Simulation of PV based Grid connected Inverter with fuzzy based Unified control strategy

N. Hari krishna1 & p. sankar BABU2

1PG Student, Dept. of EEE, MREC(A)
2Associate Professor, Dept. of EEE, MREC(A)

1 harikrishna0274@gmail.com; 2 psrbabu@gmail.com.

Abstract—
Distributed generation (DG) is emerging as a viable alternative when renewable or nonconventional energy resources are available, such as wind turbines, photovoltaic arrays, fuel cells, micro turbines. Most of these resources are connected to the utility through power electronic interfacing converters, i.e., three-phase inverter. DG is a suitable form to offer high reliable electrical power supply, as it is able to operate either in the grid-tied mode or in the islanded mode. In the grid-tied operation, DG delivers power to the utility and the local critical load. The proposed control strategy composes of an inner inductor current loop, and a novel voltage loop in the synchronous reference frame. The inverter is regulated as a current source just by the inner inductor current loop in grid-tied operation, and the voltage controller is automatically activated to regulate the load voltage upon the occurrence of islanding. To create a stable mode when different kinds of loads are connected locally or when working under contingency, the step-up converter must regulate the dc link voltage, allowing the VSI to stabilize its terminal voltage. PI and fuzzy controllers are used to regulate voltages and currents, while a phase-locked loop algorithm is used to synchronize the grid and DG.

Index Terms— Unified Power Quality Conditioner; Three Phase Inverter; Distributed generation (DG); islanding; load current; seamless transfer

I. INTRODUCTION
In contemporary world interconnection of distributed generations (DG) which operate in parallel with electrical power networks, is currently changing the paradigm we are used to live with. Distributed generation is gaining worldwide interest because of environmental issues and rising in energy prices and power plant construction costs. Distributed generations are relatively small and many of them make use of renewable energy such as fuel cells, gas turbines, micro-hydro, wind turbines and photovoltaic. Many DGs use power electronic inverters, instead of rotating generators. The inverters typically have fast current limiting functions for self protection, and may not be damaged by out-of-phase reclosing. The operation of distributed generation will enhance the power quality in power system and this interconnection especially with reverse power flow may lead to some problems like voltage and frequency deviation, harmonics, reliability of the power system and islanding phenomenon. Islanding is one of the most technical concerns associated with the proliferation of distributed generation connected to utility networks. Islanding can be defined as a condition in which a portion of the utility system contains both load and distributed generation remains energized while being isolated from the remainder of the utility system. Islanding detection is a mandatory feature for grid-connected inverters as specified in international standards and guidelines. Inverters usually operate with current control and unity power factor and employ passive monitoring for islanding detection methods based on locally measured parameters. Under islanding conditions, the magnitude and frequency of the voltage at the point of common coupling (PCC) tend to drift from the rated grid values as a function of the power imbalance (ΔP and ΔQ). As it is known that distribution system does not have any active power generating source and does not receive power in case of a fault in transmission line.

However, with Distributed Generation this presumption is no longer valid. In current practice DG is required to disconnect the utilities from the grid in case of islanding. The main issues about islanding are:
1). Safety issues since a portion of the system remains energized while it is not expected.
2). Islanded system may be inadequately grounded by the DG interconnection.
3). Instantaneous reclosing could cause out of phase in the system.
4). Loss of control over voltage and frequency in the system.
5). Excessive transient stresses upon reconnection to the grid.
6). Uncoordinated protection.

The strategy of islanding detection is to monitor the DG output parameters for the system and based on the measurements decide whether an islanding situation has occurred from monitoring of these parameters. Islanding detection techniques can be divided into remote and local techniques.

A multilevel inverter is a power electronic system that synthesizes a desired output voltage from several levels of dc voltages as inputs. Recently, multilevel power conversion technology has been developing the area of power electronics very rapidly with good potential for further developments. As a result, the most attractive applications of this technology are in the medium to high voltage ranges [3].

![Fig.1. Schematic diagram of the DG based on the proposed control strategy.](image)

Its applications are in the field of high-voltage high-power applications such as laminators, mills, conveyors, compressors, large induction motor drives, UPS systems, and static var compensation. Its working principle is based on producing small output voltage steps which results in better power quality. They operate at low voltage levels and also at a low switching frequency so that the switching losses are also reduced.

