

New Inverter Topology for Grid Support and Harmonic Mitigation For Interconnecting Renewable Power Generation Systems

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Abstract: Renewable generation affects power quality due to its nonlinearity, since solar generation plants and wind power generators must be connected to the grid through high-power static PWM converters. This paper presents active power filter implemented with a four-leg voltage-source inverter. A Novel predictive control scheme is implemented to control the inverter. The main features of this control scheme is 1) To control power converter to inject power generated from RES to the grid, and 2)To act as a shunt APF to compensate current unbalance, load current harmonics, load reactive power demand and load neutral current. The compensation performance of the proposed active power filter and the associated control scheme under steady state and transient operating conditions is demonstrated through simulations results. 3) The results are presented for both wind & solar type renewable power generation systems.

I.INTRODUCTION

Electric utilities and end users of electric power are becoming increasingly concerned about meeting the growing energy demand. Seventy five percent of total global energy demand is supplied by the burning of fossil fuels. But increasing air pollution, global warming concerns, diminishing fossil fuels and their increasing cost have made it necessary to look towards renewable sources as a future energy solution. Since the past decade, there has been an enormous interest in many countries on renewable energy for power generation. The market liberalization and government's incentives have further accelerated the renewable energy sector growth.

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 [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]. In [5], 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.

This paper presents the mathematical model of the 4L-VSI and the principles of operation of the proposed predictive control scheme, including the design procedure. The complete description of the selected current reference generator implemented in the active power filter is also presented. 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.

II. SYSTEM DESCRIPTION

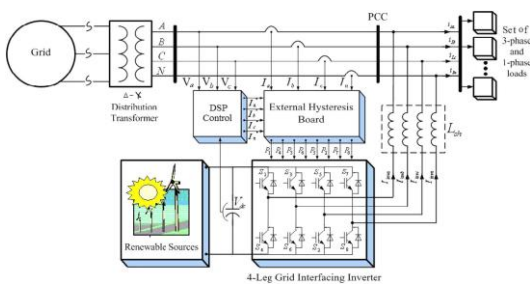


Fig. 1.Schematic of proposed renewable based distributed generation system.

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 [6]–[8]. The dc-capacitor decouples the RES from grid and also allows independent control of converters on either side of dc-link.

III.MODELLING OF INVERTER

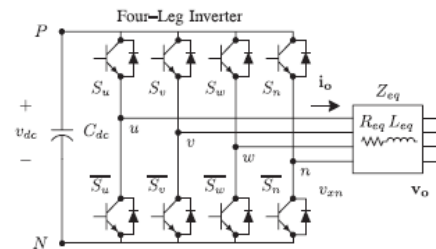


Fig. 2.Two-level four-leg PWM-VSI topology.

NOMENCLATURE

- AC Alternating current.
- Dc Direct current.
- PWM Pulse width modulation.
- PC Predictive controller.

- PLL Phase-locked-loop.
- Vdc Dc-voltage.
- Vs System voltage vector $[vsuvsvvsw]^T$.
- Is System current vector $[isuisvisiw]^T$.
- I Load current vector $[iLuiLviLw]^T$.
- Vo VSI output voltage vector $[vouovovw]^T$.
- Io VSI output current vector $[iouioviow]^T$.
- Io* Reference current vector $[i^*ou i^*v i^*w]^T$.
- In Neutral current.
- Lf Filter inductance.
- Rf Filter resistance.

The four-leg PWM converter topology is shown in Fig. 2. This converter topology is similar to the conventional three-phase converter with the fourth leg connected to the neutral bus of the system. The fourth leg increases switching states from 8 (2^3) to 16 (2^4), improving control flexibility and output voltage quality[9], and is suitable for current unbalanced compensation. The voltage in any leg x of the converter, measured from the neutral point (n), can be expressed in terms of switching states,as follows:

$$v_{xn} = S_x - S_n v_{dc}, \quad x = u, v, w, n. \quad (1)$$

The mathematical model of the filter derived from the equivalent circuit

$$v_o = v_{xn} - R_{eq}i_o - L_{eq}di_o/dt \quad (2)$$

where R_{eq} and L_{eq} are the 4L-VSI output parameters expressed as Thevenin impedances at the converter output terminals Z_{eq} . Therefore, the Thevenin equivalent impedance is determined by a series connection of the ripple filter impedance Z_f and a parallel arrangement between the system equivalent impedance Z_s and the load impedance Z_L

$$Z_{eq} = Z_s Z_L / (Z_s + Z_L) + Z_f \approx Z_s + Z_f. \quad (3)$$

For this model, it is assumed that $Z_L > Z_s$, that the resistive part of the system's equivalent impedance is neglected, and that the series reactance is in the range of 3–7% p.u., which is an acceptable approximation of the real system. Finally, in (2) $R_{eq} = R_f$ and $L_{eq} = L_s + L_f$.

