

## **Application of Advanced Inverters in Interconnection of Renewable Energy Sources (RES) to the Electrical Grid at the Distribution System**

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**Abstract-** This paper suggests a new method that consists of a four leg inverters that is capable of simultaneously compensating problems like current unbalance and current harmonics, power factor and also of injecting the energy generated by renewable energy power sources when installed in 3-phase 4-wire distribution systems. The fourth leg of inverter is used to compensate the neutral current of load. This grid-interfacing inverter can thus be utilized as power converter to inject power generated from RES to the grid, and shunt APF to compensate current unbalance, load current harmonics, load reactive power demand and load neutral current. The inverter is actively controlled in such a way that it draws/supplies fundamental active power from/to the grid. All of these functions may be accomplished either individually or simultaneously. This new control concept is demonstrated with extensive MATLAB/Simulink simulation studies.

**Keywords:** Renewable energy source (RES), distributed generation (DG), Active power filter (APF), distribution system, grid interconnection, power quality (PQ).

### **I. INTRODUCTION**

The global electrical energy consumption is still rising and there is a steady demand to increase the power capacity. As concerns about climate change, rising fossil fuel prices and energy security increase, there is growing interest around the world in renewable energy resources. 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. 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.

**Interface between the Grid and Renewables:** An electrical grid is an interconnected network for delivering electricity from suppliers to consumers. It consists of three main components: 1) generating plants that produce electricity from combustible fuels (coal, natural gas, biomass) or non-combustible fuels (wind, solar, nuclear, hydro power); 2) transmission lines that carry electricity from power plants to demand centers; and 3) transformers that reduce voltage so distribution lines carry power for final delivery. Basic power quality requirements must be met for harmonics, voltage, frequency, etc. for interconnecting any equipment to the grid. Renewable energy generators with their associated power electronics generate harmonics and have electrical characteristics under voltage and frequency excursions that may make it difficult to meet those requirements. Large-scale wind farms and large-scale PV systems present a spectrum of technical challenges arising mostly from the expanding application of power electronic devices at high power ratings. The connection of Renewables at the distribution levels also requires significant modification of the distribution design to accommodate bidirectional power flow. Facilitating the integration of distributed energy resources requires innovations in micro grid and energy management systems that transparently provide control and regulation.

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 p-q 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.

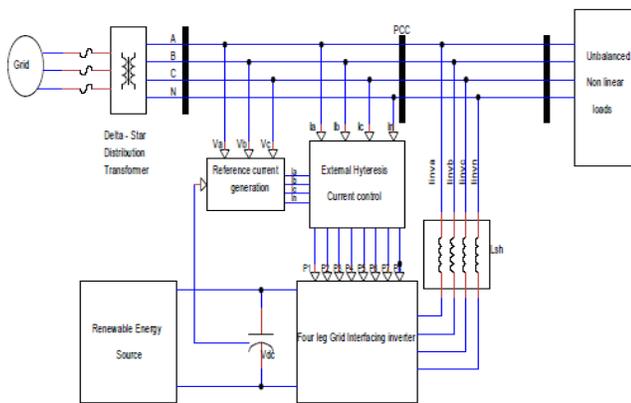


Figure.1: Schematic diagram of Renewable energy distributed system

The paper is arranged as follows: Section II describes the system Topology under consideration and the controller for grid-interfacing inverter. A digital simulation study is presented in Section III. Finally, Section IV concludes the paper

## II. SYSTEM TOPOLOGY & CONTROL STRATEGY

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.

Generally, the power circuit of shunt APF consists of a three-phase Voltage Source PWM Inverter (VSI) using IGBTs coupled at the Point of Common Coupling (PCC) via

coupling inductance. The active filter compensates the harmonics generated by nonlinear loads by generating the same harmonic components in the opposite phase. Harmonics are thus cancelled and the result is a non-distorted sinusoidal current. Each leg of VSI consists of two IGBT.