The principle includes as the number of levels in the inverter increases, the output voltage has more step generation i.e. staircase waveform, which has a reduced harmonic distortion. The main disadvantage of number of levels includes more number of switching devices, diodes, and other passive elements. Hence inverter becomes bulky, more control complexity and introduces voltage-imbalance. To solve the above problem, an asymmetric topology H-bridge inverter with three unequal DC sources is used. This topology has the capability of utilizing different DC voltages on the individual H-bridge cells.

A. Passive methods
This method is fast to detect the islanding. But it has large non-detection zone and it need special care to set the thresholds for it is parameters. Passive method can be classified into: Rate of change of output power, Rate of change of frequency, rate of change of frequency over power, Change of impedance, voltage unbalance, and harmonic distortion

B. Active Methods
Active method tries to overcome the shortcomings of passive methods by introducing perturbations in the inverter output. Active method can detect the islanding
even under the perfect match of generation and load, which is not possible in case of
the passive detection schemes but it caused degradation
of power quality. Active method can be classified into:
Reactive power export error detection , Impedance
measurement method, Phase (or frequency) shift
methods , Active Frequency Drift , Active Frequency
Drift with Positive Feedback Method , Adaptive Logic
Phase Shift , Current injection with positive feedback.

C. Hybrid Methods

Hybrid method based on implementing of two
assortment of active and passive method. The active
technique is implemented only when the islanding is
suspected by the passive technique. It can be classified
into: Technique based on voltage and reactive power
shift, Technique based on positive feedback and voltage
imbalance In current into the utility for mitigating
the harmonic component of the grid current, is presented.
General, once the main grid source supply is lost the DG
has to take charge of the remaining network and the
connected loads. Passive detection scheme, on the other
hand, monitors parameters for detecting the islanding
operations of DG: voltage unbalance, frequency, active
and reactive power along with total harmonic distortion
(THD).

In the hybrid voltage and current mode control, there is a
need to switch the controller when the operation mode of
DG is changed. During the interval from the occurrence
of utility outage and switching the controller to voltage
mode, the load voltage is neither fixed by the utility, nor
regulated by the DG, and the length of the time interval
is determined by the islanding detection process.
Therefore, the main issue in this approach is that it
makes the quality of the load voltage heavily reliant on
the speed and accuracy of the islanding detection method
[6]–[10]. Another issue associated with the
aforementioned approaches is the waveform quality of
the grid current and the load voltage under nonlinear
local load. In the

grid-tied mode, the output current of DG is generally
desired to be pure sinusoidal [18].

When the nonlinear local load is fed, the harmonic
component of the load current will fully flow into the
utility. The voltage mode control is enhanced by
controlling the DG to emulate a resistance at the
harmonic frequency, and then the harmonic current
flowing into utility can be mitigated. This paper
presents a unified control strategy that avoids the
aforementioned shortcomings. First, the traditional
inductor current loop is employed to control the three-

![Fig. 2. Overall block diagram of the proposed unified control strategy](image)
phase inverter in DG to act as a current source with a given reference in the synchronous reference frame (SRF). Second, a novel voltage controller is presented to supply reference for the inverter current loop, where a proportional-plus-integral (PI) compensator and a proportional (P) compensator are employed in D-axis and Q-axis, respectively. In the grid-tied operation, the load voltage is dominated by the utility, and the voltage compensator in D-axis is saturated, while the output of the voltage compensator in Q-axis is forced to be zero by the PLL. Therefore, the reference of the inner current loop cannot regulated by the voltage loop, and the DG is controlled as a current source just by the inner current loop. Moreover, the proposed control strategy, benefiting from just utilizing the current and voltage feedback control, endows a better dynamic performance, compared to the voltage mode control.

II. PROPOSED CONTROL STRATEGY

A. Power Stage

This paper presents a unified control strategy for a three phase inverter in DG to operate in both islanded and grid-tied modes. The schematic diagram of the DG based on the proposed control strategy is shown by Fig. 1. The DG is equipped with a three-phase interface inverter terminated with a LC filter. The primary energy is converted to the electrical energy, which is then converted to dc by the front-end power converter, and the output dc voltage is regulated by it. Therefore, they can be represented by the dc voltage source Vdc in Fig. 1. In the ac side of inverter, the local critical load is connected directly. It should be noted that there are two switches, denoted by Su and Si, respectively, in Fig. 1, and their functions are different. The inverter transfer switch Si is controlled by the DG, and the utility protection switch Su is governed by the utility. When the utility is normal, both switches Si and Su are ON, and the DG in the grid-tied mode injects power to the utility. When the utility is in fault, the switch Su is tripped by the utility instantly, and then the islanding is formed. After the islanding has been confirmed by the DG with the islanding detection scheme [6]–[10], the switch Si is disconnected, and the DG is transferred from the grid-tied mode to the islanded mode. When the utility is restored, the DG should be resynchronized with the utility first, and then the switch SI is turned ON to connect the DG with the grid.

