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A Novel Control Strategy Using Grid Interfacing Inverters In 3-Phase 4-Wire Distributed Systems With Power Quality Improvement Techniques

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Abstract:

Modern technology, incorporating sensitive components, present new challenges for plant managers and engineers. This paper presents a strategy to mitigate the effects of these sensitive devices using grid interfacing inverters when installed in three phase four wire systems. This inverter acts as an shunt APF to compensate the current harmonics, load reactive power demand and load neutral current. Moreover this paper deals with usage of renewable energy to compensate the above effects .this inverter also acts as an converter to inject power generated from RES to grid. All these works of the inverter is done either individually or combined to overcome the unbalanced effects of all types of non-linear loads at the point of common coupling to make the load to be linear to the grid. This concept is demonstrated with the extensive MATLAB\SIMULINK simulation studies and Effectiveness of the system is confirmed by the experimental results .

Index Terms—Active power filter (APF), distributedgeneration(DG),distributionsystem,grid interconnection, power quality
(PQ), renewable energy

1. Introduction

Power sources act as non-linear loads, drawing a distorted waveform that contains harmonics. It is important to gauge the total effect of these harmonics. This paper will attempt to explain the concept of THD and its effects on electrical equipment. It will also outline the low THD of the Associated Power Technologies (APT) line of programmable sources and how these can be used to more effectively test equipment Total harmonic distortion.Renewable energy source (RES) integrated at distribution level is termed as distributed generation (DG). The utility is concerned due to the high penetration level of intermittent RES in distribution systems.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 PCC.Generally, current controlled voltage source inverters are used to interface the intermittent RES in distributed system.A approach in which a shunt active filter acts as active conductance to damp out the harmonics in distribution network is proposed .a control strategy for renewable interfacing inverter based on – theory is proposed. In this strategy both load and inverter current sensing is required to compensate the load current harmonics. 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. 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-interfacing inverter can effectively be utilized to perform following important functions: 1) transfer of active power harvested from the renewable resources (wind, solar, etc.); 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.

2.System Description

The PQ constraints at the PCC can be strictly maintained within the utility standards without additional hardware cost. The active filter concept uses power electronic equipment to produce harmonic current components that cancel the harmonic current components from the nonlinear loads. The current wave form for canceling harmonics is achieved with the voltage source inverter in the current controlled mode and an interfacing filter. The desired current waveform is obtained by accurately controlling the switching of the insulated gate bipolar transistors (IGBT's) in the inverter. The driving voltage across the interfacing inductance determines the maximum di/dt that can be achieved by the filter A large inductor is better for isolation from the power system and protection from transient disturbances. However, the larger inductor limits the ability of the active filter to cancel higher order harmonics.

