An Efficient Control Strategy for Three-Phase Inverter in Distributed Generation using Artificial Neural Networks

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Abstract—**This paper presents a efficient control strategy that enables both islanded and grid-tied operations of three-phase inverter in distributed generation using Artificial Neural Technology, with no need for switching between two corresponding controllers or critical islanding detection. The proposed control strategy composes of an inner inductor current loop, and a 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. Furthermore, the waveforms of the grid current in the grid-tied mode and the load voltage in the islanding mode are distorted under nonlinear local load with the conventional strategy. And this issue is addressed by proposing a load current feedforward in this paper. Additionally, this paper presents the detailed analysis of the control strategy. Finally, the effectiveness of the proposed control strategy is validated by the simulation and experimental results.**

Index Terms—**Distributed generation (DG), ANN technology, three-phase inverter, efficient control.**

I. INTRODUCTION

The integration of Distributed Generation systems into the main electricity network is currently changing the paradigm we used to live with, where the electric power was generated in large power plants, sent to the consumption areas through transmission plants, sent to the consumption areas through transmission lines and delivered to the consumers through a passive distribution infrastructure. The integration of DG into distribution networks in recent years has transformed them from being passive to active networks. The progress of Distributed Generation as an important energy option in the present scenario is the result of combination of utility restructuring, technology evolutions and recent environmental policies.

Distributed or embedded generator is generally defined /accepted as a plant which is connected directly to utilities of distribution network or can operate independently. They are generally considered to be less than 100MW in capacity and are not centrally planned or dispatched. Distributed generation can be based on renewable technologies such as wind turbine, photovoltaic or recent promising non-renewable technologies such as micro turbine and fuel cell. 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. Distributed generation using micro turbine is a typical and practical solution because of its environment-friendliness and high energy efficiency. Various applications such as peak saving, co-generation, remote power and premium power makes its penetration wide spread.

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. 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. 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. 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. 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. 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.

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.

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. When the nonlinear local load is fed, the harmonic component of the load current will fully flow into the utility.

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.

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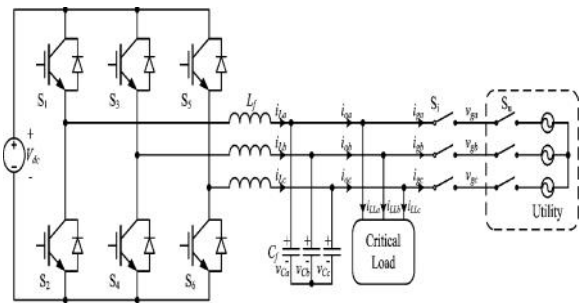

Fig. 1. Schematic diagram of the DG based on the proposed control strategy

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. In the islanded mode, the nonlinear load may distort the load voltage, and many control schemes have been proposed to improve the quality of the load voltage, including a multiloop control method, resonant controllers, sliding mode control. 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 an efficient control strategy.

This paper proposes an efficient 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. Second, a novel voltage controller is presented to supply reference for the inner inductor current loop, where Artificial neural networks is 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 be 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 modified 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 modified 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 feedforward, 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 feedforward can be extended into the islanded operation mode, due to the improved quality of the load voltage.

II. PROPOSED CONTROL STRATEGY

This paper presents an efficient control strategy for a three phase inverter in DG using Artificial neural networks to operate in both islanded and grid-tied modes. The transition is done for the operations of the grid-tied mode and islanded mode using the efficient method proposed. 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, 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. The overall block diagram of the proposed control strategy is shown in the Fig. 2.

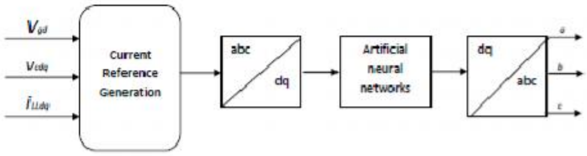

Fig. 2. Overall block diagram of the proposed control strategy.