B. Basic Idea

With the hybrid voltage and current mode control [17], the inverter is controlled as a current source to generate the reference power P_{DG} + jQ_{DG} in the grid-tied mode. And its output power P_{DG} + jQ_{DG} should be the sum of the power injected to the grid P_{g} + jQ_{g} and the load demand P_{load} + jQ_{load}, which can be expressed as follows by assuming that the load is represented as a parallel RLC circuit:

\[ P_{load} = \frac{3}{2} \cdot \frac{V_{m}^2}{R} \tag{1} \]
\[ Q_{load} = \frac{3}{2} \cdot V_{m}^2 \cdot \left( \frac{1}{\omega L} - \omega C \right) \tag{2} \]

In (1) and (2), V_{man} d\omega represent the amplitude and frequency of the load voltage, respectively. When the nonlinear local load is fed, it can still be equivalent to the parallel RLC circuit by just taking account of the fundamental component.

During the time interval from the instant of islanding happening to the moment of switching the control system to voltage mode control, the load voltage is neither fixed by the utility nor regulated by the inverter, so the load voltage may drift from the normal range [6]. And this phenomenon can be explained as below by the power relationship. During this time interval, the inverter is still controlled as a current source, and its output power is kept almost unchanged. However, the power injected to utility decreases to zero rapidly, and then the power consumed by the load will be imposed to the output power of DG. If both active power P_{g} and reactive power Q_{g} injected into the grid are positive in the grid-tied mode, then P_{load} and Q_{load} will increase after the islanding happens, and the amplitude and frequency of the load voltage will rise and drop, respectively, according to (1) and (2). With the previous analysis, if the output power of inverter P_{DG} + jQ_{DG} could be regulated to match the load demand by changing the current reference before the islanding is confirmed, the load voltage excursion will be mitigated. And this basic idea is utilized in this paper. In the proposed control strategy, the output power of the inverter is always controlled by

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regulating the three-phase inductor current $i_a, i_b, i_c$, while the magnitude and frequency of the load voltage $v_{abc}$ are monitored. When the islanding happens, the magnitude and frequency of the load voltage may drift from the normal range, and then they are controlled to recover to the normal range automatically by regulating the output power of the inverter.

C. Control Scheme

Fig. 2 describes the overall block diagram for the proposed unified control strategy, where the inductor current $i_{Lref}$, the utility voltage $v_{gabc}$, the load voltage $v_{abc}$, and the load current $i_{Lref}$ are sensed. And the three-phase inverter is controlled in the SRF, in which, three phase variable will be represented by dc quantity. The control diagram is mainly composed by the inductor current loop, the PLL, and the current reference generation module.

In the inductor current loop, the PI compensator is employed in both D- and Q-axes, and a decoupling of the cross coupling denoted by $ω0L/k$ PWM is implemented in order to mitigate the couplings due to the inductor. The output of the inner current loop dq, together with the decoupling of the capacitor voltage denoted by $1/k$ PWM, sets the reference for the standard space vector modulation that controls the switches of the three-phase inverter. It should be noted that k PWM denotes the voltage gain of the inverter, which equals to half of the dc voltage in this paper.

In Fig. 2, it can be found that the inductor current is regulated to follow the current reference $i_{Lref}dq$, and the phase of the current is synchronized to the grid voltage $v_{gabc}$. If the current reference is constant, the inverter is just controlled to be a current source, which is the same with the traditional grid-tied inverter. The new part in this paper is the current reference generation module shown in Fig. 2, which regulates the current reference to guarantee the power match between the DG and the local load and enables the DG to operate in the islanded mode. Moreover, the unified load current feed forward, to deal with the nonlinear local load, is also implemented in this module.