Current Reference Generator: This unit is designed to generate the required current reference that is used to compensate the undesirable load current components. In this case, the system voltages, the load currents, and the dc-voltage converter are measured, while the neutral output current and neutral load current are generated directly from these signals

IV.SYNCHRONOUS REFERENCE THEORY (SRF) FOR CURRENT REFERENCE GENERATION

In the SRF, the load current signals are transformed into the conventional rotating frame d-q. If θ is the transformation angle, The transformation is defined by:

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (7)$$

Where x denotes voltages or currents. In the SRF θ is a time varying angle that represents the angular position of the reference frame which is rotating at constant speed in synchronism with the three phase ac voltages. To

implement the SRF method some kind of synchronizing system should be used. In phase-locked loop (PLL) is used for the implementation of this method. In this case the speed of the reference frame is practically constant, that is, the method behaves as if the reference frame's moment of inertia is infinite. The fundamental currents of the d-q components are now dc values

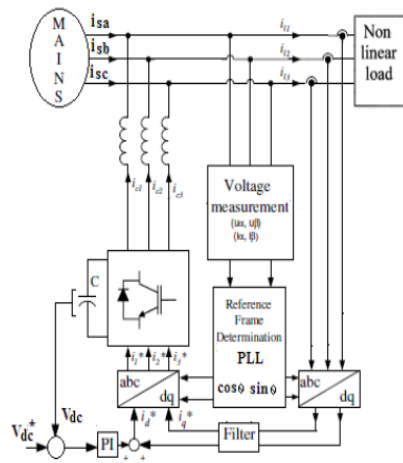


Fig. 4: Basic Synchronous Reference Frame Configuration
The harmonics appear like ripple. Harmonic isolation of the d-q transformed signal is achieved by removing the dc offset. This is accomplished using high pass filters (HPF). In spite of a high pass filter, a low pass filter is used to obtain the reference source current in d-q coordinates. Fig 4 illustrates a configuration of the SRF method. There is no need to supply voltage waveform for a SRF based controller. However the phase position angle must be determined using voltage information. The SRF harmonic detection method can be reasonably summarized as a block diagram as shown in Fig.5.

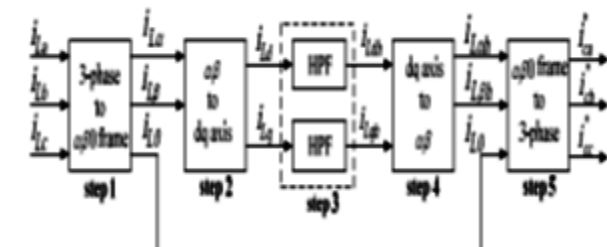


Fig.5: SRF harmonic detection

The current that flows through the neutral of the load is compensated by injecting the same instantaneous value obtained from the phase-currents, phase-shifted by 180°, as shown next

$$i_{on}^* = -(i_Lu + i_Lv + i_Lw) \quad (8)$$

V. DC-LINK VOLTAGE AND POWER CONTROL OPERATION

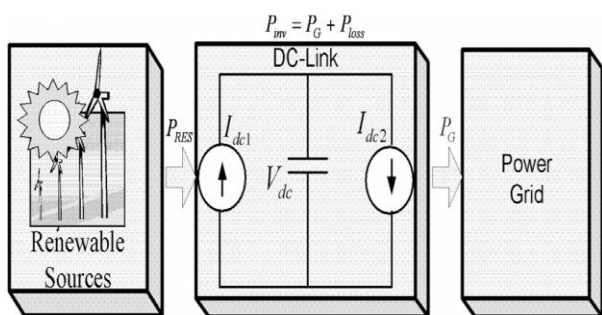


Fig. 6. DC-Link equivalent diagram.

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. Fig. 6 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 can be given as

$$I_{dc1} = P_{res} / V_{dc} \quad (9)$$

where P_{res} is the power generated from RES. The current flow on the other side of dc-link can be represented as,

$$I_{dc2} = P_{inv} / V_{dc} = P_G + P_{LOSS} \quad (10)$$

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

$$P_{res} = P_G \quad (11)$$

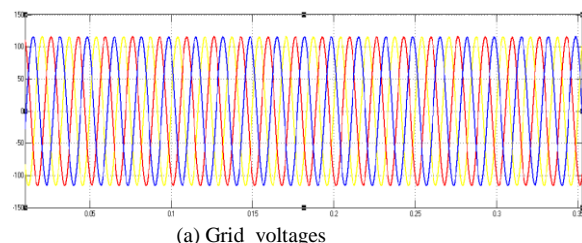
VI. SIMULATED RESULTS

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 voltages (V_a, V_b, V_c), grid currents (I_a, I_b, I_c, I_n), unbalanced load currents ($I_{1a}, I_{1b}, I_{1c}, I_{1n}$) 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.