A. Overview

With the hybrid voltage and current mode control, 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:

$$P_{\text{load}} = \frac{3}{2} \cdot \frac{V_m^2}{R} \quad (1)$$

$$Q_{\text{load}} = \frac{3}{2} \cdot V_m^2 \cdot \left(\frac{1}{\omega L} - \omega C\right). \quad (2)$$

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. 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 *vCabc* 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. The general parameters for the power stage are given in table I. These parameters are used during the simulation of the circuit developed for the control strategy that has been proposed in this paper. Each value has been taken into consideration for obtaining the experimental results.

TABLE I
PARAMETERS OF THE POWER STAGE

Parameters	Value
DC voltage V_{dc}	400 V
Filter inductor L_f	3.5 mH
Filter capacitor C_f	15 μF
Switching frequency f_s	10 kHz
Sampling frequency f_{smp}	20 kHz
Rated power of DG P_{DG}	3000 W
Rated RMS phase voltage V_n	115 V
Rated utility angle frequency ω_0	50×2π rad/s
Rated linear local load $R_{load\ ac}$	60 Ω
Rated nonlinear local load $R_{load\ dc}$	120 Ω

B. Scheme of control

Fig. 2 describes the overall block diagram for the proposed unified control strategy, where the inductor current *iLabc*, the utility voltage *vgabc* , the load voltage *vCabc*, and the load current *iLLabc* 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 Artificial neural network is employed in both *D*- and *Q*-axes. The PLL in the proposed control strategy is based on the SRF PLL, which is widely used in the three-phase power converter to estimate the utility frequency and phase. Furthermore, a limiter is inserted between the Artificial neural network and *G*PLL, 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 *iLref dq* , and the phase of the current is synchronized to the grid voltage *vgabc* . 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 feedforward, 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 neural network is adopted in both *D*-axes and *Q*-axis. Besides, an extra limiter is added in the *D*-axis. Moreover, the load current feedforward is implemented by adding the load current *iLLdq* to the final inductor current reference *iLref 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 *iLredq* composes of four parts in *D*- and *Q*-axes respectively: 1) the output of voltage controller *iref dq* ; 2) the grid current reference *Igref dq* ; 3) the load current *iLLdq* ; and 4) the current flowing through the filter capacitor *Cf* . In the grid-tied mode, the load voltage *vCdq* is clamped by the utility. The current reference is irrelevant to the load voltage, due to the saturation in *D*-axis, and the output of the neural network 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 feedforward. The sensed load current is added as a part of the inductor current reference *iLref dq* to compensate the harmonic component in the grid current under nonlinear local load. In the islanded mode, the load current feedforward 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.

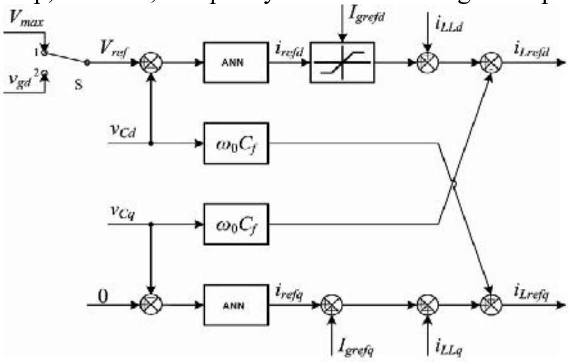

Fig. 3. Block diagram of the current reference generation module.

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. INTRODUCTION TO ARTIFICIAL NEURAL NETWORKS

Artificial Neural Networks are relatively crude electronic models based on the neural structure of the brain. The brain basically learns from experience. It is natural proof that are beyond the scope of current computers are indeed solvable by small energy efficient packages. This brain modeling also promises a less technical way to develop machine solutions. These biologically inspired methods of computing are thought to be the next major advancement in the computing industry. Even simple animal brains are capable of functions that are currently impossible for computers. Computers do rote things well, like keeping ledgers or performing complex math. But computers have trouble recognizing even simple patterns much less generalizing those patterns of the past into action of the future.

