Abstract—This paper presents a novel control strategy of a 3-phase four-leg grid interfacing inverter to perform as a multifunctional device for improving power quality in grid interconnected systems. The inverter is controlled to perform as a multifunctional device by incorporating active power filter functionality. With this control scheme, despite of non-linear loads at point of common coupling (PCC), it appears as a balanced linear load to the grid. The inverter is utilized as shunt active power filter to compensate current unbalance, load current harmonics, load reactive power demand and load neutral current. Moreover whenever the power generated from renewable energy source (RES) is more than load demand the inverter can be utilized as power converter to inject power generated from RES to grid. The fuzzy logic controller is employed in this control scheme due to its advantages over PI controller. To validate the proposed approach, simulated results are presented and discussed.

Index Terms—Renewable Energy Source (RES), Grid Interconnection, Power Quality.

I. INTRODUCTION

Electricity grid interconnections have played a key role in the history of electric power systems. Most national and regional power systems that exist today began many decades ago as isolated systems, often as a single generator in a large city. As power systems expanded out from their urban cores, interconnections among neighboring systems became increasingly common. Groups of utilities began to form power pools, allowing them to trade electricity and share capacity reserves. One of the great engineering achievements of the last century has been the evolution of large synchronous alternating current (AC) power grids, in which all the interconnected systems maintain the same precise electrical frequency.

Centralized power generation systems are facing the twin constraints of shortage of fossil fuel and the need to reduce emissions. Long transmission lines are one of the main causes for electrical power losses. Therefore, emphasis has increased on distributed generation networks with integration of renewable energy systems into the grid, which lead to energy efficiency and reduction in emissions. With the increase of the renewable energy penetration to the grid power quality of the medium to low voltage power transmission system is becoming a major interest. Most of the integration of renewable energy systems to the grid takes place with the aid of power electronic converters. The main purpose of power electronic converters is to integrate the distributed generation to the grid in compliance with power quality standards. However high frequency of inverters can inject additional harmonics to the system creating major power quality problems if not implemented properly. Solar and wind are the promising renewable energy sources and their penetration level to the grid is also on rise. Although the benefits of distributed generation includes voltage support, diversification of power sources, reduction in transmission and distribution losses and improved reliability, power quality problems are also of growing concern [1].

Generally, current controlled voltage source inverters are used to interface the intermittent renewable energy source (RES) in distributed system. However, the extensive use of power electronic based equipments and non-linear loads at PCC may deteriorate the power quality [2], [3]. Recently, a few control strategies for grid connected inverters incorporating PQ solution have been proposed. In [4] 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 [5]. In [6], 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. In [13], a control strategy of three phase 4-leg grid interfacing inverter is proposed. In this strategy the control scheme employs a PI controller. But since fuzzy logic controller has more advantages over PI controller, the control scheme employing fuzzy controller for the control of three phase 4-leg grid interfacing inverter has been proposed in this paper.

In this paper the grid interconnected RES with highly non-linear unbalanced loads is effectively controlled with the...
proposed approach in order to compensate the load reactive power, current unbalance and current harmonics at PCC. With this control scheme there is no need of any additional equipment such as active power filter’s (APF) for power quality improvement. The proposed control scheme incorporates APF functionality. Fuzzy logic controller is used in this control scheme due to its advantages over PI-controller. The performance of the proposed approach during different operating conditions of RES are studied in this paper.

II. SYSTEM DESCRIPTION

The system under study consists of a grid inter connected RES as shown in Figure 1. The grid interfacing inverter is the key element of the system as it interfaces the RES to grid. The power generated from RES is a may be either dc or ac. If the RES is an ac source, it is rectified and then coupled to the dc-link. The power generated from photovoltaic energy sources is at variable low dc voltage. The power generated from variable speed wind turbines is at variable ac voltage.

