IJARCCE

ISSN (Online) 2278-1021
ISSN (Print) 2319 5940

International Journal of Advanced Research in Computer and Communication Engineering
Vol. 5, Issue 5, May 2016

Power Quality Enhancement using Distributed Generation Inverters with Active Power Control

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Abstract: Renewable Energy Sources (RES) based Distributed Power Generation use Power Electronic Converters for grid interfacing. This paper deals with a multi objective control strategy for a current controlled three phase Distributed Generation (DG) inverter. The DG inverter incorporates active filter functionality in forward and reverse power flow modes when connected to a nonlinear load. The multifunctional grid connected inverter (MFGCI) can compensate for load current harmonics, load unbalance and load reactive power demand with closed loop active power control. The proposed closed loop power control scheme achieves accurate power tracking with zero steady state errors under ideal and non-ideal supply conditions. A hysteresis band current controller is used to generate the switching pulses for the interfaced inverter. Extensive simulation studies are done in MATLAB/Simulink software to validate the effectiveness of the proposed control strategy.

Index Terms: Renewable Energy Sources (RES), Distributed Generation (DG), Multifunctional grid connected inverter (MFGCI), Power quality, Total Harmonic Distortion (THD).

I. INTRODUCTION

In recent years Distributed Generation (DG) based on Renewable Energy Sources (RES) has undergone tremendous development globally. Due to the increasing energy demand reducing fossil fuels and clean energy concepts more and more DG units are connected to the grid at the distribution level [1]. Micro grids which integrate RESs, energy storage devices and local loads are a solution to the present day energy crisis [2]. Power quality is a major issue in a conventional distribution system in the presence of increased usage of nonlinear loads and power electronic based equipments. Poor power quality is a big challenge for the stable, effective and economic operation of an inverter dominated micro grid [1,3,4,8].

In the near future electricity will be a commodity marketed by judging its quality in a competitive environment [8]. A number of active power filtering techniques have been developed to mitigate the traditional distribution system harmonic issues [6]. The basic structure of an active filter is similar to that of a DG inverter and the primary function of these grid interfacing inverters is to inject active power to the grid. The DG inverter may not operate at its full capacity at all the time due to the stochastic nature of the renewable energy sources like solar andlor wind [7]. If controlled properly the unused capacity of DG inverters can be effectively used for providing ancillary services like harmonic, reactive power compensation and unbalance mitigation of the power distribution system [2, 7, 8, 9]. Such an inverter can be called as a multifunctional grid connected inverter (MFGCI). With the recent developments in microgrid technology power quality enhancement using flexible control of MFGCI is an interesting research topic [10]. Use of MFGCI eliminates the necessity of additional compensating devices and results in a cost effective system [7-9]. Voltage Source inverters are used as the interfacing converters in most of the DG systems. Normally these inverters operate in current controlled mode (CCM) during grid connected operation due to its superior harmonic compensation capability when compared to the voltage controlled mode (VCM). Various control strategies and techniques for enhanced power quality in a grid connected system have been reported recently [8-[4]. During harmonic compensation of the nonlinear load current, the fundamental DG current supplied by the interfacing inverter has to be calculated based on the active and reactive power reference. A control technique with power quality improvement features for the integration of DG systems to the grid is discussed in [12]. In this strategy generation of fundamental DG current component assumes a stiff voltage source at the grid side and does not consider non ideal supply conditions. An open loop power control strategy for optimal power quality compensation in Microgrids using multifunctional grid connected inverters is proposed in [13]. An electrical distribution system is subjected to power fluctuations and uncertainties which cause the voltage at the point of common coupling (PCC) to be unbalanced. The interaction between the DG inverter nonlinear current and distorted PCC voltages may contribute power control errors in the steady state [14-16].

Hence a closed loop power control strategy is necessary for accurate power tracking in the case of distorted voltages at the PCC. In [14], a closed loop power control strategy for single phase inverters with active harmonic filtering in stationary frame is proposed for harmonic compensation. The objective of this paper is to develop a control strategy for harmonic current filtering in a three phase grid connected DG system without using extra compensating device. The proposed closed loop control is able to track the active power reference and improve the

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International Journal of Advanced Research in Computer and Communication Engineering
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power quality in the presence of unbalanced and distorted supply voltages. The effectiveness of the control scheme is validated by elaborate simulation studies for different operating modes of the DG inverter under ideal and non-ideal supply conditions. The rest of the paper is organized into four sections. Section II gives a schematic representation of the system under consideration. Generation of the reference currents for the proposed method is dealt in section III. Section IV relates to the simulation results for different operating modes of the DG inverter under various load and supply conditions. Conclusion is given in section V.