The block diagram of the proposed current reference generation module is shown in Fig. 3, which provides the current reference for the inner current loop in both grid-tied and islanded modes. In this module, it can be found that an unsymmetrical structure is used in D- and Q-axes. The PI compensator is adopted in D-axes, while the P compensator is employed in Q-axis. Besides, an extra limiter is added in the D-axis. Moreover, the load current feed forward is implemented by adding the load current $i_{Lref}$ dq to the final inductor current reference $i_{Lref}dq$. The benefit brought by the unique structure in Fig. 3 can be represented by two parts: 1) seamless transfer capability without critical islanding detection; and 2) power quality improvement in both grid-tied and islanded operations. The current reference $i_{Lref}dq$ composes of four parts in D-and Q-axes respectively: 1) the output of voltage controller $u_{ref}dq$; 2) the grid current reference $I_{gref}dq$; 3) the load current $i_{Lref}dq$; and 4) the current flowing through the filter capacitor $C_f$.

In the grid-tied mode, the load voltage $v_c$ dq is clamped by the utility. The current reference is irrelevant to the load voltage, due to the saturation of the PI compensator in D-axis, and the output of the P compensator being zero in Q-axis, and thus, the inverter operates as a current source. Upon occurrence of islanding, the e voltage by regulating the current reference, and the inverter acts as a current source to supply stable voltage to the local load; this relieves the need for switching between different control architectures. Another distinguished function of the current reference generation module is the load current feed forward. The sensed load current is added as a part of the inductor current reference $i_{Lref}dq$ to
compensate the harmonic component in the grid current under nonlinear local load. In the islanded mode, the load current feed forward operates still, and the disturbance from the load current, caused by the nonlinear load, can be suppressed by the fast inner inductor current loop, and thus, the quality of the load voltage is improved.

The inductor current control in Fig. 2 was proposed in previous publications for grid-tied operation of DG [18], and the motivation of this paper is to propose a unified control strategy for DG in both grid-tied and islanded modes, which is represented by the current reference generation module in Fig. 3. The contribution of this module can be summarized in two aspects. First, by introducing PI compensator and P compensator in D-axis and Q-axis respectively, the voltage controller is in activated in the grid-tied mode and can be automatically activated upon occurrence of islanding. Therefore, there is no need for switching different controllers or critical islanding detection, and the quality of the load voltage during the transition from the grid-tied mode to the islanded mode can be improved. The second contribution of this module is to present the load current feed forward to deal with the issue caused by the nonlinear local load, with which, not only the waveform of the grid current in grid-tied is improved, but also the quality of the load voltage in the islanded mode is enhanced. Besides, it should be noted that a three-phase unbalanced local load cannot be fed by the DG with the proposed control strategy, because there is no flow path for the zero sequence current of the unbalanced load, and the regulation of the zero sequence current is beyond the scope of the proposed control strategy.

### III. OPERATING PRINCIPLE OF DG

The operation principle of DG with the proposed unified control strategy will be illustrated in detail in this section, and there are in total four states for the DG, including the grid-tied mode, transition from the grid-tied mode to the islanded mode, the islanded mode, and transition from the islanded mode to the grid-tied mode.

#### A. Grid-Tied Mode

When the utility is normal, the DG is controlled as a current source to supply given active and reactive power by the inductor current loop, and the active and reactive power can be given by the current reference of D- and Q-axis independently. First, the phase angle of the utility voltage is obtained by the PLL, which consists of a Park transformation expressed by (3), a PI compensator, a limiter, and an integrator

\[
\begin{align*}
(x_d) &= \frac{2}{3} \left( \cos \theta \cos \left( \frac{\theta}{3} \right) + \cos \left( \frac{\theta}{3} \right) - \sin \theta \sin \left( \frac{\theta}{3} \right) \right) \\
&\quad \times \left( \frac{x_a}{x_b} \right) \\
&\quad \left( \frac{x_c}{x_d} \right).
\end{align*}
\] (3)

Second, the filter inductor current, which has been transformed into SRF by the Park transformation, is fed back and compared with the inductor current reference \(i_{Lref \ dq}\), and the inductor current is regulated to track the reference \(i_{Lref \ dq}\) by the PI compensator \(G_I\). The reference of the inductor current loop \(i_{Lref \ dq}\) seems complex and it is explained as below. It is assumed that the utility is stiff, and the three-phase utility voltage can be expressed as

\[
\begin{align*}
\begin{cases}
\nu_{ga} &= V_g \cos \theta^* \\
\nu_{gb} &= V_g \cos \left( \theta^* - \frac{2\pi}{3} \right) \\
\nu_{gc} &= V_g \cos \left( \theta^* + \frac{2\pi}{3} \right)
\end{cases}
\end{align*}
\] (4)