![Fig. 1. Block Diagram of Grid Interconnected RES system.](image_url)

Thus power generated from these RES needs to be converted from ac to dc before connecting to grid [7]-[9]. The dc-link plays a key role in interfacing the RES to grid. The dc-link capacitor decouples RES from grid and allows independent control of converter on either side.

III. CONTROL SCHEME

The control scheme block diagram of grid interfacing inverter in 3-phase four wire distribution systems is as shown in Figure 2. The main objective of control scheme is to regulate power at PCC during:

i. $P_{RES} = 0$

ii. $P_{RES} < P_L$

iii. $P_{RES} > P_L$

Where, $P_{RES}$ is power generated from renewable energy source and $P_L$ is the load demand.

During all the above cases, the inverter is actively controlled in such a way that it always draws/ supplies power from/to the grid. The neutral current to the load is compensated by the fourth leg of inverter. The given control approach also compensates the harmonics and unbalance even when the load connected to the PCC is non-linear or unbalanced or combination of both. The switching signals to the inverter are controlled in such a way that the combination of load and inverter injected current appear as balanced resistive load to grid.

![Fig. 2. Block diagram of proposed control scheme](image_url)

The grid source voltages $V_{sa}$, $V_{sb}$ and $V_{sc}$ are given as inputs to the phase locked loop (PLL) to obtain the grid synchronizing angle ($\theta$), which is used to generate unity vector templates as

$$U_{sa} = \sin(\theta) \quad (1)$$
$$U_{sb} = \sin(\theta - \frac{2\pi}{3}) \quad (2)$$
$$U_{sc} = \sin(\theta + \frac{2\pi}{3}) \quad (3)$$

The dc-link voltage at which the RES is connected to grid is sensed and is called the actual dc-link voltage ($V_{dc}$). This actual dc-link voltage is compared with the reference dc-link voltage ($V_{dc}^*$) and the error is fed to a fuzzy logic controller. The in-detail discussion regarding the design of fuzzy logic controller is discussed in Section-IV. The output of this controller ($I$) is given to a multiplier circuit, where the unity vectors obtained are multiplied to output of fuzzy logic controller and the desired reference grid currents ($I_{sa}^*$, $I_{sb}^*$ and $I_{sc}^*$) are obtained.

$$I_{sa}^* = I \cdot U_{sa} \quad (4)$$
$$I_{sb}^* = I \cdot U_{sb} \quad (5)$$
$$I_{sc}^* = I \cdot U_{sc} \quad (6)$$

Where, $I$ is proportional to the magnitude of current that is to
be injected so as to make grid currents balanced. This ensures that the grid currents are controlled to be sinusoidal irrespective of unbalanced non-linear load currents. The neutral current drawn by the loads connected at PCC must be compensated by fourth leg of inverter thus should not be drawn from grid. Hence the reference neutral current ($I_{sn^*}$) is considered as zero and is expressed as

$$I_{sn^*} = 0$$ (7)

The actual currents ($I_{sa}$, $I_{sb}$ and $I_{sc}$) are detected by current sensor and they are subtracted from desired reference currents so that error current is generated and is given to hysteresis controller to generate the switching pattern.

$$\Delta I_{sa} = I_{sa}^* - I_{sa}$$ (8)
$$\Delta I_{sb} = I_{sb}^* - I_{sb}$$ (9)
$$\Delta I_{sc} = I_{sc}^* - I_{sc}$$ (10)
$$\Delta I_{sn} = I_{sn}^* - I_{sn}$$ (11)

The error currents obtained are given to hysteresis controller and thus ON/OFF switching signals (P1-P8) for each IGBT inside inverter can be formulated as

- If $I_{sa} < (I_{sa^*} - HB)$, then upper switch S1 will be OFF (P1=0) and lower switch S4 will be ON (P4=1) in phase ‘a’ leg of inverter.
- If $I_{sa} > (I_{sa^*} - HB)$, then upper switch S1 will be ON (P1=1) and lower switch S4 will be OFF (P4=0) in phase ‘a’ leg of inverter.