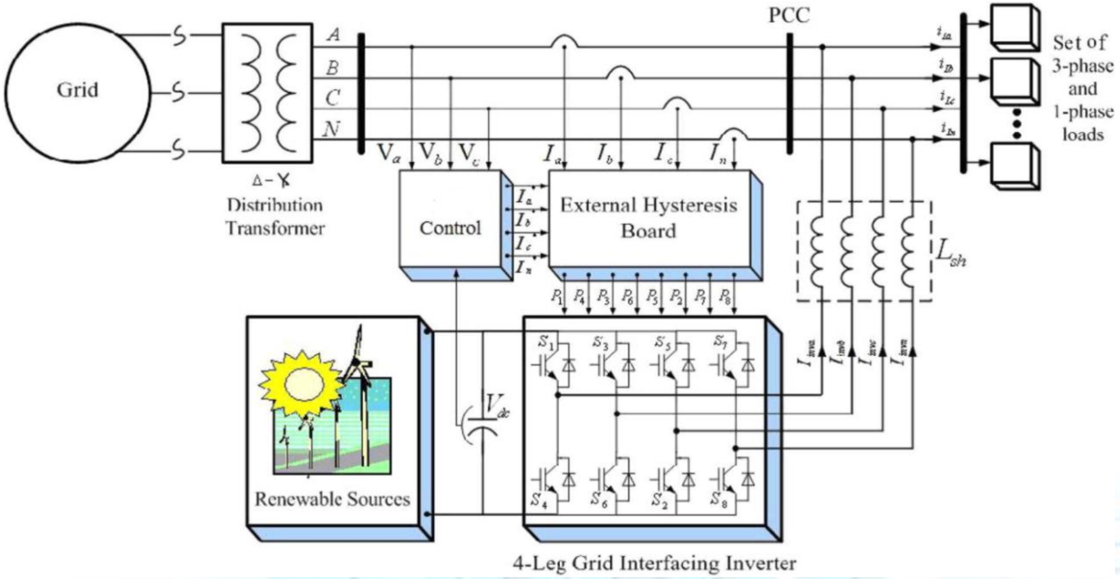

Fig. 1. Schematic of proposed renewable based distributed generation system.

2.1 Control of Grid Interfacing Inverter

The control diagram of grid- interfacing inverter for a 3-phase 4-wire system is shown in Fig. 3. The fourth leg of inverter is used to compensate the neutral current of load. The main aim of proposed approach is to regulate the power at PCC during 1)P_{RES} = 0; 2) P_{RES} <total load power(P_L) ; and 3) P_{RES} > total load power(P_L) . While performing the power management operation,the inverter is actively controlled in such a way that it always draws/ supplies fundamental active power from/ to the grid. If the load connected to the PCC is non-linear or unbalanced or the combination of both, the given control approach also compensates the harmonics, unbalance, and neutral current. The output of dc-link voltage regulator results in an active current (I_m). The multiplication of active current

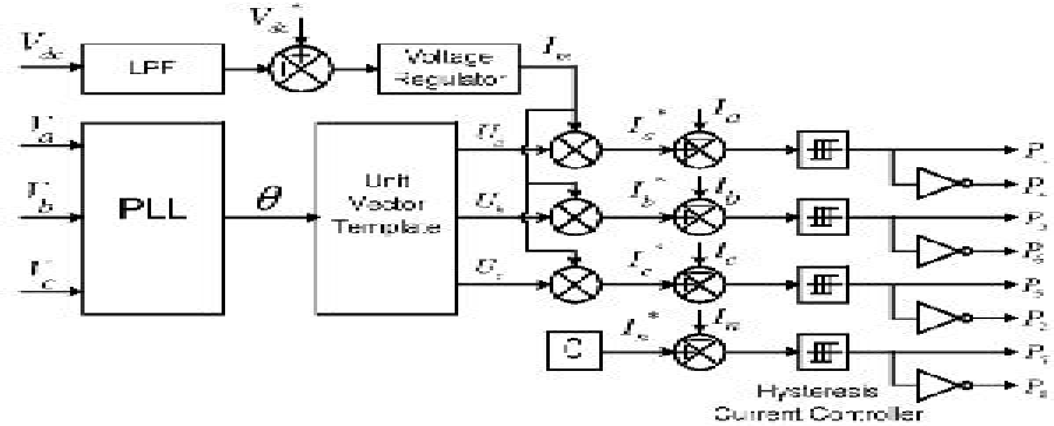

Fig. 2. Block diagram representation of grid-interfacing inverter control.

component (Im) with unity grid voltage vector templates (U_a U_b, U_c) generates the reference grid currents (I_a^*,I_b^*,and I_c^*). The reference grid neutral current (I_n^*) is set to zero, being the instantaneous sum of balanced grid currents. The grid synchronizing angle obtained from phase locked loop (PLL) is used to generate unity vector template $\mathbf{U_a=Sin(\theta), U_b=Sin(\theta-2\pi/3), U_c=Sin(\theta+2\pi/3)}$

The actual dc-link voltage (V_{dc}) is sensed and passed through a first-order *low pass filter* (LPF) to eliminate the presence of switching ripples on the dc-link voltage and in the generated reference current signals. The difference of constant dc-link voltage under varying generation and load conditions. The dc-link voltage error $V_{dcerr(n)}$ at th sampling instant is given as,$\mathbf{V_{dcerr(n)}= V_{dc(n)}^{*} -V_{dc(n)}}$

