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Power Quality Improvement Using Grid Interconnected Renewable Energy Sources At Distribution Level

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ABSTRACT: A Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure or a disoperation of end user equipments. Utility distribution networks, sensitive industrial loads and critical commercial operations suffer from various types of outages and service interruptions which can cost significant financial losses. Renewable energy resources (RES) are being increasingly connected in distribution systems utilizing power electronic converters. This paper presents a novel control strategy for achieving maximum benefits from these grid-interfacing inverters when 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 inject power generated from RES to the grid, and 2) 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. This new control concept is demonstrated with extensive MATLAB/Simulink .Finally the proposed shceme is applied for both balanced and unbalanced linear non linear loads.

Index Terms: Power quality, Photo Voltaic (PV) System, distributed generation (DG), distribution system, grid interconnection, power quality (PQ), renewable energy.

I. INTRODUCTION

Power quality is one of the most important topics that electrical engineers have been noticed in recent years. Voltage sag is one of the problems related to power quality. This phenomenon happens continuously in transmission and distribution systems. During a voltage sag event, amplitude of the effective load voltage decrease from 0.9 of the nominal load voltage to 0.1 in very short time (less than one minute). Short circuit, transformer energizing, capacitor bank charging etc are causes of voltage sag. Voltage sag has been classified in 7 groups from A to G . According to this classification most of voltage sags are companion with a phase angle jump (types C, D, F and G). Phase angle jump for power electronics systems such as ac-ac and ac-dc converters, motor drives etc is harmful. Therefore, phase angle jump compensation is one of the voltage sag mitigation goals.

Most industries and companies prefer electrical energy with high quality. If delivered energy to these loads has poor quality, products and equipment of these loads such as microcontrollers, computers, motor drives etc are damaged. Hurt of this phenomenon in companies that dealing with information technology systems is serious. According to a study in U.S., total damage by voltage sag amounts to 400 Billion Dollars. For these reasons power quality mitigation in power systems is necessary. Nowadays, Custom Power equipments are used for this purpose.

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 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 PCC. However, the extensive use of power electronics based equipment and non-linear loads at PCC generate harmonic currents, which may deteriorate the quality of power.

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 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 this paper 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. This results in an additional hardware cost. However, in this paper authors have incorporated the features of APF in the, conventional inverter interfacing renewable with the grid, without any additional hardware cost. 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. Moreover, with adequate control of grid-interfacing inverter, all the four objectives can be accomplished either individually or simultaneously. The PQ constraints at the PCC can therefore be strictly maintained within the utility standards without additional hardware cost.

In this paper RES used were solar and wind. The paper is arranged as follows: Section II describes the proposed circuit. Section III describes simulation study.

II. PROPOSED CONCEPT

The proposed system consists of RES connected to the dc-link of a grid-interfacing inverter as shown in Fig. 1. The voltage source inverter is a key element of a DG system as it interfaces the renewable energy source to the grid and delivers the generated power. 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. The dc-capacitor decouples the RES from grid and also allows independent control of converters on either side of dc-link source to the grid. RES are represented as current sources connected to the dc-link of a grid-interfacing inverter. Fig. 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 into dc-link at voltage level V_{dc} can be given as