II. SYSTEM DESCRIPTION

A schematic representation of the proposed system is given in Fig.I. Rg and Lg represents the grid resistance and inductance up to the point of common coupling; Rig and Ldg represents the equivalent resistance and inductance of the inverter filter, coupling transformer and connecting cables; Ls represents the smoothing inductance inserted in series with the load to reduce the spikes in the grid current due to switching transients; v'" Vh. Vc represents the voltages at the PCC and if", hb, he represents the load currents.

III. REFERENCE CURRENT GENERATION PRINCIPLE

The control technique employed is based on the analysis of load voltage, load current and inverter currents in the dq synchronous rotating frame. Independent control of active and reactive power can be achieved with more effectiveness in dq frame. The instantaneous angle of the voltage at PCC is obtained by using a phase locked loop (PLL). A) Calculation of d-axis and q-axis reference currents to supply load active and reactive power The active and reactive power injected from the DG link to the grid at the fundamental frequency is

$$P_{dg} = \frac{3}{2}\left(v_d I_{dgd} + v_q I_{dgq}\right) \qquad (1)$$

$$Q_{dg} = \frac{3}{2}\left(v_q I_{dgd} - v_d I_{dgq}\right) \qquad (2)$$

where Idgd and Idgq and are the dq- components of DG inverter current at fundamental frequency to manage the active power and reactive power exchange between the grid and RES. Vd and Vq are the the PCC voltages in dq frame. The currents at fundamental frequency required to deliver the active and reactive power from the RES has to be supplied by the DG inverter. The corresponding reference currents at fundamental frequency are 1* dgd and 1* dgq, which can be calculated using the open loop and the proposed closed loop power control strategy as explained below,

1) Open loop power control

In a practical case, the PCC voltages may contain ripple due to the unexpected power fluctuations and excessive use of harmonic polluted loads connected to the system. Hence to generate the fundamental current components, the PCC voltages are filtered in dq frame [13].

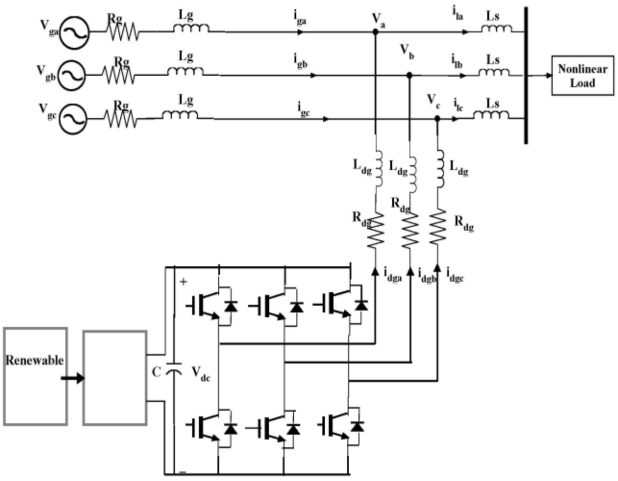

Fig.I. Schematic of the proposed distribution generation system connected to the electrical network

$$\begin{bmatrix} I^*_{dgd} \\ I^*_{dgq} \end{bmatrix} = \frac{1}{\tilde{v}_d^{\,2}+\tilde{v}_q^{\,2}} \begin{bmatrix} P^* & Q^* \\ -Q^* & P^* \end{bmatrix} \begin{bmatrix} \tilde{v}_d \\ \tilde{v}_q \end{bmatrix} \frac{2}{3}$$

~ [redacted] ~ [redacted]

where Vd and Vq are the voltages after passing through a low pass filter. P * and Q * are the active and reactive power

