A Fuzzy Adaptive Voltage Control Strategy of 3-Phase Inverter for Stand-Alone Distributed Generation Systems

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Abstract—**This paper presentss a control strategy of three-phase voltage source inverter for a distributed generation system in a standalone operation. The proposed adaptive voltage control technique combines an adaption control term and a state feedback control term. The algorithm is easy to implement, but it is very robust to system uncertainties and sudden load disturbances. The proposed control strategy guarantees excellent voltage regulation performance (i.e., fast transient response, zero steady-state error, and low THD) under various types of loads such as balanced load, unbalanced load, and nonlinear load. The simulation results are implemented using MATLAB/Simulink.**

Index Terms—**Adaptive control, distributed generation (DG) system (DGS), load current observer, stand-alone, three-phase inverter, voltage control**

I. Introduction

In recent years, eco-friendly distributed generation systems (DGS) such as wind turbines, solar cells, and fuel cells are dramatically growing because they can fulfill the increasing demand of electric power due to the rapid growth of the economy and strict environmental regulations regarding greenhouse gas emissions. Generally, the DGSs are interconnected in parallel with the electric utility grid and provide maximum electric power to the grid. However, there are some areas (e.g., remote islands or villages) where the connection to the grid is expensive or impractical and then small scaled standalone DGSs are the only efficient and economical options. In such DGSs, depending on consumers' power demand, there are situations where some DGSs operate in parallel or independently.In either case, a stable operation of each DGS unit is as important as the stability of the parallel operating DGSs in which the proper load sharing of each unit is one of main research issues since the voltage controller is commonly used in a single DGS unit or multiple DGS units. For this reason, the voltage controller design for a single DGS unit, which can guarantee a good voltage regulation under unbalanced and nonlinear loads, is an interesting topic in the field of the DGSs control.

For the purpose of improving the quality of inverter output voltage, many researchers are working on designing the controllers for dc–ac power converters. In a control scheme based on the transfer function of the nominal plant is proposed for an electronically coupled DG unit in an islanded mode. This control method is suitable for a pre-specified and balanced load condition, but cannot cover the large load variations. In a robust controller is developed for balanced and unbalanced systems, which considers the uncertainties of the load parameters. However, nonlinear load is not fully addressed. In a repetitive control is used to regulate the UPS inverters. However, the slow response and lack of the systematic method to stabilize the error dynamics with the repetitive control are being the main problems. In an alternative control strategy with a feed forward compensation component can significantly mitigate the effect of load disturbance and make the controller design simple.

Nevertheless, the application of this method is mainly limited to balanced load conditions. In a current control technique based on the spatial repetitive control is applied to a single-phase inverter and it also improves the performance of the current controller by estimating the disturbances. Although this control can obtain good results under nonlinear load, it may not guarantee a good voltage tracking capacity for a three-phase system. In a robust servomechanism voltage controller and a discrete-time sliding mode current controller are presented to control a single distributed generation unit in a standalone mode which can operate well under a sudden load change, an unbalanced load, and a nonlinear load. However, the controller provided in is quite complicated. In a voltage and frequency control strategy based on a discrete-time mathematical model is proposed for the islanded operation of dispatch able electronically coupled distributed-resource units. The method can achieve good voltage regulation under various load types. However, no experimental results are shown to verify the usefulness of the proposed method. An adaptive feed forward compensation controller is presented in for microgrid applications. Because a Kalman filter is applied for online estimating the system parameters, this control scheme is robust to parameter variations.

However, the tuning of covariance matrices, which is one of difficult tasks, is not stated in the paper. In a complementary controller is suggested for DGS units in grid-connected applications. Although this controller can deal with nonlinearities and grid disturbances, the design of the current control loop seems to be complicated. In addition, this control scheme is not applicable in an islanded mode because it is lack of voltage control loop.

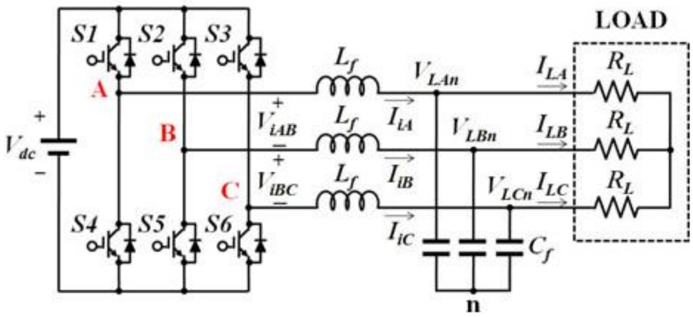

Fig. 1.1 Schematic diagram of a three-phase dc to ac inverter with an *LC* filter in a standalone application