$$I_{\mathrm{dc1}} = \frac{P_{\mathrm{RES}}}{V_{\mathrm{dc}}} \qquad (1)$$

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

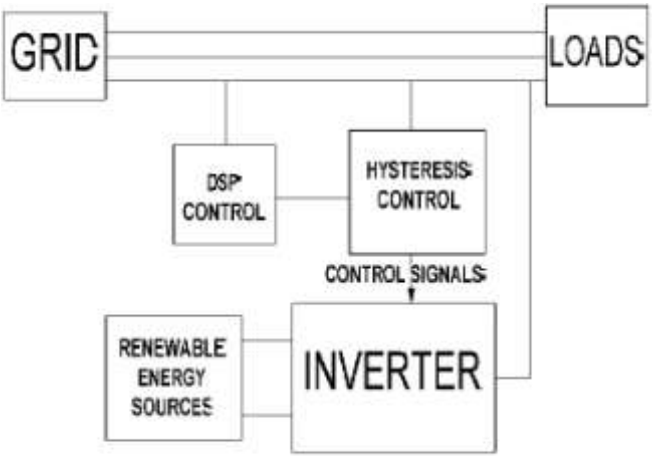


Fig.1 Schematic diagram of a proposed converter with RES

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

$$I_{\mathrm{dc2}} = \frac{P_{\mathrm{inv}}}{V_{\mathrm{dc}}} = \frac{P_G + P_{\mathrm{Loss}}}{V_{\mathrm{dc}}} \qquad (2)$$

Where P_{IN} 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_{RESS}=P_G

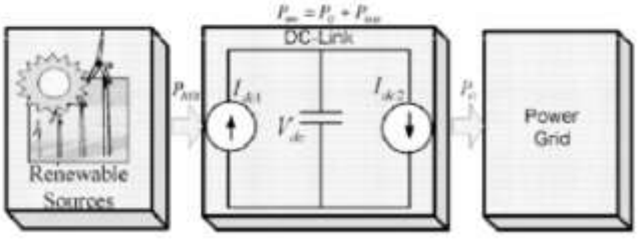


Fig. 2. DC-Link equivalent diagram

B. 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_{RESS}=0; 2) P_{RESS}< total load power(P_L);

A. DC-Link Voltage and Power Control Operation and 3) $P_{RESS}>P_L$. While performing the power management

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 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 duty ratio of inverter switches are varied in a power cycle such that the combination of load and inverter injected power appears as balanced resistive load to the grid. The regulation of dc-link voltage carries the information regarding the exchange of active power in between renewable source and grid. Thus the output of dc-link voltage regulator results in an active current (I_m). The multiplication of active current component (I_m) with unity grid voltage vector templates (U_a,U_b,U_c) generates the reference grid currents(I^*_a,I^*_b,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 as

$$U_a = \mathrm{Sin}(\theta) \qquad (3)$$

$$U_b = \mathrm{Sin}(\theta - \frac{2\pi}{3}) \qquad (4)$$

$$U_c = \mathrm{Sin}(\theta + \frac{2\pi}{3}). \qquad (5)$$

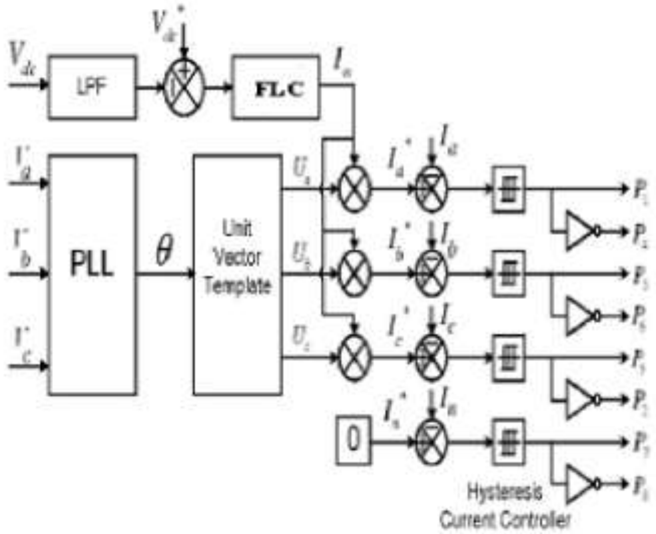


Fig.. 3 A FLC Control method for proposed converter

$$I_{m(n)} = I_{m(n-1)} + K_{PV_{dc}}(V_{\text{dcerr}(n)} - V_{\text{dcerr}(n-1)}) + K_{IV_{dc}} V_{\text{dcerr}(n)} \quad (7)$$

Where K_{PVdc} =10and K_{IVdc}=0.05 are proportional and integral gains of dc-voltage regulator. The instantaneous values of reference three phase grid currents are computed as

$$I_a^* = I_m \cdot U_a \quad (8)$$
$$I_b^* = I_m \cdot U_b \quad (9)$$
$$I_c^* = I_m \cdot U_c. \quad (10)$$