Now, advance in biological research promise an initial understanding of the natural thinking mechanism. This research shows that brain stores information, as patterns. Some of these patterns are very complicated and allow us the ability to recognize individual faces from any different angles. This process of storing information as patterns, utilizing those patterns, and then solving problems encompasses a new field in computing. This field does not utilize traditional programming but involves the creation of massively parallel networks and the training of those networks to solve specific problems. This field also utilizes words very different from traditional computing, words like behave, react, self-organize, learn, generalize, and forgot. An artificial neural network (ANN), often just called a "neural network" (NN), is a mathematical model or computational model based on biological neural networks. It consists of an interconnected group of artificial neurons and processes information using a connectionist approach to computation. In most cases an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase. In more practical terms neural networks are non-linear statistical data modeling tools. They can be used to model complex relationships between inputs and outputs or to find patterns in data. A neural network is an interconnected group of nodes, akin to the vast network of neurons in the human brain.

IV. PRINCIPLE OF OPERATION

The principle of operation involves in total four states, 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).

$$\begin{pmatrix} x_d \\ x_q \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos\theta & \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta + \frac{2}{3}\pi\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2}{3}\pi\right) & -\sin\left(\theta + \frac{2}{3}\pi\right) \end{pmatrix} \times \begin{pmatrix} x_a \\ x_b \\ x_c \end{pmatrix}. \tag{3}$$

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 *iLref dq* , and the inductor current is regulated to track the reference *iLref dq*

The reference of the inductor current loop *iLref 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

$$\begin{cases} v_{ga} = V_g \cos\theta^* \\ v_{gb} = V_g \cos\left(\theta^* - \frac{2\pi}{3}\right) \\ v_{gc} = V_g \cos\left(\theta^* + \frac{2\pi}{3}\right) \end{cases} \tag{4}$$

where *Vg* is the magnitude of the grid voltage, and θ is the actual phase angle. By the Park transformation, the utility voltage is transformed into the SRF, which is shown as

$$\begin{cases} v_{gd} = V_g \cos(\theta^* - \theta) \\ v_{gq} = V_g \sin(\theta^* - \theta). \end{cases} \quad (5)$$

vgq is regulated to zero by the PLL, so *vgd* equals the magnitude of the utility voltage *Vg* . As the filter capacitor voltage equals the utility voltage in the gird-tied mode, *vCd* equals the magnitude of the utility voltage *Vg* , and *vCq* equals zero, too.

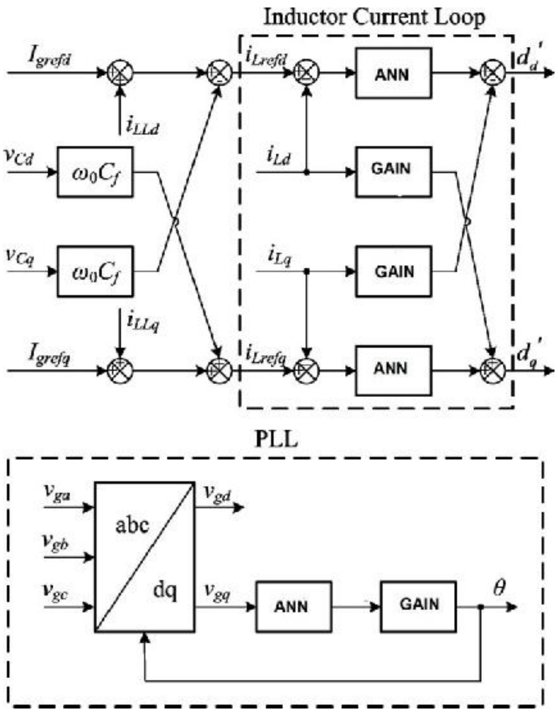

Fig. 4. Simplified block diagram of the unified control strategy when DG operates in the grid-tied mode.

