A Novel Fuzzy Based Control Strategy For Three Phase Inverter In On Site Generation System

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Abstract: This paper presents a fuzzy based three-phase inverter in distributed generation which can be implemented for both islanded and grid-tied operations. With no need for switching between two Corresponding controllers or critical islanding detection. In the proposed strategy the three-phase inverter is regulated as just current source by inner inductor current loop in grid-tied and for islanding mode a voltage loop in the synchronous reference frame will automatically regulates the load voltage. This paper proposes a unified load current feed forward to maintain the grid current waveforms in grid-tied mode and load voltage waveforms in islanding mode to be undistorted even under nonlinear local load. The effectiveness of the proposed strategy is validated by the simulation.

Keywords— Fuzzy logic, Distributed Generation, Current Reference Generation Model

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1 INTRODUCTION :

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 [1], [3]. Most of these resources are connected to the utility through power electronic interfacing converters, i.e., three-phase inverter. Moreover, 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 [2]. In the grid-tied operation, DG deliveries power to the utility and the local critical load. Upon the occurrence of utility outage, the islanding is formed. Under this circumstance, the DG must be tripped and cease to energize the portion of utility as soon as possible according to IEEE Standard 929-2000 [4]. However, in order to improve the power reliability of some local critical load, the DG should disconnect to the utility and continue to feed the local critical load [5]. The load voltage is key issue of these two operation modes, because it is fixed by the utility in the grid-tied operation, and formed by the DG in the islanded mode, respectively. Therefore, upon the happening of islanding, DG must take over the load voltage as soon as possible, in order to reduce the transient in the load voltage. And this issue brings a challenge for the operation of DG. Droop-based control is used widely for the power sharing of parallel inverters [11], [12], which is called as voltage mode control in this paper, and it can also be applied to DG to realize the power sharing between DG and utility in the grid-tied mode [13]–[16], [53]. In this situation, the inverter is always regulated as a voltage source by the voltage loop, and the quality of the load voltage can be guaranteed during the transition of operation modes. However, the limitation of this approach is

That the dynamic performance is poor, because the bandwidth of the external power loop, realizing droop control, is much lower than the voltage loop. Moreover, the grid current is not controlled directly, and the issue of the inrush grid current during the transition from the islanded mode to the grid-tied mode always exists, even though phase-locked loop (PLL) and the virtual inductance are adopted [15]. The hybrid voltage and current mode control is a popular alternative for DG, in which two distinct sets of controllers are employed [17]–[40]. The inverter is controlled as a current source by one sets of a controller in the grid-tied mode, while as a voltage source by the other sets of controller in the islanded mode. As the voltage loop or current loop is just utilized in this approach, a nice dynamic performance can be achieved. Besides, the output current is directly controlled in the grid-tied mode, and the inrush grid current is almost eliminated. 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.

A single-phase DG, which injects harmonic current into the utility for mitigating the harmonic component of the grid current, is presented in [41].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 [42]. In the islanded mode, the nonlinear load may distort the load voltage [43], and many control schemes have been proposed to improve the quality of the load voltage, including a multi loop control method [43]–[46], resonant controllers [48], [49], sliding mode control [47]. However, existing control strategies, dealing with the nonlinear local load in DG, mainly focus on either the quality of the grid current in the grid-tied mode or the one of the load voltage in the islanded mode, and improving both of them by a unified control strategy is seldom. This paper proposes a unified control strategy that avoids the aforementioned shortcomings. First, the traditional inductor current loop is employed to control the three-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 inner inductor current loop, where a proportional-plus-integral (PI) compensator

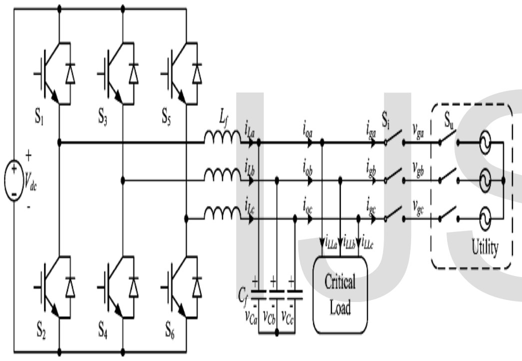


Fig. 1. Schematic diagram of the DG based on the proposed control strategy.

And proportional (P) compensators 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. Upon the occurrence of the grid outage, the load voltage is no more determined by the utility, and the voltage controller is automatically activated to regulate the load voltage. These happen naturally, and, thus the proposed control strategy does not need a forced switching between two distinct sets of controllers. Further, there is no need to detect the islanding quickly and accurately, and the islanding detection method is no more critical in this approach. 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. Third, the proposed control strategy is enhanced by introducing a unified load current feed forward, in order to deal with the issue caused by the nonlinear local load, and this scheme is implemented by adding the load current into the reference of the inner current loop. In the grid-tied mode, the DG injects harmonic current into the grid for compensating the harmonic component of the grid current, and thus, the harmonic component of the grid current will be mitigated. Moreover, the benefit of the proposed load current feed forward can be extended into the islanded operation mode, due to the improved quality of the load voltage.