The instantaneous values of reference three phase grid currents are computed as ,$\mathbf{I_a^* = I_m. U_a}$,,$\mathbf{I_b^*= I_m. U_b}$,,$\mathbf{I_c^*= I_m. U_c}$.The neutral current, present due to the loads connected to the neutral conductor should be compensated by forth leg of grid-interfacing inverter and thus should not be drawn from the grid. It can be expressed as $\mathbf{I_n^*=0}$

The reference grid currents (I_a^*, I_b^*,I_c^* and I_n^*) are compared with actual grid currents (I_a, I_b,I_c and I_n)) to compute the current errors as

$\mathbf{I_{aerr}= I_a^*-I_a, I_{berr}= I_b^*-I_b, I_{cerr}= I_c^*-I_c, I_{nerr}= I_n^*-I_n}$.These current errors are given to hysteresis current controller. 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}<(I_{Inva}^*-h_b), then upper switch S_1will be OFFand lower switchS_4 will be ONin the phase "a" leg of inverter.If I_{Inva}>(I_{Inva}^*-h_b), then upper switch S_1 will be ONand lower switch S_4will be OFFin 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.

3. Simulation Results

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 on PCC. The waveforms of grid voltage(V_a,V_b,V_c) grid currents (I_a , I_b, I_c , I_n), unbalanced load current(I_{la} , I_{lb}, I_{lc} , I_{ln})and inverter currents(I_{Inva}, I_{Invb} , I_{Invc} , I_{Invn})are shown in Fig. 4. Positive values of grid active-reactive powers and inverter active-reactive powers imply that these powers flow from grid side towards PCC and from inverter towards PCC, respectively. The active and reactive powers absorbed by the load are denoted by positive signs. Initially, the grid-interfacing inverter is not connected to the network (i.e., the load power demand is totally supplied by the grid alone). Therefore, before time s, the grid current profile in Fig. 3(b) is identical to the load current profile of Fig. 3(c). At s, the grid-interfacing 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 nonlinear to balanced sinusoidal current as shown in Fig. 3(b). As the inverter also supplies the load neutral current demand, the grid neutral current(I_n) becomes zero after t=0.72 s. At t=0.72 s, the inverter starts injecting active power generated from RES(P_{RES}~P_{inv}). Since the generated power is more than the load power demand the additional power is fed back to the grid. The negative sign of P_{grid}, after time 0.72 s suggests that the grid is now receiving power from RES.The inverter is in operation the grid only supplies/receives fundamental active power. At t=0.82s, 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. The additional power generated from RES flows towards grid, which can be noticed from the increased magnitude of grid current as indicated by its profile. At t=0.92s, the power available from RES is reduced. The corresponding change in the inverter and grid currents can be seen from Fig. 4. The active and reactive power flows between the inverter, load and grid during increase and decrease of energy generation from RES enables the grid to supply/ receive sinusoidal and balanced power at UPF.

4. Experimental Validation

The performance of the proposed control approach is validated with the help of a scaled laboratory prototype that has system parameters as given in Table I. The RES is emulated

