of the grid-connected inverter based on the proposed control strategy, an experimental setup is developed where the 61703 Chroma Programmable AC source is used as the three phase supply. The sensor unit consists of LEM LA 55-P Hall-effect current sensors and LEM LV20-P Hall-effect voltage sensors for the measurement of the source and load currents, and the source and dc-link voltages, respectively. The digital signal processing board dSPACE DS1103 implements the proposed control algorithm in MATLAB/SIMULINK environment with the sampling frequency of 50kHz. The ADCs and DACs of DS1103 provide the discretized measurement signals for the dSPACE-MATLAB/SIMULINK platform and the analog reference currents for the hysteresis current controller, respectively. Based on the difference between the reference and actual source currents, the analog hysteresis current controller decides the switching state for the grid-connected inverter.

Two different loads are considered for this experimental study, Load-1: 6-pulse uncontrolled rectifier with an R-L load of (60+jω0.1)H, and Load-II: combination of 3-phase R-L load of (60+jω0.1)H in parallel with a 6-pulse uncontrolled rectifier with an R-L load of (60+jω0.1)H. The performance of the developed grid- connected inverter system for these two different load conditions is evaluated for the steady state and the dynamic conditions. The measurements are orderly shown in the four oscilloscope sub-screens as (a) source voltages, (b) source currents, (c) load currents, (d) injected currents and dc-link voltage.

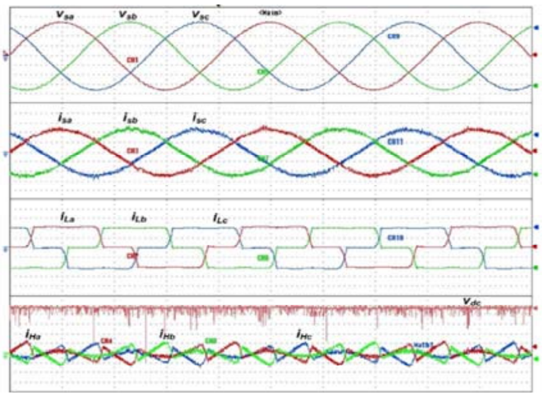


Figure 5. The Performance of Grid-connected Inverter with Load-I

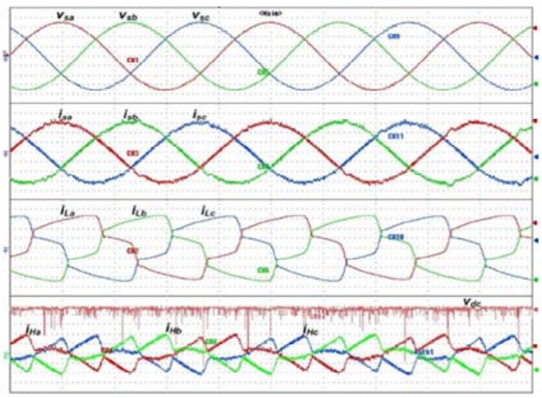


Figure 6. The Performance of Grid-connected Inverter with Load-II

The experimental results for the grid- connected inverter with the proposed control scheme with Load-I and Load-II are respectively shown in Figures 5-6. The source voltage is sinusoidal with the peak amplitude of 70V and frequency of 50Hz. With Load-I, the load current is highly distorted with a total harmonic distortion (THD) of 25.7% and the peak amplitude of

2.2A. Whereas, with Load-II the load current THD is 18% with the peak amplitude of 3.25A as the linear load is in parallel with the diode rectifier. With grid- connected inverter, the source is relieved of the harmonics and reactive currents, and is required to supply only the fundamental active currents. Hence, the source currents are sinusoidal with the THD of 2.9% and 2.6% for Load-I and Load-II, respectively. The source current THD will be within the permissible limit of 5%. This prevents the introduction of harmonics in the grid and thereby improves the quality of the power being delivered.

5. Conclusion

This paper has presented a novel control for an existing grid-connected inverter to improve the quality of power at PCC for a 3-phase 4-wire DG system. It has been shown that the grid-connected inverter can be effectively utilized for power conditioning without affecting its normal operation of real power transfer. The grid-connected inverter with the proposed approach can be utilized to:

a) inject real power generated from RES to the grid, and/or,
b) operate as a shunt Active Power Filter (APF).

This approach thus eliminates the need for additional power conditioning equipment to improve the quality of power at PCC. Extensive MATLAB/SIMULINK simulation and experimental results have validated the proposed approach and have shown that the grid-connected inverter can be utilized as a multi-function device.

It is further demonstrated that the current unbalance, current harmonics and load reactive power, due to unbalanced and non-linear load connected to the PCC, are compensated effectively such that the grid side currents are always maintained as balanced and sinusoidal at unity power factor. Moreover, the load neutral current is prevented from flowing into the grid side by compensating it locally from the fourth leg of inverter. When the power generated from RES is more than the total load power demand, the grid-interfacing inverter with the proposed control approach not only fulfills the total load active and reactive power demand (with harmonic compensation) but also delivers the excess generated sinusoidal active power to the grid at unity power factor.

Acknowledgements

This work was financially supported by the Natural Science Foundation of Hebei Province (E2013205173), Educational Commission of Hebei Province (2009141), and PhD Foundation of Hebei Normal University (L2008B04) .

References

[1] Guerrero JM, De Vicuna LG, Matas J, Castilla M, Miret J. A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems. *IEEE Trans. Power Electron.* 2004; 19(5): 1205-1213.
[2] Enslin JHR, Heskes PJM. Harmonic interaction between a large number of distributed power inverters and the distribution network. *IEEE Trans. Power Electron.* 2004; 19(6): 1586-1593.
[3] Borup U, Blaabjerg F, Enjeti PN. Sharing of nonlinear load in parallel-connected three-phase converters. *IEEE Trans. Ind. Appl.* 2001; 37(6): 1817-1823.
[4] Jintakosonwit P, Fujita H, Akagi H, Ogasawara S. Implementation and performance of cooperative control of shunt active filters for harmonic damping throughout a power distribution system. *IEEE Trans. Ind. Appl.* 2003; 39(2): 556-564.
[5] Blaabjerg F, Teodorescu R, Liserre M, Timbus A V. Overview of control and grid synchronization for distributed power generation systems. *IEEE Trans. Ind. Electron*. 2006; 53(5): 1398-1409.
[6] Carrasco JM, Franquelo LG, Bialasiewicz JT, Galván E, Guisado RCP, Prats MÁM, León JI, Alfonso N M. Powerelectronic systems for the grid integration of renewable energy sources: A survey. *IEEE Trans. Ind. Electron.* 2006; 53(4): 1002-1016.
[7] Renders B, De Gusseme K, Ryckaert WR, Stockman K, Vandevelde L, Bollen MHJ. Distributed generation for mitigating voltage dips in low-voltage distribution grids. *IEEE Trans. Power. Del.* 2008; 23(3): 1581-1588.