2 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 *V*dc 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.

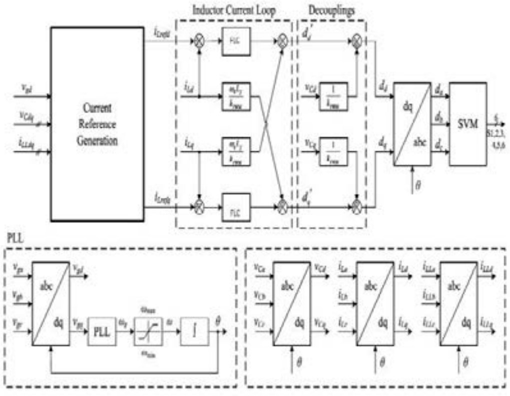


Fig. 2. Overall block diagram of the proposed unified control strategy.

B. Basic Idea

With the hybrid voltage and current mode control [17]–[40], the inverter is controlled as a current source to generate the reference power *P*DG + j*Q*DG in the grid-tied mode. And its output power *P*DG + j*Q*DG should be the sum of the power injected to the grid *Pg* + j*Qg* and the load demand *P*load +j*Q*load, which can be expressed as follows by assuming that the load is represented as a parallel *RLC* circuit:

In (1) and (2), *Vm* and *ω* 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 *Pg* and reactive power *Qg* 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 + j*Q*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 regulating the three-phase inductor current *iLabc*, while the magnitude and frequency of the load voltage *vC 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 iL abc, the utility voltage vg abc, the load voltage vC abc, and the load current iLL abc 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 ω0Lf /kPWM is implemented in order to mitigate the couplings due to the inductor. The output of the inner current loop ddq, together with the decoupling of the capacitor voltage denoted by 1/kPWM , sets the reference for the standard space vector modulation that controls the switches of the three-phase inverter. It should be noted that kPWM denotes the voltage gain of the inverter, which equals to half of the dc voltage in this paper.

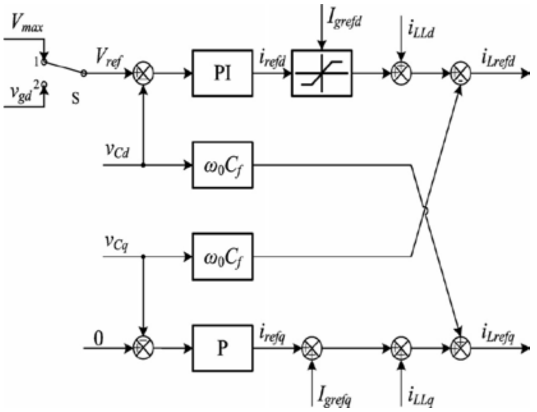


Fig. 3. Block diagram of the current reference generation module.

The PLL in the proposed control strategy is based on the SRF PLL [50], [51], which is widely used in the three-phase power converter to estimate the utility frequency and phase. Furthermore, a limiter is inserted between the PI compensator *G*PLL and the integrator, in order to hold the frequency of the load voltage within the normal range in the islanded operation. In Fig. 2, it can be found that the inductor current is regulated to follow the current reference

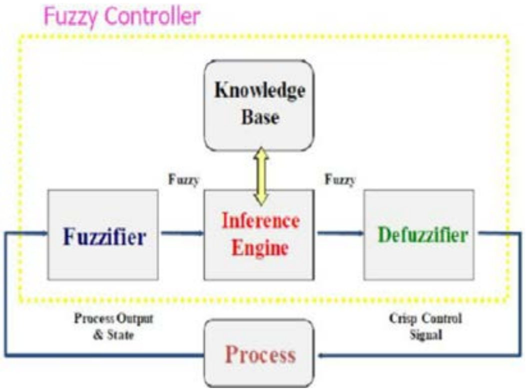
$I\ Lref\ dq$, and the phase of the current is synchronized to the grid voltage $vg\ abc$. If the current reference is constant, the inverter is just controlled to be a current source, which is the same with the traditional grid-tied inverter. The new part in this paper is the current reference generation 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 $LLdq$ to the final inductor current reference $iL\ ref\ dq$. 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 $iL\ redq$ composes of four parts in *D*- and *Q*-axes respectively: 1) the output of voltage controller $iref\ dq$; 2) the grid current reference $I\ gref\ dq$; 3) the load current $iL\ Ldq$; and 4) the current flowing through the filter capacitor Cf . In the grid-tied mode, the load voltage $vC\ dq$ 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 voltage controller takes over automatically to control the load voltage by regulating the current reference, and the inverter acts as a voltage 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 inactivated 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.