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 *Igref dq* and the load current *iLLdq* . In other words, the inductor current tracks the current reference and the load current. If the steady state error is zero, *Igref dq* represents the grid current.

B. 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 interval 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 . During the first time interval, the utility voltage *vgabc* is still the same with the load voltage *vCabc* as the switch Si is in ON state. As the dynamic of the inductor current loop and the voltage loop is much faster than the PLL, while the load voltage and current are varying dramatically, the angle frequency of the load voltage can be considered to be not varied.

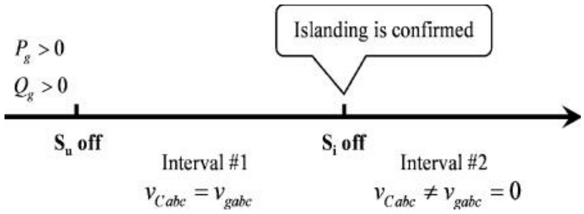

Fig. 5. Operation sequence during the transition from the grid-tied mode to the islanded mode.

In the hybrid voltage and current mode control, 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 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 *vCdq* . 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.

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 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 *vCabc* will follow the grid voltage *vgabc*. 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 *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 Artificial neural network will saturate, and the limiter outputs its upper value *Igref d*. At the same time, *vCq* is regulated to zero by the PLL according to (5), so the DG is controlled as a current source just by the inductor current loop.

V. SIMULATION AND EXPERIMENTAL RESULTS

To investigate the feasible of the proposed efficient control strategy, the simulation has been done in SIMULINK. The power rating of a three-phase inverter is 3kWin the simulation. In the grid-tied mode, the dynamic performance of the conventional voltage mode control and the proposed control strategy is compared by stepping down the grid current reference. The simulation results can be seen that the dynamic performance of the proposed control strategy is better than the conventional voltage mode control. During the transition from the grid-tied mode to the islanded mode, the proposed control strategy is compared with the hybrid voltage and current mode control. The SIMULINK model for the proposed control strategy is shown in the below Fig. 6.

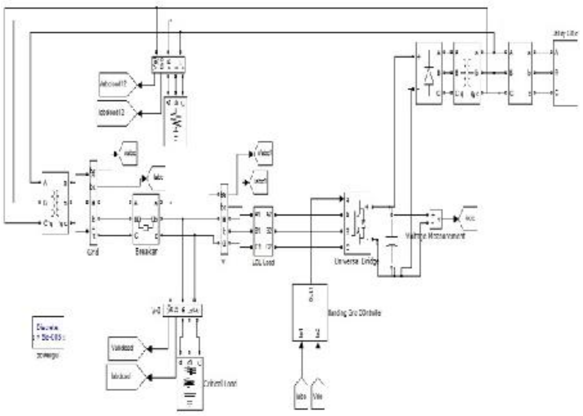

Fig. 6. SIMULINK model of proposed control strategy.

The SIMULINK model used for the Artificial neural network is shown in Fig. 7.

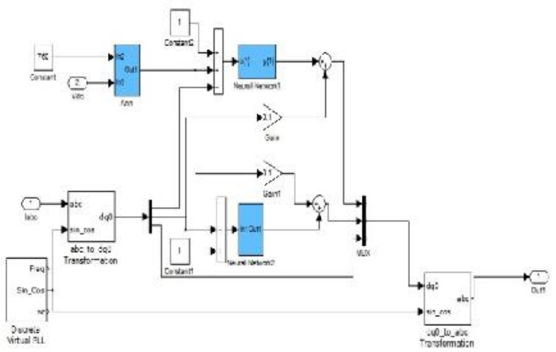

Fig. 7. SIMULINK model for the control using ANN Technology.