2) Proposed closed loop power control

In the proposed closed loop control strategy, the calculated DG active and reactive power are filtered through a low pass fi lter and compared with the reference powers to get the error signal. The dq - components of inverter reference current at fundamental frequency can be generated by passing the error signal through a PI controller and can be expressed as

$$I^*_{dgd} = (P^* - \tilde{P}_{dg})\left(k_{p1} + \frac{k_{i1}}{s}\right) \qquad (4)$$

$$I^*_{dgq} = (Q^* - \tilde{Q}_{dg})\left(k_{p2} + \frac{k_{i2}}{s}\right) \qquad (5)$$

where Pdg and Qdg represent the filtered real and reactive power of the DG inverter, kPI .kil, kP2 and kil are the proportional and integral gains for minimizing the real and reactive power control errors, As per IEEE 1547 the inverters in a distributed generation system are not permitted to inject reactive power to the grid [5]. As such, the total q-axis reference current for the inverter is limited to meet only the reactive power demand of the load so that ld * = O. Hence only active power control IS gq done in both open loop and closed loop control schemes. In rotating synchronous frame the quadrature component of load current i1q is perpendicular to the direct component of voltage CI q □ vd) [[2]. Accordingly the q-axis reference current of the DO inverter can be expressed as

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$$i^*_{dga} = i_{la}$$

B. Calculation of total d-axis reference current

The d-axis component of the load current can be expressed as [[2]

$$i_{ld} = i_{ld_1} + \tilde{i}_{ld}$$

where in1d is the oscillating component of the load current and hdl is the fundamental component of load current. [n dq frame the fundamental frequency component of the load current appears as a dc component. The harmonic components of the load current can be obtained by using a high pass filter. But due to the excessive phase lag associated with the high pass filter, a second order low pass filter having a cut off frequency of 25 Hz is used to extract the harmonic component of the load current. iU1d can be expressed as

$$\tilde{i}_{ld} = \sum_{n=2}^{\infty} i_{ld_n}$$

$$\sum_{n=2}^{\infty} i_{ld_n} = i_{ld}(1 - LPF)$$

The DO inverter has to supply the d-axis component of harmonic load current given by equation (8) and the d-axis component of current at fundamental frequency given by equation (3) or (4) depending upon the type of the power control scheme. Hence the total d-axis reference current for the DO inverter can be expressed as

$$i^*_{dgd} = \tilde{i}_{ld} + I^*_{dgd}$$

C. DC link voltage control

When the power from the RES is equal to zero, the inverter operates in shunt active filter mode. The DO inverter draws an active power component of current ide for maintaining the dc bus voltage constant and to meet the losses in the inverter. The DC link voltage error can be expressed as

$$v_{dc\,err} = v^*_{dc} - v_{dc}$$

The current ide can be obtained by passing the error through a P[controller and is given by

$$i_{dc} = k_p v_{dc\,err} + k_i \int v_{dc\,err} dt$$

where kp and k; are the proportional and integral gain constants.

D. Hysteresis Current Control Scheme

A Hysteresis band current controller is used to generate the switching pulses for the DO inverter. The reference currents generated in dq frame are transformed to natural abc frame and compared with the inverter currents to generate the error signals. [fi:xa - idxa > hh' then upper switch is switched ON and lower switch is switched OFF in the inverter leg of phase 'a'. If i;ga - idga < hb ,then upper switch is switched OFF and lower switch is switched ON in the inverter leg of phase 'a', where hb is the assigned hysteresis band. Using the same principle switching pulses for the other switches in phase 'b'& 'c' are produced. The hysteresis band directly controls the amount of ripples in the current injected into the grid. The main advantages of hysteresis current controller are ease of implementation, extremely good dynamic response, outstanding robustness and independence of load parameter changes [17]. The switching frequency depends on the width of hysteresis band, the size of interfacing inductor Ldg to the grid, and the DC voltage. As per [18], the relation between switching frequency and the filter inductance can be expressed as

$$L_{dg} = \frac{2V_{dc}}{9h_b f_{sw,max}}$$

where Vde is the DC link voltage, hh is the hysteresis band and f' max is the maximum switching frequency.

IV. SIMULATION RESULTS

To verify the effectiveness and validity of the proposed technique, detailed simulations are done for various load conditions in MATLAB Simulink environment using Power System Blockset. The schematic of the control block diagram is given in Fig.2. The inverter has got a power rating of 20 KVA and the maximum available active power from the DO is 8KW [[8]. The active power reference is taken as 8KW in simulation and is assumed to be constant for all load conditions. The capability of the DO inverter to function as an active power filter is examined first by putting the reference active power as zero. Next the performance of the DO inverter in the forward and reverse power flow modes in the ideal supply voltage conditions are analyzed using the closed loop active power control. The effectiveness of the proposed closed loop control strategy is compared with open loop control under the non-ideal supply conditions at the end. The parameters used for simulations are given in Table 1.