The neutral current, present if any, 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. In other words, the reference current for the grid neutral current is considered as zero and can be expressed as

$I^*_n=0$ (11)

The reference grid currents (I^*_a, I^*_b, I^*_c and I^*_n) are compared with actual grid currents (and) to compute the current errors as

$$I_{\text{aerr}} = I_a^* - I_a \quad (12)$$
$$I_{\text{berr}} = I_b^* - I_b \quad (13)$$
$$I_{\text{cerr}} = I_c^* - I_c \quad (14)$$
$$I_{\text{nerr}} = I_n^* - I_n. \quad (15)$$

These current errors are given to hysteresis current controller. The hysteresis controller then generates the switching pulses (P_1 to P_8) for the gate drives of grid-interfacing inverter. The average model of 4-leg inverter can be obtained by the following state space equations

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 this filtered dc-link voltage and reference dc-link voltage (V^*_{dc}) is given to a discrete- PI regulator to maintain a constant dc-link voltage under varying generation and load

$$\frac{dI_{\text{Inva}}}{dt} = \frac{(V_{\text{Inva}} - V_a)}{L_{\text{sh}}} \quad (16)$$
$$\frac{dI_{\text{Invb}}}{dt} = \frac{(V_{\text{Invb}} - V_b)}{L_{\text{sh}}} \quad (17)$$
$$\frac{dI_{\text{Invc}}}{} = \frac{(V_{\text{Invc}} - V_c)}{} \quad (18)$$

conditions. The dc-link voltage error $V_{dcerr(n)}$ at n th sampling instant is given as:

$$V_{\text{dcerr}(n)} = V^*_{\text{dc}(n)} - V_{\text{dc}(n)}. \quad (6)$$

The output of discrete-PI regulator at th sampling instant is expressed as

$$dt \qquad L_{\text{sh}}$$
$$\frac{dI_{\text{Invn}}}{dt} = \frac{(V_{\text{Invn}} - V_n)}{L_{\text{sh}}} \quad (19)$$
$$\frac{dV_{\text{dc}}}{dt} = \frac{(I_{\text{Invad}} + I_{\text{Invbd}} + I_{\text{Invcd}} + I_{\text{Invnd}})}{C_{\text{dc}}} \quad (20)$$

Where, VI_{nva}, $VI_{nvb,}$ $VI_{nvc,}$ and VI_{nvn} are the three-phase ac switching voltages generated on the output terminal of

inverter. These inverter output voltages can be modelled in terms of instantaneous dc bus voltage and switching pulses of the inverter as

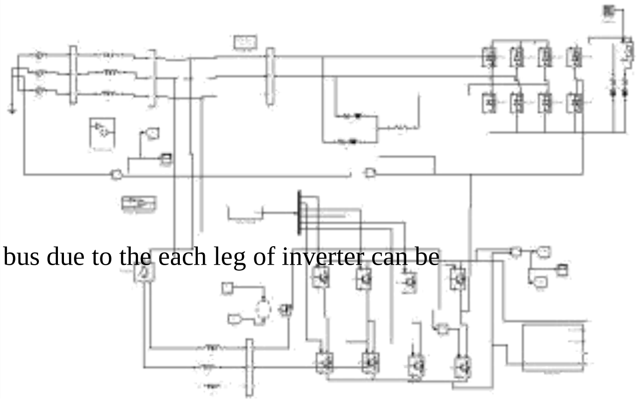
$$V_{\mathrm{Inva}} = \frac{(P_1 - P_4)}{2} V_{\mathrm{dc}} \qquad (21)$$