### A. Control of Grid Interfacing Inverter:

The control diagram of grid- interfacing inverter for a 3-phase 4-wire system is shown in Fig.2. The fourth leg of inverter is used to compensate the neutral current of load.

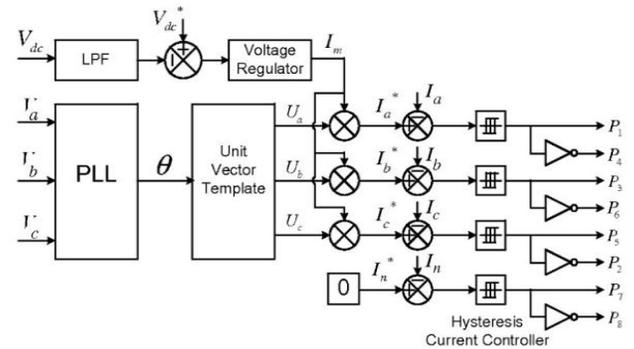


Figure.2. Block diagram representation of grid-interfacing inverter control.

The main aim of proposed approach is to regulate the power at PCC during: 1)  $P_{res}=0$ ; 2)  $P_{res} < \text{total load power (P load)}$ ; and 3)  $P_{res} > P_{load}$ . 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 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.

### B. Voltage control of DC capacitor

The actual dc-link voltage 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 DC link voltage is sensed and compared with reference value and the error is passed through a PI controller. 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 conditions. Thus the output of dc-link voltage regulator results in an active current ( $I_m$ ). The dc-link voltage error  $V_{dcerr}(n)$  at  $n^{\text{th}}$  sampling instant is given as:

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

The output of discrete-PI regulator at  $n^{\text{th}}$  sampling instant is expressed as

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

Where  $K_{PV_{dc}}=10$  and  $K_{IV_{dc}}=0.05$  are proportional and integral gains of dc-voltage regulator.

**C. Current Control of VSI**

The multiplication of active current component ( $I_m$ ) with unity grid voltage vector templates ( $U_a$ ,  $U_b$  and  $U_c$ ) 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 ( $\theta$ ) obtained from phase locked loop (PLL) is used to generate unity vector template as [9]–[11].

$$U_a = \sin(\theta) \quad \text{--- (3)}$$

$$U_b = \sin(\theta - \frac{2\pi}{3}) \quad \text{--- (4)}$$

$$U_c = \sin(\theta + \frac{2\pi}{3}) \quad \text{--- (5)}$$

The instantaneous values of reference three phase grid currents are computed as

$$I_a^* = I_m \cdot U_a \quad \text{--- (8)}$$

$$I_b^* = I_m \cdot U_b \quad \text{--- (9)}$$

$$I_c^* = I_m \cdot U_c \quad \text{--- (10)}$$

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

$$I_n^* = 0 \quad \text{--- (11)}$$

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 ,

$$I_{aerr} = I_a^* - I_a \quad \text{--- (12)}$$

$$I_{berr} = I_b^* - I_b \quad \text{--- (13)}$$

$$I_{cerr} = I_c^* - I_c \quad \text{--- (14)}$$

$$I_{nerr} = I_n^* - I_n \quad \text{--- (15)}$$

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.

**D. Switching Control of IGBTs:**

Switching pulses are generated using hysteresis current controller. There are various current control methods for active power filter configurations but hysteresis method is preferred among other current control methods because of quick current controllability, easy implementation and unconditioned stability [13]. The conventional current control scheme is the hysteresis method where the actual filter currents are compared with their reference currents with a predefined hysteresis band in their respective phases. Thus the actual currents track the reference currents generated by current control loop. 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  $S_1$  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  $I_{Inva} > (I_{Inva}^* + h_b)$ , 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.