TABLE 1

Simulation Parameters

Parameter	Value
Grid voltage	400V
Grid resistance	0.01 Ω
Grid inductance	0.15 mH
DC link voltage set point	800V
DC link capacitance	3000μF
Interfacing resistance	0.15 Ω
Interfacing inductance	5.5mH
Nonlinear load	25Ω/50Ω,10mH
Smoothing filter inductance	1mH

DOI 10.17148/IJARCCE.2016.55236

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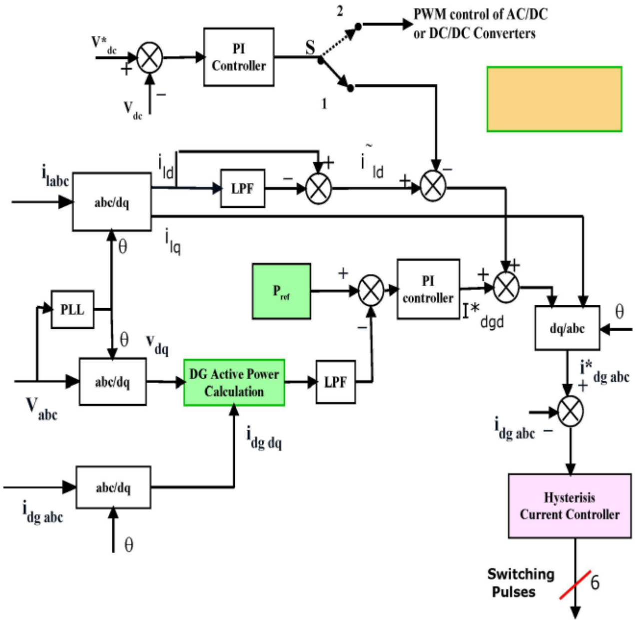


Fig. 2. Control block diagram for generation of switching pulses for the DG inverter.

A. Shunt active filter mode (Pref=O).

When there is no power from the RES the DG inverter operates in shunt active filter mode. The performance of the system with an unbalanced nonlinear load is shown in Fig.3.After the connection of DG at t =0.02 second, the grid currents are balanced and sinusoidal with a total harmonic distortion (THD) of 0.9, 0.89 &0.91 in phases a, b and c. The DC voltage is maintained at the reference value of 800V as shown in Fig. 3

B. Forward Power flow mode (Pret< PJ)

Accurate power tracking. A three phase diode rectifier feeding a load of resistance of 25 n and an inductance of 15mH is connected to the PCC. The nonlinear load currents make the grid currents highly polluted. The DG inverter is connected to the grid at t=0.06 second The DG link DC voltage is assumed constant in this mode in order to evaluate the capability of the proposed control strategy for. The nonlinear part of the load current is supplied by the DG inverter and the grid currents become sinusoidal. Since the load power is greater than the maximum power capacity Pre! of the inverter, the grid also supplies positive power to the load as shown in Fig.4 (a).The grid voltage which is exactly in phase with the grid current is shown in Fig.5 (a), which indicates an improvement

C. Reverse Power flow mode (Pret>PJ)

The resistance of the nonlinear load is increased to 50 n in order to reduce the load power than the reference active power of the DG. Figure 4(b) indicates negative grid power, which means that the excess power from the DG is fed back to the grid during this mode. The grid currents are exactly out of phase with the grid voltage as shown in Fig. 5 (b). The THD of in the input power factor. In all the three modes of operation, the reactive power demand of the load is met by the DG inverter and the reactive power supplied by the grid becomes zero as shown in Fig. 4