$$V_{\mathrm{Inva}} = \frac{(P_3 - P_6)}{2} V_{\mathrm{dc}} \qquad (22)$$

$$V_{\mathrm{Inva}} = \frac{(P_5 - P_2)}{2} V_{\mathrm{dc}} \qquad (23)$$

$$V_{\mathrm{Inva}} = \frac{(P_7 - P_8)}{2} V_{\mathrm{dc}}. \qquad (24)$$

A. Modeling of power circuit:



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

$$I_{\mathrm{Invad}} = I_{\mathrm{Inva}}(P_1 - P_4) \qquad (25)$$

$$I_{\mathrm{Invbd}} = I_{\mathrm{Invb}}(P_3 - P_6) \qquad (26)$$

$$I_{\mathrm{Invcd}} = I_{\mathrm{Invc}}(P_5 - P_2) \qquad (27)$$

$$I_{\mathrm{Invad}} = I_{\mathrm{Inva}}(P_7 - P_8). \qquad (28)$$

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 $I_{\mathrm{Inva}} < (I^*_{\mathrm{Inva}} - h_b)$, then upper switch S_1 will be OFF ($P_1 = 0$) and lower switch S_4 will be ON ($P_4 = 1$) in the phase "a" leg of inverter.

If $I_{Inva} > (I^*_{\mathrm{Inva}} - h_b)$, then upper switch S_1 will be ON ($P_1 = 1$) and lower switch S_4 will be OFF ($P_4 = 0$) 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.

III. 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 on PCC. The waveforms of grid voltage (Va, Vb,Vc), grid currents (Ia,Ib,Ic,In), 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. The corresponding active-reactive powers of grid (P_{grid}, Q_{grid}), load (P_{load}, Q_{load}) and inverter (P_{inv},Q_{inv}) are shown in Fig. 5. 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.

Fig. 4 Matlab/Simulink Model of Proposed Power Circuit

Fig. 4 shows the complete MATLAB model of proposed power circuit along with control circuit. The power circuit as well as control system are modeled using Power System Block set and Simulink. The grid source is represented by three-phase AC source. Three-phase AC loads are connected at the load end. Converter is connected in shunt and it consists of PWM voltage source inverter circuit and a DC capacitor connected at its DC bus. An IGBT-based PWM inverter is implemented using Universal bridge block from Power Electronics subset of PSB. Snubber circuits are connected in parallel with each IGBT for protection. Simulation of proposed system is carried out for non-linear load. The non-linear load on the system is modeled using R and R-C circuits connected at output of the diode rectifier. Provision is made to connect loads in parallel so that the effect of sudden load addition and removal is studied. The feeder connected from the three-phase source to load is modeled using appropriate values of resistive and inductive components.

B. Modeling of Control Circuit using PI controller.

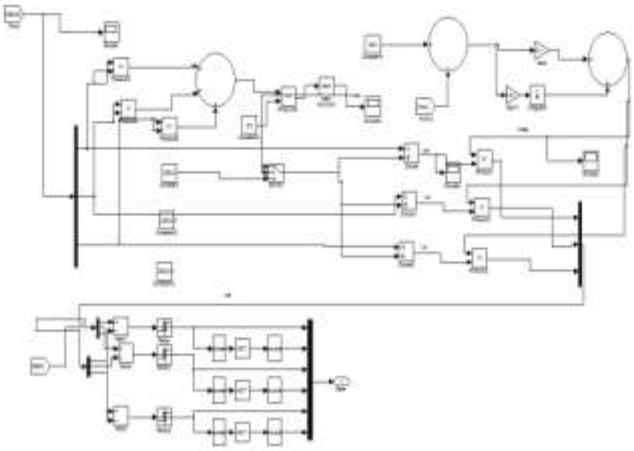


Fig. 5 Control Circuit

Fig. 5 shows the control algorithm of proposed converter with PI controller. PI controller regulates the DC link voltage. The in-phase components of inverter reference currents are responsible for power factor correction of load and the quadrature components of supply reference currents are to regulate the AC system voltage at PCC.