Where HB is a hysteresis current-band, similarly switching functions can be derived for phases ‘b’ and ‘c’.

### IV. DESIGN OF FUZZY LOGIC CONTROLLER

#### A. Fuzzy Logic

Fuzzy logic, which is the logic on which fuzzy control is based, is interpretation of human thinking and natural language. Fuzzy logic efficiently handles approximate, inexact nature of data. Fuzzy logic provides a simple way to achieve a definite conclusion based upon vague ambiguous, imprecise noisy or missing input information. Fuzzy logic is rule based logic. Hence essential part of fuzzy logic controller is a set of linguistic rules. Fuzzy logic controller provides an algorithm which can convert linguistic control strategy based on human knowledge into automatic control strategy [14]-[17].

#### B. Advantages of Fuzzy Logic Controller

As Compared to conventional PI, PID and their adaptive versions fuzzy logic controller has some advantages such as:

- It does not need any exact system mathematical model
- It can handle non-linearity of arbitrary complexity
- It is based on linguistic rules with an IF-THEN general structure, which is the basis of human logic.
- It provides more robustness and flexibility

- It is independent of any environmental variations such as temperature, humidity etc.

Fuzzy logic gives better response in terms of overshoot, steady state error and fast response.

#### C. Design of Fuzzy Logic Controller

The first step towards designing of fuzzy logic controller is to decide which state variable represents dynamic performance and they should be taken as input signal for the controller [20]. In this work error between measured dc-link voltage and reference dc-link voltage and its derivative are taken as inputs for fuzzy logic controller. The output here is taken as the active current (I). Figure 3 shows the fuzzy interface system.

![Fig. 3. Fuzzy Inference System](image)

After choosing proper variables as input and output of fuzzy controller; it is required to decide membership functions (mf’s). For the system under study, seven membership functions for each input and output are used. These membership functions are as shown in Table 1.

<table>
<thead>
<tr>
<th>TABLE I MEMBERSHIP FUNCTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ZE</strong></td>
</tr>
<tr>
<td><strong>PVS</strong></td>
</tr>
<tr>
<td><strong>PS</strong></td>
</tr>
<tr>
<td><strong>PM</strong></td>
</tr>
<tr>
<td><strong>PL</strong></td>
</tr>
<tr>
<td><strong>PVL</strong></td>
</tr>
<tr>
<td><strong>PVVL</strong></td>
</tr>
<tr>
<td><strong>NS</strong></td>
</tr>
<tr>
<td><strong>NM</strong></td>
</tr>
<tr>
<td><strong>NL</strong></td>
</tr>
</tbody>
</table>

In this design Sugeno Inference engine is used. The membership functions of the inputs error and Derror and output (I) are as shown in Figure 4, Figure 5 and Figure 6. The two inputs error and Derror (derivative of error) each with seven membership functions results in 49 rules. The next step is defuzzification in which controller output which is in fuzzy
form is to be converted in numeric values. In this method centroid method is used for fuzzification. The set of rules framed with seven membership functions are as shown in Table II. On the basis of these rules fuzzy logic controller output can be seen on surface viewer as shown in Figure 7.

### Table II

**RULE BASE WITH SEVEN MEMBERSHIP FUNCTIONS**

<table>
<thead>
<tr>
<th>Output (Active Current)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NL</td>
</tr>
<tr>
<td>Derror</td>
<td>NL</td>
</tr>
<tr>
<td></td>
<td>NM</td>
</tr>
<tr>
<td></td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>ZE</td>
</tr>
<tr>
<td></td>
<td>PS</td>
</tr>
<tr>
<td></td>
<td>PM</td>
</tr>
<tr>
<td></td>
<td>PL</td>
</tr>
</tbody>
</table>

- Fig. 4. Membership Function for error
- Fig. 5. Membership Function for Derror
- Fig. 6. Membership Function for Output
- Fig. 7. Surface viewer for Fuzzy logic controller

### V. SIMULATION RESULTS

The grid connected RES with proposed control scheme is simulated in SIMLINK using SimPower System Block set. The system parameters used are as shown in Table III.