Where \(V_g\) is the magnitude of the grid voltage, and \(\theta^*\) is the actual phase angle. By the Park transformation, the utility voltage is transformed into the SRF, which is shown as

\[
\begin{align*}
\begin{cases}
\nu_{gd} &= V_g \cos (\theta^* - \theta) \\
\nu_{gq} &= V_g \sin (\theta^* - \theta)
\end{cases}
\end{align*}
\] (5)

\(\nu_{gq}\) is regulated to zero by the PLL, so \(\nu_{gd}\) equals the magnitude of the utility voltage \(V_g\). As the filter capacitor voltage equals the utility voltage in the grid-tied mode, \(\nu_{Cd}\) equals the magnitude of the utility voltage \(V_g\), and \(\nu_{Cq}\) equals zero, too. In the D-axis, the inductor current reference \(i_{Lref \ d}\) can be expressed by (6) according to Fig. 3

\[
i_{Lref \ d} = I_{ref \ d} + i_{LLd} - \omega_0 C_f \cdot \nu_{Cq}.
\] (6)

The first part is the output of the limiter. It is assumed that the given voltage reference \(V_{max}\) is larger than the magnitude of the utility voltage \(V_{Cd}\) in steady state, so the PI compensator, denoted by \(GVD\) in the following part, will saturate, and the limiter outputs its
upper value Igref d. The second part is the load current of D-axis LLd, which is determined by the characteristic of the local load. The third part is the proportional part $-\omega_0 C_f \cdot v_{Cq}$, where $\omega_0$ is the rated angle frequency, and $C_f$ is the capacitance of the filter capacitor. It is fixed as $v_{Cq}$ depends on the utility voltage. Consequently, the current reference $i_{Lref d}$ is imposed by the given reference $I_{gref d}$ and the load current $i_{LLd}$, and is independent of the load voltage.

In the Q-axis, the inductor current reference $i_{Lref q}$ consists of four parts as

$$i_{Lref q} = v_{Cq} \cdot k_{Gvq} + I_{gref q} + i_{LLq} + \omega_0 C_f \cdot v_{Cd} \tag{7}$$

Where $k_{Gvq}$ is the parameter of the P compensator, denoted by $GVQ$ in the following part. The first part is the output of $GVQ$ which is zero as the $v_{Cq}$ has been regulated to zero by the PLL. The second part is the given current reference $I_{gref q}$, and the third part represents the load current in Q-axis. The final part is the proportional part $-\omega_0 C_f \cdot v_{Cd}$, which is fixed since $v_{Cd}$ depends on the utility voltage. Therefore, the current reference $IL_{ref q}$ cannot be influenced by the external voltage loop and is determined by the given reference $I_{gref q}$ and the load current $i_{LLq}$.

With the previous analysis, the control diagram of the inverter can be simplified as Fig. 4 in the grid-tied mode, and the inverter is controlled as a current source by the inductor current loop with the inductor current reference being determined by the current reference $I_{gref dq}$ and the load current $I_{LLdq}$. In other words, the inductor current tracks the current reference and the load current. If the steady state error is zero, $I_{gref dq}$ represents the grid current actually, and this will be analyzed in the next section.

**B. Transition from the Grid-Tied Mode**

To the Islanded Mode When the utility switch $S_u$ opens, the islanding happens, and the amplitude and frequency of the load voltage will drift due to the active and reactive power mismatch between the DG and the load demand. The transition, shown in Fig. 5, can be divided into two time intervals. The first time intervals are from the instant of turning off $S_u$ to the instant of turning off $S_i$ when islanding is confirmed. The second time interval begins from the instant of turning off inverter switch $S_i$ during the first time interval, the utility voltage $v_{gabc}$ is still the same with the load voltage $v_{Cabc}$ as the switch $S_i$ is in ON state.

As the dynamic of the inductor current loop and the voltage loop is much faster than the PLL [52], while the load voltage and current are varying dramatically, the angle frequency of the load voltage can be considered to be not varied. The dynamic process in this time interval can be described by Fig. 6, and it is illustrated later.
load, shown in (10), represented by a series connected
RLC circuit with the lagging power factor
\[
P_g = \frac{3}{2} \left( v_{C_d} i_{g_d} + v_{C_q} i_{g_q} \right) = \frac{3}{2} v_{C_d} i_{g_d}
\]
(8)
\[
Q_g = \frac{3}{2} \left( v_{C_q} i_{g_q} - v_{C_d} i_{g_d} \right) = -\frac{3}{2} v_{C_d} i_{g_q}
\]
(9)
\[
Z_{s_{load}} = R_s + j \omega L_s + \frac{1}{j \omega C_S}
\]
\[
= R_s + j \left( \omega L_s - \frac{1}{\omega C_S} \right)
\]
\[
= R_s + j X_s.
\]
When islanding happens, \(i_{g_d}\) will decrease from positive to zero, and \(i_{g_q}\) will increase from negative to zero. At the same time, the load current will vary in the opposite direction. The load voltage in D- and Q-axes is shown by (11) and (12), and each of them consists of two terms. It can be found that the load voltage in D-axis \(v_{Cd}\) will increase as both terms increase.