**F. ADVANCED INVERTERS:**

**i. Z - SOURCE INVERTERS**

In 2002, the topology of the Z-source inverter was proposed as an alternative solution to overcome the limitations of traditional inverter such as the boosting mode and the problems of short circuit. The idea of this topology is based on building an impedance network (Z network) which is used to replace the traditional DC link as shown in Fig.3. Therefore; an additional zero state will appear following to the leg shoot-through of one phase, two phases or three phases, this case is not allowed in the control strategy of the traditional inverter. On the other side, this alternative topology gives more flexibility and allows boosting the voltage across the DC-Link bus. In addition, the reliability of the inverter is greatly improved because the uncontrolled shoot through caused by electromagnetic interference (EMI) noises which can destroy the inverter circuitry will be no longer faced. Thus, this solution provides a low-cost, reliable, and highly efficient single-stage structure for buck and boost power conversion. Indeed, a lot of papers present the modeling and the controller design of Z-source with ignoring the parasitic elements [13].

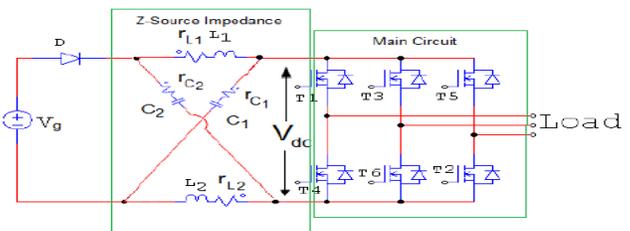


Figure.3. Z-Source Inverter

**ii. TRANS-Z-SOURCE INVERTERS**

In the voltage-fed quasi Z-source inverter with continuous input current, two dc inductors can be separated or coupled. When the two inductors are coupled as shown in Fig. 4, the voltage across the inductor  $L_1$  is reflected to the inductor  $L_2$  through magnetic coupling. Then one of the two capacitors, for instance,  $C_2$  can be removed from the circuit. The rearrangement of the circuit yields the structure as shown in Fig.5. Furthermore, the voltage across  $L_2$  can be made proportional to the voltage across  $L_1$  by changing the turns ratio  $n_2 / n_1$ . As the voltage constraint associated with one of the capacitors is released, the two windings, to some extent, behave more like a fly back transformer rather than the original coupled inductors [15], except that the currents flow simultaneously through both

windings in some of the operation states. Therefore, it is named as the voltage-fed trans-quasi-Z-source inverter (trans-qZSI). Like the Z-source inverter, the trans-quasi-Z-source [14] inverter has an extra shoot-through zero state besides the six active states and two traditional zero states.

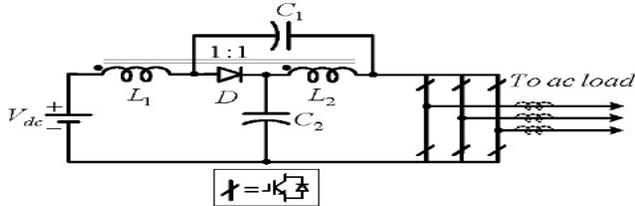


Figure.4. Voltage-fed quasi-Z-source inverter with coupled inductors.

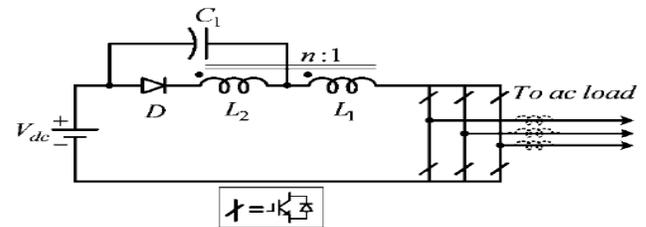


Figure.5. Voltage-fed trans-quasi-Z-source inverter. The shoot-through zero state can be realized by short-circuiting both the upper and lower switching devices of any one phase leg, any two phase legs, or all three phase legs. The shoot-through zero state contributes to the unique buck-boost feature of the inverter. Otherwise, when the dc voltage is sufficient to produce the desirable ac output voltage, a traditional PWM without shoot through zero state is used.