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, load current and inverter injected current as shown in Figure 8.

- Fig. 8. Grid voltage, Load current and Inverter injected current
TABLE III
SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Phase Grid Voltage</td>
<td>$V_{ph}=100V$, 50Hz</td>
</tr>
<tr>
<td>3-Phase Non-linear Load</td>
<td>$R=26.66\Omega$, $L=10mH$</td>
</tr>
<tr>
<td>1-Phase Linear Load (A-N)</td>
<td>$R=36.66\Omega$, $L=10mH$</td>
</tr>
<tr>
<td>1-Phase Non-Linear Load (C-N)</td>
<td>$R=26.66\Omega$, $L=10mH$</td>
</tr>
<tr>
<td>DC-Link Capacitance &amp; Voltage</td>
<td>$C_{dc}=3000\mu F$, $V_{dc}=300V$</td>
</tr>
<tr>
<td>Coupling Inductance</td>
<td>$L_{sh}=2.0mH$</td>
</tr>
</tbody>
</table>

Initially the grid interfacing inverter is not connected to the grid. Thus during the time before $t=0.72s$ the grid current is identical to that of load current. The grid currents are highly unbalanced. Now when grid interfacing inverter is connected at $t=0.72s$ the inverter injects current in such a way that the highly unbalanced non-linear load at PCC is appeared as balanced resistive load to the grid. Thus it can be observed that after $t=0.72s$ the grid currents are changed from unbalanced form to balanced form as shown in Figure 9.

Fig. 9. Waveform of Grid Currents

It can also be observed that the grid interfacing inverter also supplies the neutral current needed to the load. During the time before the grid interfacing inverter is connected at $t=0.72s$ the neutral current to the loads is supplied by the grid. When grid interfacing inverter is connected at $t=0.72s$ the grid stops supplying neutral current and instead this current is compensated by the fourth leg of the inverter as shown in Figure 10.

Fig. 10. Neutral current supplied by fourth leg of inverter

The active and reactive power of grid, load and inverter are as shown in Figure 11, Figure 12 and Figure 13. 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 when grid interfacing inverter is not connected to the grid the total load demand is supplied by the grid. Therefore before time $t=0.72s$ the grid supplies active and reactive power needed by the load. At time $t=0.72s$ when grid interfacing inverter is connected, the inverter starts supplying active and reactive power to the load. Now when the power generated by the RES is more than the load power demand the additional power is fed back to grid. The negative sign of the active power of grid implies the grid is absorbing power from RES. It can also be seen that the reactive power needed by the load is being supplied by the RES and it is not drawn from the grid. The grid reactive power becomes zero after time $t=0.72s$.

At $t=0.82s$ the power generated from RES is increased to observe the performance under variable power generations. The corresponding change in inverter currents is seen. Now the amount of active power received by the grid from RES is also increased accordingly. Again at $t=0.92s$ the power generated from RES is reduced. The corresponding change in active powers of grid and inverter can be noticed. During all these operating conditions the dc-link capacitor voltage is always maintained constant as shown in Figure 14.

Fig. 11. Active and Reactive powers of Grid

Fig. 12. Active-Reactive powers of Load

Fig. 13. Active-Reactive powers of Inverter
The proposed control scheme enables the grid to supply/receive sinusoidal balanced power at UPF. The grid current is maintained sinusoidal and in phase with grid voltage indicating unity power factor as shown in Figure 15.

VI. CONCLUSION

The proposed control scheme of grid interfacing inverter for power quality improvement in grid interconnected RES has been simulated. It is evident from the results that the grid interfacing inverter can be actively controlled to compensate load reactive power, current unbalance and current harmonics in addition to power injection from RES.

REFERENCES