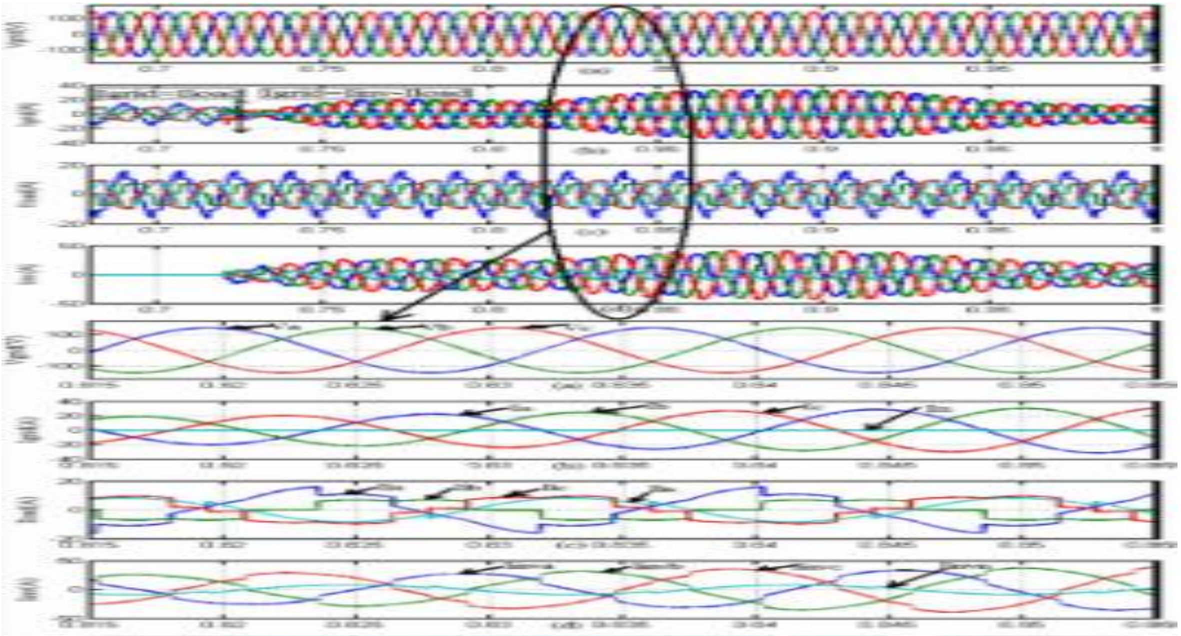

Fig. 3. Simulation results: (a) Grid voltages, (b) Grid Currents (c) Unbalanced load currents, (d) Inverter Currents

TABLE I
SYSTEM PARAMETER

3-phase Supply (r.m.s.)	:	V_g=30 V, 60 Hz
3-phase Non-linear Load	:	R=26.66Ω, L=10 mH
1-phase Linear Load (A-N)	:	R=36.66Ω, L=10 mH
1-phase Non-Linear Load (C-N)	:	R=26.66Ω, L=10 mH
DC-Link Capacitance & Voltage:		C_{dc}=3000 μF, V_{dc}=90 V
Coupling Inductance	:	L_{sh}=2.0 mH

transistor using an auxiliary controlled converter, which injects varying active power at the dc-link of an insulated gate bipolar (IGBT) based 4-leg voltage source inverter connected to grid. A 3-phase 4-wire nonlinear load, composed of 3-phase non-linear balanced load, 1-phase R-L load between phase a and neutral and 1-phase non-linear load between phase and neutral, is connected to the grid. The total harmonics distortions (THDs) of phase a,b and c load currents are noticed as 14.21%, 22.93%, and 16.21%, respectively. The difference of reference and actual grid current signals is applied to external hysteresis board to generate the gate pulses for IGBT's. The experimental results are divided into three different modes of operation in order to highlight the validity of proposed controller. First mode of operation considers a situation when there is no power generation from RES. Under such condition, the grid-interfacing inverter is utilized as shunt APF to enhance the quality of power at PCC. While in second mode of operation, the inverter injects RES active power into grid and also incorporates the active power filtering functionality. In the third mode, the dynamic operation of proposed controller is examined.

4.1 Mode of Operation—PQ Enhancement (P_{RES}=0)

Fig. 6 shows the experimental results for active power filtering mode of operation when there is no power generation from RES. All the current waveforms are shown with respective to grid side phase voltage(V_a) . Fig. 5(a) shows the profile of the unbalance non-linear load currents. The grid current profile, when grid-interfacing inverter controlled as shunt APF, is shown in Fig. 6(b). It can be noticed that the highly unbalanced load currents, after compensation, appear as pure sinusoidal balanced set of currents on grid side. The grid current THD's are reduced to 2.36%, 1.68%, 3.65% for a,b and c phases, respectively. In Fig. 6(c), the compensating inverter currents are shown for each phase along with dc-link voltage. For the experimental study, the dc-link voltage is maintained at 100 V. Fig. 6(d) shows the traces for neutral current of grid, load and inverter. The load neutral current due to single-phase loads is effectively compensated by the 4th leg of