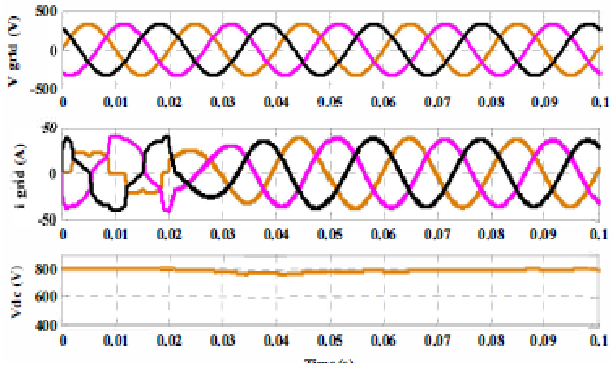


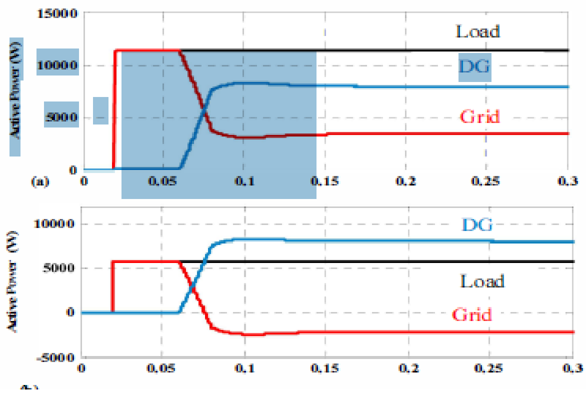
Fig3. Grid voltage, Grid currents and DC link voltage during shunt active filter mode of the DG inverter.

TABLE II
THD of grid currents under ideal supply conditions.

Mode of operation	Before Compensation			After Compensation		
	i_{ga}	i_{gb}	i_{gc}	i_{ga}	i_{gb}	i_{gc}
Forward Power flow	30.18	30.18	30.18	2.4	2.4	2.4
Reverse Power flow	31.57	31.57	31.57	3.55	3.55	3.55

D. Unbalanced and Distorted Supply

An unbalanced three phase supply can be represented using positive and negative sequence components. The presence of negative sequence components in the voltage causes power control errors which cannot be addressed in an open loop power control. To evaluate the effectiveness of the proposed method, the supply voltages are modified by introducing 10% unbalance with 3% third and fifth harmonics. The performance of the inverter is analyzed using the open loop and proposed closed loop power control strategy. The supply voltage is made unbalanced and distorted at t=0.02 sec. The grid currents are balanced and sinusoidal as shown in Fig.6. Figure 7 shows that the closed loop power control strategy is able to track the active power reference with zero steady state errors. With closed loop control the ripples in the injected fundamental current of DG inverter is reduced as shown in Fig. 8. The distortion in the grid currents is also less than that of open loop control and a comparative analysis of THD is given in Table III.



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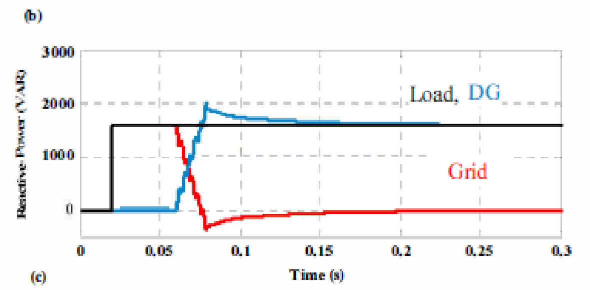


Fig. 4. Grid, DG and Load Active Power in a) Forward power flow mode, b) Reverse power flow mode and c) Reactive Power in both modes.