However, the trend of the load voltage in Q-axis \(v_{Cq}\) is uncertain because the first term decreases and the second term increases, and it is not concerned for a while.

\[
v_{Cd} = i_{LL_d} \cdot R_s - i_{LL_q} \cdot X_s
\]
(11)
\[
v_{Cq} = i_{LL_q} \cdot R_s + i_{LL_d} \cdot X_s.
\]
(12)

With the increase of the load voltage in D-axis \(v_{Cd}\), when it reaches and exceeds \(V_{max}\), the input of the PI compensator \(GVD\) will become negative, so its output will decrease. Then, the output of limiter will not imposed to \(I_{g_d}\) dary longer, and the current reference \(I_{Lref}\) will drop. With the regulation of the inductor current loop, the load current in D-axis \(i_{LLd}\) will decrease. As a result, the load voltage inD-axis \(v_{Cd}\) will drop and recover to \(V_{max}\). After \(i_{LLd}\) has almost fallen to the normal value, the load voltage inQ-axis \(v_{Cq}\) will drop according to (12). As \(v_{Cq}\) is decreased from zero to negative, then the input of the PI compensator \(GPLL\) will be negative, and its output will drop. In other words, the angle frequency \(\omega\) will be reduced. If it falls to the lower value of the limiter \(\omega_{min}\), then the angle frequency will be fixed a to min. Consequently, at the end of the first time interval, the load voltage in D-axis \(v_{Cd}\) will be increased to and fixed at \(V_{max}\), and the angle frequency of the load voltage owill drop. If it is higher than the lower value of the limiter \(\omega_{min}\), the PLL can still operate normally, and the load voltage in Q-axis \(v_{Cq}\) will be zero. Otherwise, if it is fixed at \(\omega_{min}\), the load voltage inQ-axis \(v_{Cq}\) will be negative. As the absolute values of \(v_{Cd}\) and \(v_{Cq}\), at least one of \(v_{Cd}\), is raised, the magnitude of the load voltage will increase finally.

The variation of the amplitude and frequency in the load voltage can also be explained by the power relationship mentioned before. When the islanding happens, the local load must absorb the extra power injected to the grid, as the output power of inverter is not changed instantaneously. According to (1), the magnitude of the load voltage \(V_{m}\) will rise with the increase of \(P_{load}\). At the same time, the angle frequency \(\omega\) should drop, in order to consume more reactive power with (2). Therefore, the result through the power relationship coincides with the previous analysis.

The second time interval of the transition begins from the instant when the switch \(S_i\) is open after the islanding has been confirmed by the islanding detection method. If the switch \(S_i\) opens, the load voltage \(v_{abc}\) is independent with the grid voltage \(v_{gabc}\). At the same time, \(v_{gabc}\) will reduce to zero theoretically as the switch \(S_u\) has opened. Then, the input of the compensator \(GPLL\) becomes zero and the angle frequency is invariable and fixed to the value at the end of the first interval. Under this circumstance, \(v_{Cdq}\) is regulated by the voltage loop, and the inverter is controlled to be a voltage source. With the previous analysis, it can be concluded that the drift of the amplitude and frequency in the load voltage is restricted in the given range when islanding happens. And the inverter is transferred from the current source operation mode to the voltage source operation mode autonomously.

In the hybrid voltage and current mode control [17], the time delay of islanding detection is critical to the drift of the frequency and magnitude in the load voltage, because the drift is worse with the increase of the delay time. However, this phenomenon is avoided in the proposed control strategy.

### C. Islanded Mode

In the islanded mode, switching \(S_i\) and \(S_u\) are both in OFF state. The PLL cannot track the utility voltage normally, and the angle frequency is fixed. In this situation, the DG is controlled as a voltage source, because voltage compensator \(GVD\) and \(GVQ\) can...
regulate the load voltage vCdq. The voltage references in D and Q-axis are Vmax and zero, respectively. And the magnitude of the load voltage equals to Vmax approximately, which will be analyzed in Section IV. Consequently, the control diagram of the three-phase inverter in the islanded mode can be simplified as shown in Fig. 7.