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 $t=0.72s$, the grid current profile in Fig. 4(b) is identical to the load current profile of Fig. 4(c). At $t=0.72s$, 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 non linear to balanced sinusoidal current as shown in Fig. 4(b). As the inverter also supplies the load neutral current demand, the grid neutral current (I_n) becomes zero after $t=0.72s$.



(a) Grid voltages

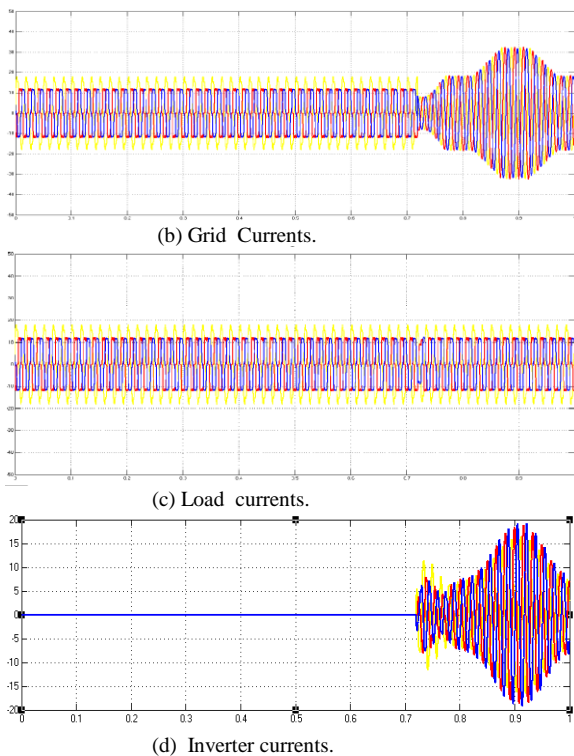


Fig. 4. Simulation results: (a) Grid voltages, (b) Grid Currents (c) Unbalanced load currents, (d) Inverter Currents.

At $t=0.72s$, 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 $0.72s$ suggests that the grid is now receiving power from RES. 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 $t=0.82s$, 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. 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.

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 can be noticed from Fig. 8

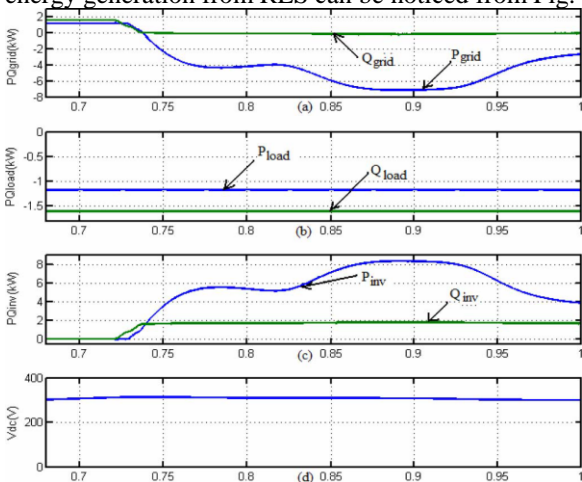


Fig. 5. Simulation results for WIND RES: (a) PQ-Grid, (b) PQ-Load, (c) PQ-Inverter, (d) dc-link voltage.

The dc-link voltage across the grid- interfacing inverter (Fig. 8(d)) during different operating condition is maintained at constant level in order to facilitate the active and reactive power flow. Thus from the simulation results, it is evident that the grid-interfacing 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.

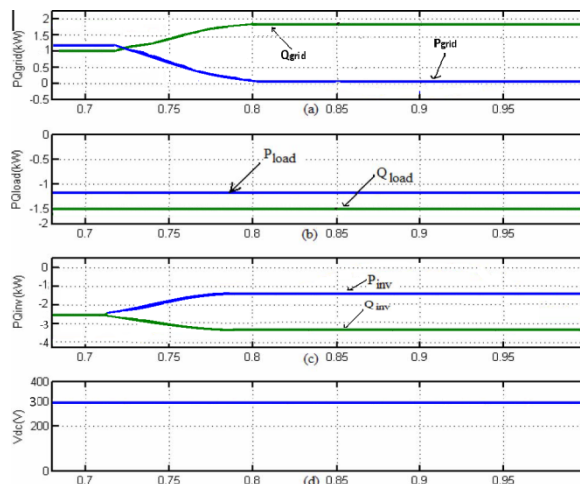


Fig. 6. Simulation results for SOLAR RES: (a) PQ-Grid, (b) PQ-Load, (c) PQ-Inverter, (d) dc-link voltage.

VII. 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. 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 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. Extensive MATLAB/Simulink simulation for both wind & solar RES has been validated results have validated and 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. 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.

VIII. REFERENCES

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