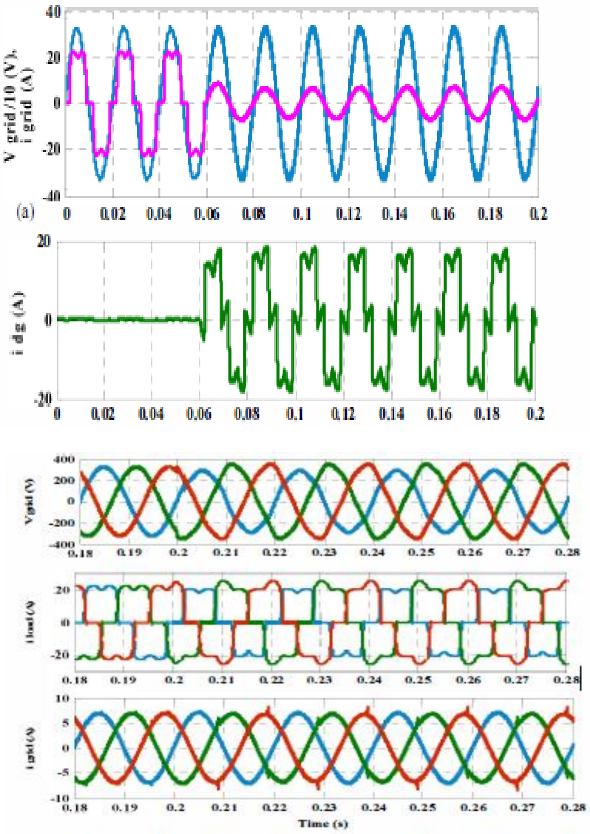


Fig.6. Grid voltage, load and grid currents under unbalanced and distorted supply voltages with closed loop power control.

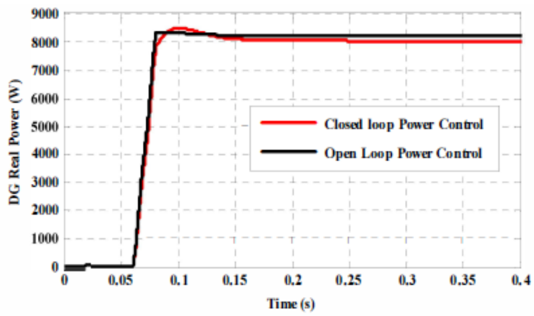
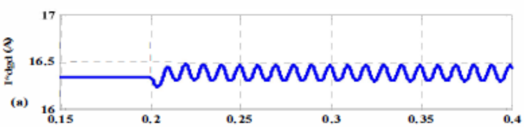


Fig. 7. DG Real power under non ideal supply conditions using open loop and closed loop control.



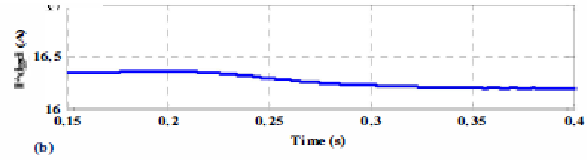


Fig. 8. Fundamental current tracking in a) Open loop and b) Closed loop control.

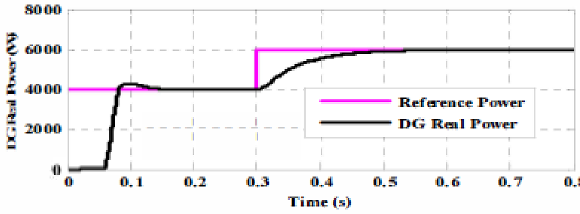


Fig. 9. Dynamic performance of the proposed closed loop power control.

TABLE III
THD of grid currents under unbalanced and distorted supply conditions

Mode of operation	Open Loop Power Control			Closed Loop Power Control		
	i_{ga}	i_{gb}	i_{gc}	i_{ga}	i_{gb}	i_{gc}
Forward Power flow	2.54	4.46	4.24	2.25	4.17	4.1
Reverse Power flow	3.99	4.00	3.99	3.72	3.65	3.75

E. Dynamic performance of the proposed strategy.

The capability of the OG inverter to track the changes in active power of the RES is analyzed by giving a step increase of reference power from 4000W to 6000W under the non-ideal supply conditions. Figure 9 indicates that the closed loop power strategy is able to follow the changes in the power smoothly which shows the effectiveness of the proposed scheme.

V. CONCLUSION

This paper discusses the capabilities of a MFGCI for enhancing the power quality in a grid connected distributed generation system. It has been shown that the DG inverter can be effectively utilized to inject real power from the RES in the forward and reverse power flow modes and/or operate as a shunt active power filter. The proposed closed loop active power control strategy achieves accurate power tracking with zero steady state errors under ideal and non-ideal supply conditions and can be used as a control technique for integration of DG inverters to the utility grid. The method eliminates the need of extra power conditioning devices to improve the power quality. The effectiveness of the control scheme is verified under balanced and unbalanced nonlinear load conditions. With the proposed method the combination of nonlinear loads and the DG inverter is seen as a resistive load at the PCC and the grid currents are maintained sinusoidal. the PCC and the grid currents are maintained sinusoidal.

DOI 10.17148/IJARCCE.2016.55236

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