In Fig. 7, the load current iLLdq is partial reference of the inductor current loop. So, if there is disturbance in the load current, it will be suppressed quickly by the inductor current loop, and a stiff load voltage can be achieved.

**D. Transition from the Islanded Mode**

To the Grid-Tied Mode If the utility is restored and the utility switch Su is ON, the DG should be connected with utility by turning on switch Si. However, several preparation steps should be performed before turning on switch S. First, as soon as utility voltage is restored, the PLL will track the phase of the utility voltage. As a result, the phase angle of the load voltage vCabc will follow the grid voltage vabc. If the load voltage vCabc is in phase with the utility voltage, vgd will equal the magnitude of the utility voltage according to (5).

Second, as the magnitude of the load voltage Vmax is larger than the utility voltage magnitude Vg, the voltage reference Vref will be changed to Vg by toggling the selector S from terminals 1 to 2. As a result, the load voltage will equal to the utility voltage in both phase and magnitude.

Third, the switch Si is turned on, and the selector S is reset to terminal 1. In this situation, the load voltage will be held by the utility. As the voltage reference Vref equals Vmax, which PI compensator GVD will saturate, and the limiter outputs its upper value Iref d. At the same time, vCq is regulated to zero by the PLL according to (5), so the output of GVQ will be zero. Consequently, the voltage regulators GVD and GVQ are inactivated, and the DG is controlled as a current source just by the inductor current loop.

**IV. FUZZY LOGIC CONTROLLER**

Fuzzy logic control is deduced from fuzzy set theory; which was introduced by Zadeh in 1965. In the fuzzy set theory concept, the transition is between membership and non-membership function. Therefore, limits or boundaries of fuzzy sets are undefined and ambiguous but useful in approximating systems design. In order to implement the fuzzy logic control algorithm of an active power line conditioner in a closed loop, the dc-link capacitor voltage is sensed and compared with the desired reference value. The error signal (e(n) Vdcrref Vdc) passes through a Butterworth low pass filter that allows only the fundamental component. The voltage error signal e(n) and change of error signal ce(n) are used as inputs for fuzzy processing as shown in Fig. 3. The output of the fuzzy logic controller estimates the magnitude of peak reference current Imax.

![Figure 8: Schematic diagram of the fuzzy logic controller.](image)

The fuzzy logic controller is characterized as follows:
1. Seven fuzzy sets (NB, NM, NS, ZE, PS, PM, PB) for each input and output variables.
2. Triangular membership function is used for the implicity.
3. Implication using Mamdani-type min-operator.
4. Defuzzification using the centroid method.

**FUZZIFICATION**

Fuzzy logic uses linguistic variables instead of numerical variables. In a closed loop control system, the error signal e(n), change of error signal ce(n) and output of peak reference current Imax are considered as membership functions. It can be labeled as Negative Big (NB), Negative Medium (NM), Negative Small...
(NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Big (PB) as shown in Fig.4. Converting numerical variable (real number) into a linguistic variable (fuzzy number) is the process of fuzzification.

Figure 9: Membership functions (a) the input variables $e(n)$, $ce(n)$ and (b) output variable $I_{\text{max}}$.

FUZZIFICATION INTERFACE
It transforms the crisp input data into fuzzy values that acts as input to fuzzy reasoning process.

DEFUZZIFICATION
The rules of fuzzy logic produce the set of modified control output in a linguistic variable. The defuzzification module converts these linguistic variables into a crisp value (real number) according to real time applications. The different methods of defuzzification available are Bisector, Centroid, Middle of Maximum (MOM), Smallest of Maximum (SOM) and Largest of Maximum (LOM), etc., however, the selection of method is a compromise between accuracy and computational intensity (that influences hardware requirement for real time application). The centroid (or center of gravity) method is used for simplicity and accuracy. The linguistic output variable from the rule evaluator and definition of output membership are used to calculate the hidden area. Finally, crisp output is obtained by using $\text{output} = \frac{A_i x_i}{A_i}$.