3 FUZZY LOGIC CONTROLLER

Fuzzy logic control is a non-mathematical decision algorithm that is based on an operator's experience. This type of control strategy is suited well for non- linear systems such as the synchronous generator, which exhibits non-linearity between the field current in and the armature voltage out [3]. FLC contains three basic parts: Fuzzification, Base rule, and Defuzzification. FLC has two inputs which are: error and the change in error, and one output. The Fuzzy Controller structure is represented in fig.4. The role of each block is the following:



The general structure of Fuzzy Logic Controller Fuzzifier converts a numerical variable into a linguistic label. In a closed loop control system, the error (e) between the reference voltage and the output voltage and the rate of change of error (del e) can be labeled as zero (ZE), positive small (PS), negative small (NS), etc. In the real world, measured quantities are real numbers (crisp). The FLC takes two inputs, i.e., the error and the rate of change of error. Based on these inputs, The FLC takes an intelligent decision on the amount of field voltage to be applied which is taken as the output and applied directly to the field winding of generator. Triangular membership functions were used for the controller.

4 OPERATION 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.

1)Transition from the Grid-Tied Mode to the Islanded Mode

When the utility switch Su 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 interval. The first time intervals is from the instant of turning off Su to the instant of turning off Si when islanding is confirmed. The second time interval begins from the instant of turning off inverter switch Si.

B. Islanded Mode

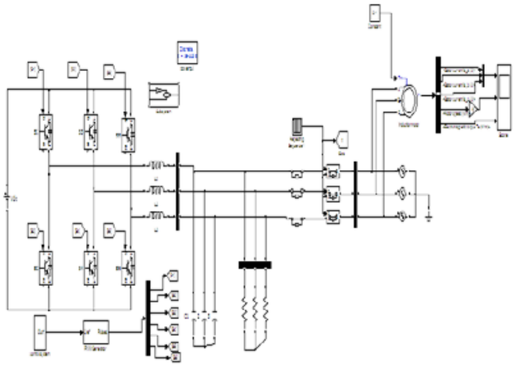
In the islanded mode, switching Si and Su are both in OFF state. The PLL cannot track the utility voltage normally, and the angle frequency is fixed. In this situation, the DG is controlled as a voltage source, because voltage compensator $GV\ D$ and $GV\ Q$ can regulate the load voltage $vC\ dq$. The voltage references in *D*and *Q*-axis are *V*max and zero, respectively. And the magnitude of the load voltage equals to *V*max approximately, which willbe analyzed consequently, the control diagram of the three-phase inverter in the islanded mode can be simplified

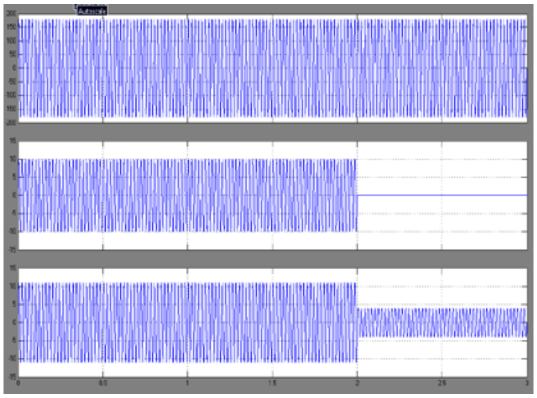
1)Transition from the Islanded Mode to the Grid-Tied Mode

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 Si. 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 $vC\ abc$ will follow the grid voltage $vgabc$. If the load voltage $vC\ abc$ 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 *V*max is larger than the utility voltage magnitude Vg , the voltage reference *V*ref 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 *V*max, which is larger than the magnitude of the utility voltage Vg , so the PI compensator $GV\ D$ will saturate, and the limiter outputs its upper value $Igref\ d$. At the same time, $vC\ q$ is regulated to zero by the PLL according to (5), so he output of $GV\ Q$ will be zero. Consequently, the voltage regulators $GV\ D$ and $GV\ Q$ are inactivated, and the DG is controlled as a current source just by the inductor current loop.

5. SIMULATION RESULTS

To investigate the feasible of the proposed control strategy, the simulation has been done in PSIM. The power rating of a three-phase inverter is 3kWin the simulation. The parameters in the simulation are shown in Tables I and II. The RMS of the rated phase voltage is 115 V, and the voltage reference *V*max is set as 10% higher than the rated value. The rated utility frequency is 50 Hz, and the upper and the lower values of the limiter in the PLL are given as 0.2 Hz higher and lower than the rated frequency, respectively.





Conclusion:

A unified control strategy was proposed for three phase inverter in DG to operate in both islanded and grid connected mode with no need for switching between two different control architectures or critical islanding detection. A novel voltage controlling technique was proposed in this it is in active 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 is proposed, and it can improve the wave form quality of both the grid current in the grid tied mode and the load voltage in the islanded mode. The proposed unified control strategy was verified by the simulation .

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