### III. SIMULATION RESULTS

#### A. Simulink - Line Model for Wind power system:

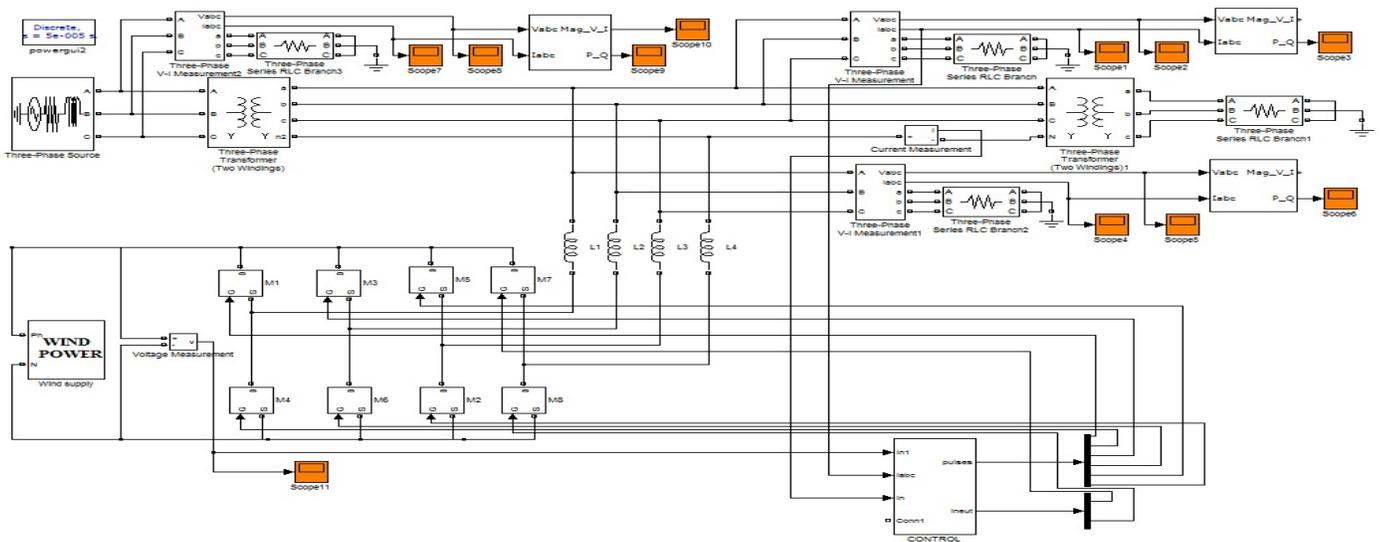


Figure.6: Simulink-Line model of wind power system

#### B. Simulink - Line Model for Solar and Wind power system:



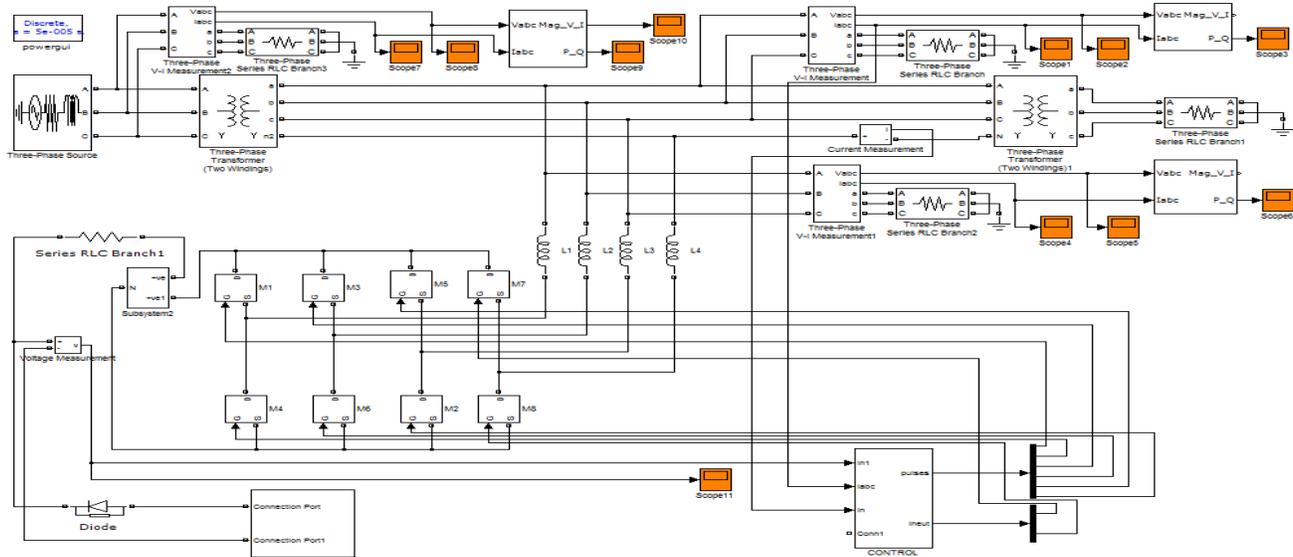


Figure.7(c): Simulink-Line model of solar and wind power system with Trans Z-Source Inverter

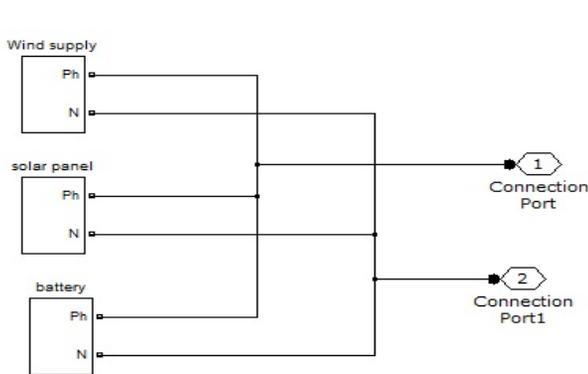


Figure.7 (d): Block diagram of Connection port Model

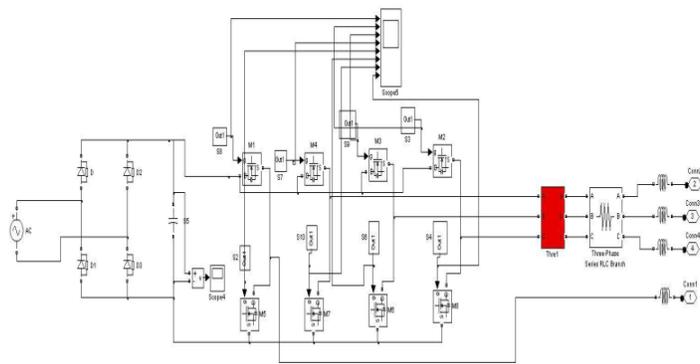


Figure.8: Simulink- Line Model of Inverter Circuit.

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.

The above figures show Simulink line models of interface between RES and Electrical Grid for different grid interfacing inverters. Figure.6 shows the Simulink model of wind power only, and Fig.7 (a) shows both solar and wind power model with 3-phase inverter (VSI), figure 7(b) shows RES Simulink model with Z-Source Inverter and finally Fig.7(c) shows RES Simulink model with Trans Z-Source Inverter. Figure.7 (d) shows internal connection port model block. Figure (8) is Simulink model of 4-leg Grid interfacing inverter.

A DC voltage equivalent to RES is connected across the dc link of the grid interfacing inverter, the inverter is effectively controlled to inject compensation current that cancel out source current harmonics. 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. 9. 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. 10. Positive values of grid active-reactive powers and inverter active-reactive 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  $t=0.72$  s, the grid current profile in Fig. 9(b) is identical to the load current profile of Fig. 9(c). At  $t=0.72$  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 non linear to balanced sinusoidal current as shown in Fig.9 (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 ( $P_{RES} \approx P_{inv}$ ). 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. 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  $t=0.82$  s, 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  $t=0.92$ s, the power available from RES is reduced. The corresponding change in the inverter and grid currents can be seen from Fig. 9.