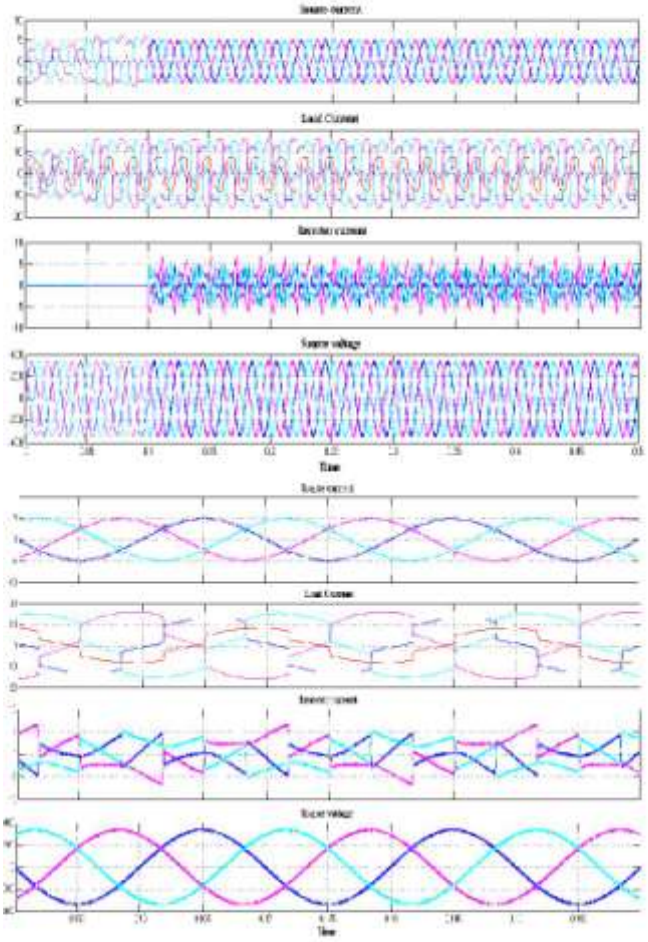


Fig. 6 Matlab/Simulink wave forms of Proposed Power Circuit indicating source current, load current, injected current, source voltage

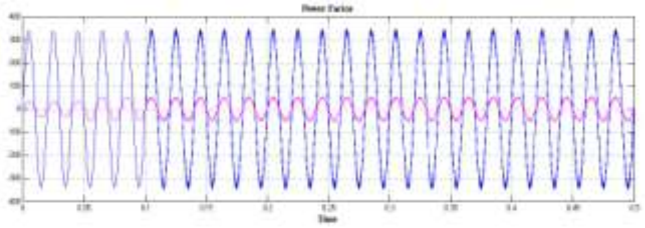


Fig. 7 Matlab/Simulink wave forms of Proposed Power Circuit indicating supply side power factor

The output of PI controller over the DC bus voltage (*I*spdr) is considered as the amplitude of the in-phase component of supply reference currents and the output of PI controller over AC terminal voltage (*I*spqr) is considered as the amplitude of the quadrature component of supply reference currents. The instantaneous reference currents (*i*sar, *i*sbr and *i*scr) are obtained by adding the in-phase supply reference currents (*i*sadr, *i*sbdr and *i*scdr) and quadrature supply reference currents (*i*saqr, *i*sbqr and *i*scqr). Once the reference supply currents are generated, a carrier less hysteresis PWM controller is employed over the sensed supply currents (*i*sa, *i*sb and *i*sc) and instantaneous reference currents (*i*sar, *i*sbr and *i*scr) to generate gating pulses to the IGBTs of converter. The controller controls the converter currents to maintain supply currents in a band around the desired reference current values. The hysteresis controller generates appropriate switching pulses for six IGBTs of the VSI working as converter.

V. **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-wireDGsystem. It has been shown that the grid-interfacing inverter can be effectively utilized for power conditioning without affecting its normal operation of real power transfer. The grid-interfacing inverter with the proposed approach can be

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. Extensive MATLAB/Simulink simulation as well as the DSP based experimental results have validated the proposed approach and have shown that the grid-interfacing inverter can be utilized as a multi-function device.

It is further 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. 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 fulfils the total load active and reactive power demand but also delivers the excess generated sinusoidal active power to the grid at unity power factor.

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