Recently, an adaptive control method has been widely considered in the standalone DGS or UPS voltage control. In and the precise voltage tracking is achieved under distorting loads by using the adaptive control for the output voltage based on the ideas of dissipativity. In these papers, the uncertainties in the system parameters are addressed through the adaptation, and the stability of the system is guaranteed even under system parameters variations. However, the major drawback of these techniques is the computation complexity. In order to reduce this complexity, a certain predefined value for the parameters is required. In an adaptive output voltage controller based on the resonant harmonic filters, which measures the capacitor current and the load currents in the same sensor, is proposed in order to compensate for the unbalance and harmonic distortion on the load. The adaptation law is also included to cope with the uncertainties in the system parameters. However, the information about output voltage THD is not presented so it is not easy to evaluate the quality of the controllers. In an adaptive control method based on the proportional-derivative control technique is presented for a pulse width modulation (PWM) inverter operation in an islanded DGS. This paper can guarantee good voltage regulation under various operating conditions such as sudden load changes, unbalanced load, and nonlinear load. However, it is not an easy task to choose the appropriate control gains according to the design procedure mentioned in the paper.

II. STAND-ALONE OPERATION FOR INVERTER

Inverters convert power from DC to AC while rectifiers convert it from AC to DC. Many inverters are bi-directional, i.e. they are able to operate in both inverting and rectifying modes. In many stand-alone PV installations, alternating current is needed to operate 230V (or 110V), 50 Hz (or 60 Hz) appliances. Generally stand-alone inverters operate at 12, 24, 48, 96, 120, or 240V DC depending upon the power level. Ideally, an inverter for a stand-alone PV system should have the following features:

- Sinusoidal output voltage.
- Voltage and frequency within the allowable limits.
- Cable to handle large variation in input voltage.
- Output voltage regulation.
- High efficiency at light loads.
- Less harmonic generation by the inverter to avoid damage to electronic appliances like television, additional losses, and heating of appliances.
- Photovoltaic inverters must be able to withstand overloading for short term to take care of higher starting currents from pumps, refrigerators, etc.
- Adequate protection arrangement for over/under-voltage and frequency, short circuit etc.
- Surge capacity.
- Low idling and no load losses.
- Low battery voltage disconnect
- Low audio and radio frequency (RF) noise.

Several different semiconductor devices such as metal oxide semiconductor field effect transistor (MOSFETs) and insulated gate bipolar transistors (IGBTs) are used in the power stage of inverters. Typically MOSFETs are used in units up to 5 kVA and 96V DC. They have the advantage of low switching losses at higher frequencies. Because the on-state voltage drop is 2V DC, IGBTs are generally used only above 96V DC systems.

Voltage source inverters are usually used in stand-alone applications. They can be single phase or three phase and there are three switching techniques commonly used: square wave, quasi-square wave, and pulse width modulation. Square-wave or modified square-wave inverters can supply power tools, resistive heaters, or incandescent lights, which do not require a high quality sine wave for reliable and efficient operation. However, many household appliances require low distortion sinusoidal waveforms. The use of true sine-wave inverters is recommended for remote area power systems. Pulse width modulated (PWM) switching is generally used for obtaining sinusoidal output from the inverters.

A general layout of a single-phase system, both half bridge and full bridge, is shown in Fig. 2.3. In Fig. 2.3(a), single phase, half bridge is with two switches, S1 and S2, the capacitors C_1 and C_2 are connected in series across the DC source. The junction between the capacitors is at the mid-potential. Voltage across each capacitor is $V_{dc}/2$. Switches S_1 and S_2 can be switched on/off periodically to produce AC voltage. Filter (L_f and C_f) is used to reduce high-switch frequency components and to produce sinusoidal output from the inverter. The output of inverter is connected to load through a transformer.

Figure 2.3(b) shows the similar arrangement for full-bridge configuration with four switches. For the same input source voltage, the full-bridge output is twice and the switches carry less current for the same load power.

The power circuit of a three phase four-wire inverter is shown in Fig. 2.5. The output of the inverter is connected to load via three-phase transformer (delta/Y). The star point of the transformer secondary gives the neutral connection. Three phase or single phase can be connected to this system. Alternatively, a center tap DC source can be used to supply the converter and the mid-point can be used as the neutral.

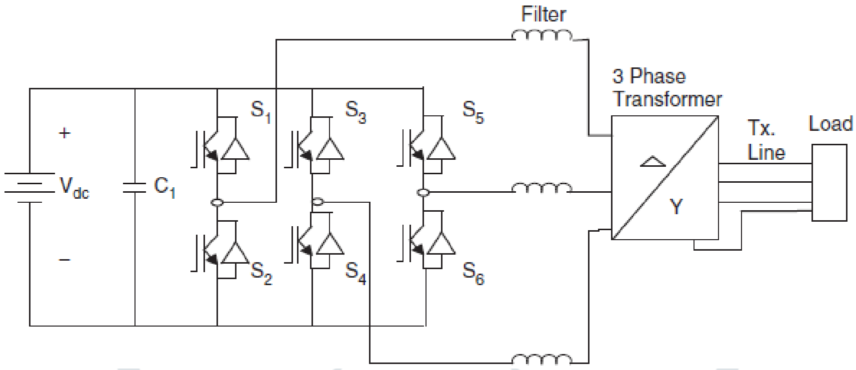

Fig. 2.1 a stand-alone three-phase four wire inverter

Figure 2.5 shows the inverter efficiency for a typical inverter used in remote area power systems. It is important to consider that the system load is typically well below the nominal inverter capacity P_{nom}, which results in low conversion efficiencies at loads below 10% of the rated inverter output power. Optimum overall system operation is achieved if the total energy dissipated in the inverter is minimized. The high conversion efficiency at low power levels of recently developed inverters for grid-connected PV systems shows that there is a significant potential for further improvements in efficiency.