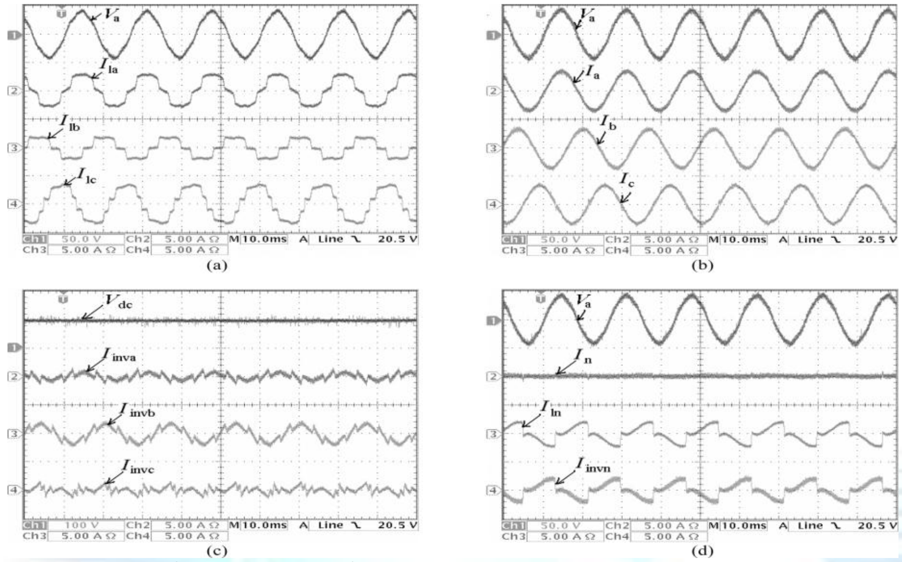

Fig. 4. Experimental results for the active power filtering mode(P_{RES}=0)(a) unbalanced load currents, (b) grid currents after compensation, (c) currents injected by grid-interfacing inverter, (d) load, grid and inverter neutral currents.

inverter such that the current in grid side neutral conductor is reduced to zero. The total active and reactive powers of grid, load and inverter. In the APF mode of operation, the inverter consumes a small amount of active power to maintain the dc-link voltage and to overcome the losses associated with inverter, while most of the load reactive power need is supported by inverter effectively. Thus, this mode of operation validates the concept of utilization of grid-interfacing inverter as shunt APF when there is no power generation from the RES. The experimental results demonstrate the effective compensations of load current unbalance, harmonics and reactive power.

4.2 Mode of Operation—Simultaneous PQ Enhancement and RES Power Injection(P_{RES}>P_L)

The experimental results for simultaneous active power filtering and RES power injection mode are shown in Fig. 7. In this case study it is considered that the generated power at grid-interfacing inverter is more than the total load power demand. Therefore, after meeting the load power demand, the additional RES power flows towards grid. The profiles of grid, load and inverter currents for individual phases are shown in Figs. 5(a),(b) & (c) for phase a, b and c respectively. As noticed from Fig. 5(a) to (c), the inverter currents consist of two components: 1) steady-state load current component and 2) grid active power injection component. Thus the grid-interfacing inverter now provides the entire load power demand (active, reactive and harmonics) locally and feeds the additional active power (sinusoidal and balanced) to the grid. The exact out-of phase relationship between phase— grid voltage and phase— grid current suggests that this additional power is fed to the grid at UPF. The three-phase grid currents (Fig. 5(d)) suggest that the injected active power from RES to the grid is supplied as balanced active power even the load on the system is unbalanced in nature. The negative sign of total grid side active power demonstrates that the excess power generated by RES flows towards grid side.

5. CONCLUSION

This paper has presented a novel control of an existing grid interfacing inverter to improve the quality of power at PCC for a 3-phase 4-wire DG system. The grid-interfacing inverter with the proposed approach can be utilized to: i) inject real power generated from RES to the grid, and/or,ii) 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. It is demonstrated that the PQ enhancement can be achieved under three different scenarios: 1) P_{RES}=0 , 2) P_{RES}>P_{LOAD} , and 3) P_{RES}<P_{LOAD} 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 UPF.