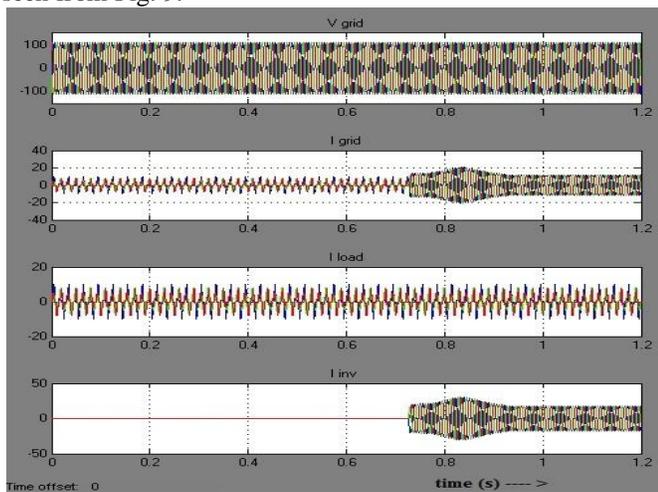


Figure.9. Simulation results: (a) Grid voltages, (b) Grid Currents (c) Unbalanced load currents, (d) Inverter Currents.

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. 10. The dc-link voltage across the grid- interfacing inverter (Fig.10 (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. 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 Figure.10.

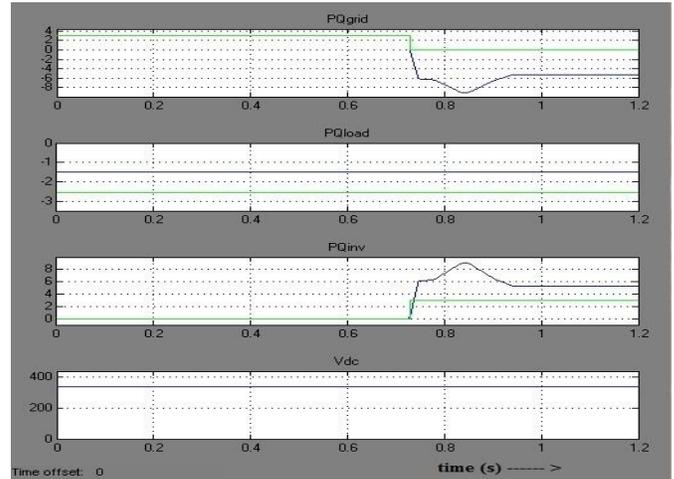


Figure.10. Simulation results for Active and Reactive Power (a) PQ-Grid, (b) PQ-Load, (c) PQ-Inverter (d) dc-link voltage.

#### IV. CONCLUSION

This paper presented a control of an Three phase Four leg grid interfacing inverter improve the quality of power at PCC for a 3 phase 4 wire system. It has been shown that the grid interfacing inverter can simultaneously be utilized to inject power generated from RES to PCC and to improve the quality of power at PCC. Thus the proposed controller precisely manages any variation in real power at dc link and effectively feeds it to the main grid. The current harmonics caused by non linear load connected at PCC are compensated effectively such that the grid currents are always maintained sinusoidal at unity power factor. This approach thus eliminates the need for additional power conditioning equipment to improve the quality of power at PCC. Thus the load neutral current is prevented from flowing into the grid side by compensating it locally from the fourth leg of the inverter. In this paper presents a Grid-interconnection of Renewable Energy Sources(RES) at the distribution system by means of Grid interfacing Inverters i.e., 3-phase four leg inverter, Z(Impedance)-source inverter and Trans Z-source Grid interfacing inverters with 3-phase 4-wire shunt active power filter[12] functionality.