The experimental waveforms when DG feeds nonlinear load in both the grid-tied mode and islanded mode during their transitions is shown in Fig.8 and Fig.9.

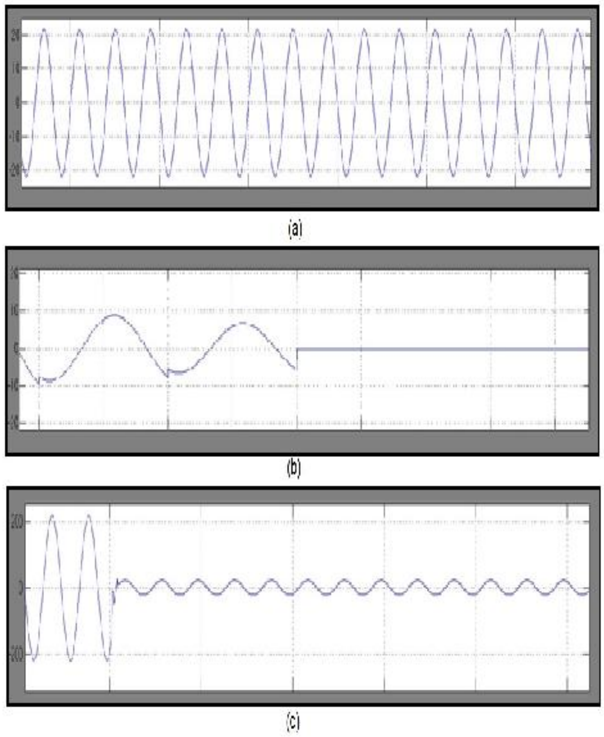

Fig. 8. Simulation waveforms of (a) load voltage *vca* , (b) grid current *iga*, and (c) inductor current *ila* when DG is transferred from the grid-tied mode to the islanded mode with proposed unified control strategy.

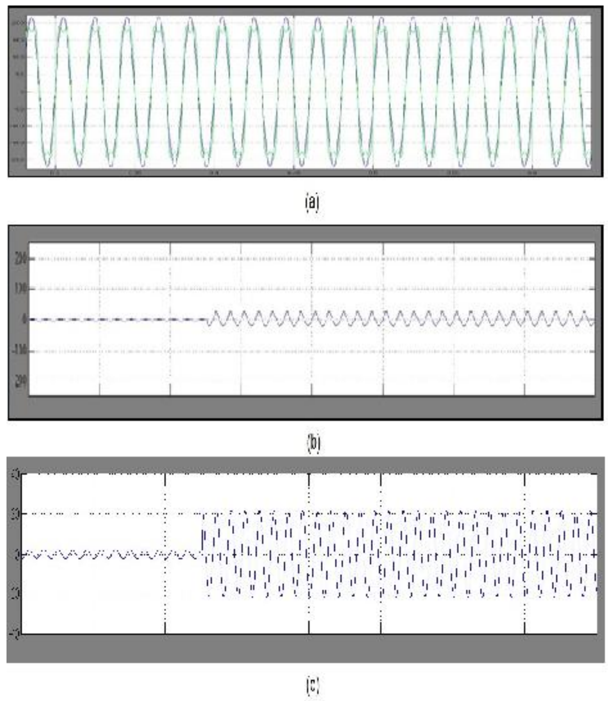

Fig. 9. Experimental waveforms when DG is transferred from the islanded mode to the grid-tied mode: (a) grid voltage *vga* , load voltage *vca* , (b) grid current *iga* ,(c) inductor current *iLa* .

VI. CONCLUSION

An efficient control strategy was proposed for three-phase inverter in DG using Artificial neural networks to operate in both islanded and grid-tied modes, with no need for switching between two different control architectures or critical islanding detection. The voltage controller 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, the load current feedforward can improve the waveform quality of both the grid current in the grid-tied mode and the load voltage in the islanded mode. The proposed efficient control strategy was verified by the simulation and experimental results.

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