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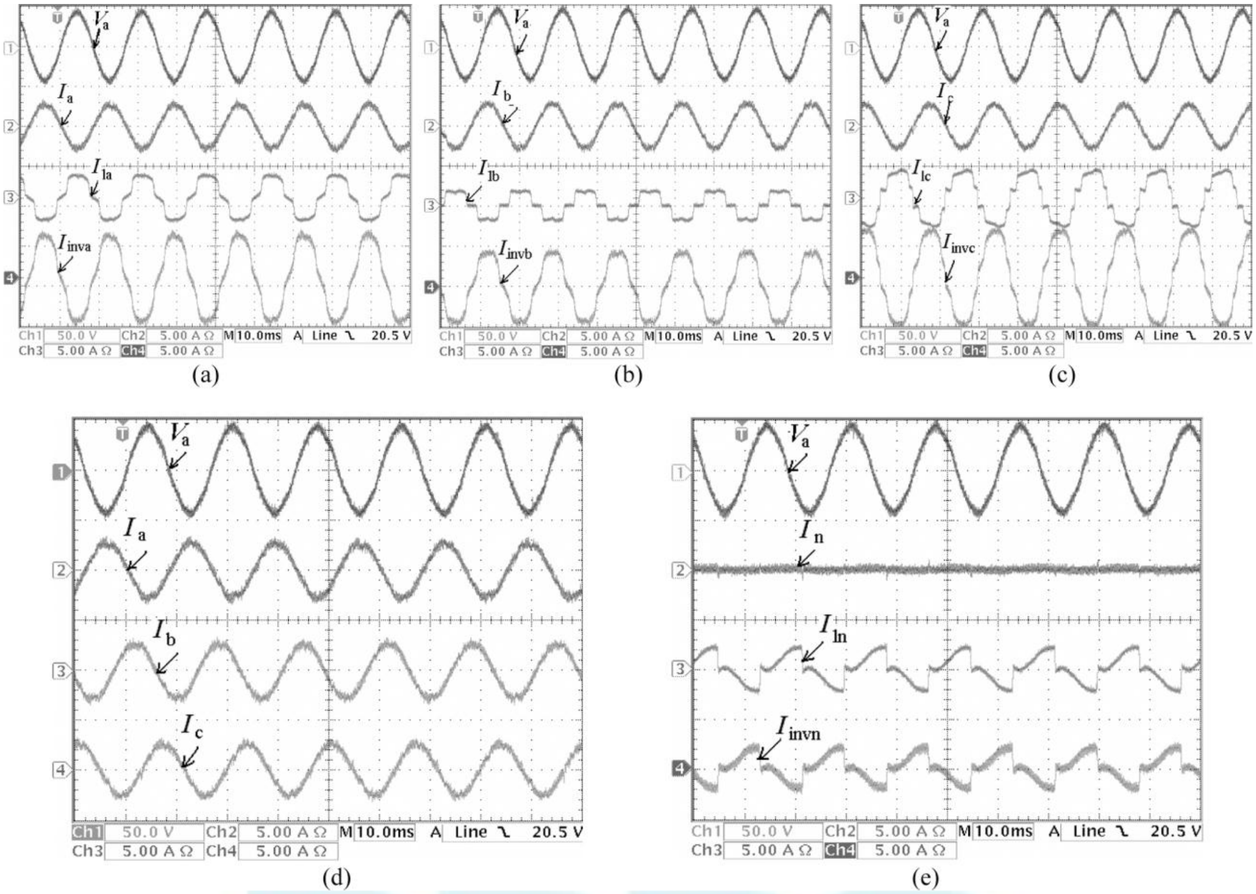

Fig. 5. Experimental results for the active power filtering and renewable power injection mode (P_{RES}>P_L)(a) phase _ performance, (b) phaseperformance,(c) phase performance, (d) grid currents (e) load, grid and inverter neutral currents.

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