DEFUZZIFICATION INTERFACE
It converts the fuzzy sets obtained from the inference process into a crisp action that constitutes the global output of the FRBS. Mamdani based fuzzy logic interfacing rule is adopted for correction of power factor. Complex power is taken from power measuring block, in which power angle is taken as input of fuzzy controller. According to power angle control output (firing angle) is provided by fuzzy controller. When power angle is large firing angle is also large. Controlled output is supplied to variable delay circuit and it is supplied to thyristor. According to the output of variable time delay circuit firing angle of thyristor is changed. When power angle is very small then firing angle is also very small. When power angle is medium then firing angle is also medium. When power angle is large then firing angle is also large.

IV. MATLAB/MODELING & RESULTS
Here simulation is carried out in different cases, in that 1). Proposed Three Phase Three level Inverter Fed Distributed Generation Scheme using Unified Control Scheme. 2). Proposed Three Phase Five level Inverter Fed Distributed Generation Scheme using Unified Control Scheme.

Case 1: Proposed Three Phase Three level Inverter Fed Distributed Generation Scheme using Unified Control Scheme

![Fig.8 Matlab/Simulink Model of Proposed Three Phase Three level Inverter Fed Distributed Generation Scheme using Unified Control Scheme](image)
Fig. 9. Simulation waveforms of load voltage $v_{Ca}$, grid current $iga$, and inductor current $iLa$ when DG is in the grid-tied mode under condition of the step down of the grid current reference from 9 A to 5 A with proposed unified control strategy.

Fig. 10. Simulation waveforms of load voltage $v_{Ca}$, grid current $iga$, and inductor current $iLa$ when DG is transferred from the grid-tied mode to the islanded mode with proposed unified control strategy.

Fig. 11. Simulation waveforms under DG is transferred from the islanded mode to the grid-tied mode, grid voltage $vga$, & load voltage $v_{Ca}$, as well as grid current $iga$ & inductor current $iLa$.

Fig. 12. Simulation waveform when DG feeds nonlinear load in islanded mode with load current feed forward.

Fig. 13. Simulation waveforms when DG feeds nonlinear load in the grid tied mode with load current feed forward control.

Case 2: Proposed Three Phase Multilevel Inverter Fed Distributed Generation Scheme using Unified Control Scheme

Fig. 14. Matlab/Simulink Model of Proposed Three Phase Multilevel Inverter Fed Distributed Generation Scheme using Unified Control Scheme

Fig. 14 shows the Matlab/Simulink Model of Proposed Three Phase Multilevel Inverter Fed Distributed...
Generation Scheme using Unified Control Scheme using Matlab/Simulink tool.

Fig.15 Simulation waveforms under DG is transferred from the islanded mode to the grid-tied mode, grid voltage \( v_{ga} \), & load voltage \( v_{ca} \), as well as grid current \( i_{ga} \) & inductor current \( i_{La} \).

Fig.16 Five Level Output Voltage

Fig.16 shows the Five Level Output Voltage of Proposed Three Phase Multilevel Inverter Fed Distributed Generation Scheme using Unified Control Scheme.

V. CONCLUSION

The multilevel inverter is a promising inverter topology for high voltage and high power applications. It has the advantages like high power quality waveforms, lower voltage ratings of devices, lower harmonic distortion, lower switching frequency and switching losses, higher efficiency, reduction of \( dv/dt \) stresses etc. A novel advanced voltage controller was presented. It is inactivated in the grid-tied mode, and the DG operates as a current source with fast dynamic performance. Upon the utility outage, the voltage controller can automatically be activated to regulate the load voltage. Moreover, a novel load current feed forward was proposed, and it can improve the waveform quality of both the grid current in the grid-tied mode and the load voltage in the islanded mode. A advanced control strategy was proposed for three-phase inverter in DG to operate in both islanded and grid-tied modes, with no need for switching between two different control architectures or critical islanding detection.

REFERENCES


AUTHORS PROFILE:

Nakirekanti Hari Krishna received the B.Tech degree in Electrical & Electronics Engineering from Malla Reddy engineering college, Hyderabad in 2013 JNTUH Hyderabad, and she currently working toward the M.Tech degree in Control Systems at Malla Reddy Engineering College, Hyderabad. His current interest includes Renewable Energy Sources, Control Systems.

Mr.P.Sankar Babu, Associate professor in the department of Electrical & Electronics Engineering, pursuing Ph.D at JNTUH Hyderabad, have finished Master of Technology from S.N.I.S.T., Hyderabad qualified through GATE, completed Bachelor of Technology from Dr.S.G.I.E.T Prakasam. I have 10 years experience in teaching field and published 23 papers which include 8 International Journals, 9 International Conferences and 6 National Conferences.