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

#### V. FUTURE SCOPE

The control strategy used for the proposed system is PI-controller. Recently, fuzzy logic controller has generated a great deal of Interest in various applications and has been introduced in the power electronics field.

The advantages of fuzzy logic controllers over the conventional PI controller are that they do not need an accurate mathematical model; they can work with imprecise inputs, can handle nonlinearity, and may be more robust than the conventional PI controller.

In future, the control circuit is implemented by using Fuzzy logic controller (FLC) approach and to achieve good results as compared to PI-controllers.

## VI. REFERENCES

- [1] J. M. Guerrero, L. G. de Vicuna, J. Matas, M. Castilla, and J. Miret, "A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1205–1213, Sep. 2004.
- [2] J. H. R. Enslin and P. J. M. Heskes, "Harmonic interaction between a large number of distributed power inverters and the distribution network," *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp. 1586–1593, Nov. 2004.
- [3] U. Borup, F. Blaabjerg, and P. N. Enjeti, "Sharing of nonlinear load in parallel-connected three-phase converters," *IEEE Trans. Ind. Appl.*, vol. 37, no. 6, pp. 1817–1823, Nov./Dec. 2001.
- [4] P. Jintakosonwitt, H. Fujita, H. Akagi, and S. Ogasawara, "Implementation and performance of cooperative control of shunt active filters for harmonic damping throughout a power distribution system," *IEEE Trans. Ind. Appl.*, vol. 39, no. 2, pp. 556–564, Mar./Apr. 2003.
- [5] J. P. Pinto, R. Pregitzer, L. F. C. Monteiro, and J. L. Afonso, "3-phase 4-wire shunt active power filter with renewable energy interface," presented at the Conf. IEEE Renewable Energy & Power Quality, Seville, Spain, 2007.
- [6] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.
- [7] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galván, R. C. P. Guisado, M. Á. M. Prats, J. I. León, and N. M. Alfonso, "Power electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002–1016, Aug. 2006.
- [8] B. Renders, K. De Gussemé, W. R. Ryckaert, K. Stockman, L. Vandeveldé, and M. H. J. Bollen, "Distributed generation for mitigating voltage dips in low-voltage distribution grids," *IEEE Trans. Power. Del.*, vol. 23, no. 3, pp. 1581–1588, Jul. 2008.
- [9] V. Khadkikar, A. Chandra, A. O. Barry, and T. D. Nguyen, "Application of UPQC to protect a sensitive load on a polluted distribution network," in *Proc. Annu. Conf. IEEE Power Eng. Soc. Gen. Meeting*, 2006, pp. 867–872.
- [10] M. Singh and A. Chandra, "Power maximization and voltage sag/swell ride-through capability of PMSG based variable speed wind energy conversion system," in *Proc. IEEE 34th Annu. Conf. Indus. Electron. Soc.*, 2008, pp. 2206–2211.
- [11] P. Rodríguez, J. Pou, J. Bergas, J. I. Candela, R. P. Burgos, and D. Boroyevich, "Decoupled double synchronous reference frame PLL for power converters control," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 584–592, Mar. 2007.
- [12] João Afonso, Maurício Aredes, Edson Watanabe, Júlio Martins, "Shunt Active Filter for Power Quality Improvement", International Conference UIE 2000 - Electricity for a Sustainable Urban Development, Lisboa, Portugal, 1-4 November 2000, pp. 683- 691.
- [13]. F. Z. Peng, "Z-source inverter," *Industry Applications, IEEE Transactions on*, vol. 39, no. 2, pp. 504-510, 2003.
- [14]. Wei Qian, Fang Zheng Peng, Fellow, IEEE, and Honnyong Cha, Member, IEEE "Trans-Z-Source Inverters".
- [15] A. F. Witulski, "Introduction to modeling of transformers and coupled inductors," *Power Electronics, IEEE Transactions on*, vol. 10, no. 3, pp. 349-357, 1995.