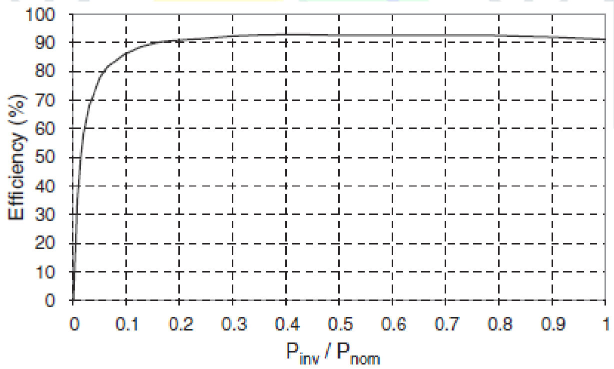

Fig. 2.2 Typical inverter efficiency curve

Space Vector Pulse Width Modulation (SVPWM)

In recent years VSI is widely used to generate a 3-phase variable frequency and variable voltage ac supply required for variable speed AC drives. The ac voltage is defined by two characteristics, namely amplitude and frequency. Hence, it is essential to work out an algorithm that permits control over both of these quantities. PWM controls the average output voltage over a sufficiently small period called sampling period or sub-cycle, by producing pulses of variable duty-cycle. The three-phase, two-level voltage source inverter (VSI) has a simple structure and generates a low-frequency output voltage with controllable amplitude and frequency by programming high-frequency gating pulses. In this VSI, there are a total of 8 states (n^3). The V_1 to V_6 vectors are known as active voltage vectors and the remaining two vectors are known as zero voltage vectors. The three-phase, two-level, six pulse voltage source inverter (VSI), there are six non-zero active voltage space vectors and two zero voltage space vectors as shown in Fig.2.7. The six active voltage space vectors can be represented as

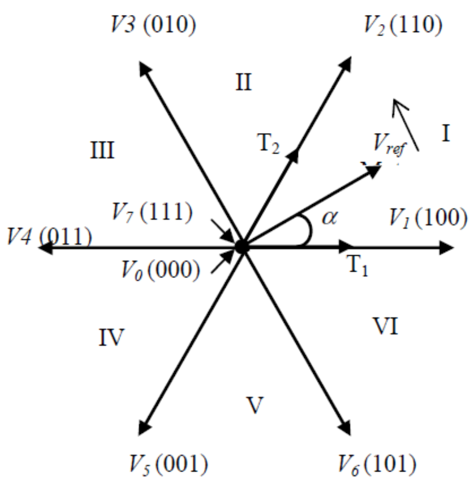

Fig. 2.3 Possible voltage space vector and vector identification

The reference voltage space vector (V_{ref}) represents the desired value of the fundamental components for the output phase voltages. In the space vector approach V_{ref} can be constructed in an average manner. The reference voltage vector (V_{ref}) is sampled at equal intervals of time, *Ts* referred to as sampling time period. The possible voltage vectors that can be produced by the inverter are applied for different time durations within a sampling time period such that the average vector produced over the T_S is equal to V_{ref}, both in magnitude and angle. It has been established that the vectors to be used to generate any sample are the zero voltage vectors and the two active voltage vectors forming the boundary of the sector in which the sample lies.

Adaptive Control

An adaptive control can be thought of as a feedback law which attempts to reshape the controller by observing its performance. This type of control is usually proposed to compensate for some kind of system uncertainty such as unknown parameters or disturbances. In this chapter, we review a brief history of adaptive control and describe its different types such as direct and indirect adaptive control techniques. Since there is no need to estimate the system parameters in the direct adaptive control method which means lower mathematical computations, this control method is used for the VSI with uncertain parameters. Next the adaptive control for nonlinear systems with linearly parameterized uncertainty is investigated. Finally, the systematic adaptive design procedure is applied to the VSI with two unknown parameters.

III. SYSTEM DESCRIPTION

The circuit model in Fig. 1.1 uses the following quantities. The inverter output lines to neutral voltage and phase current vectors are given by $V_i = [v_{iA}\ v_{iB}\ v_{iC}]^T$ and $I_i = [i_{iA}\ i_{iB}\ i_{iC}]^T$, respectively. In addition, the load lines to neutral voltage and phase current are represented by the vectors $V_L = [v_{LA}\ v_{LB}\ v_{LC}]^T$ and $I_L = [i_{LA}\ i_{LB}\ i_{LC}]^T$, respectively.

Assume that the three-phase voltages and currents used in Fig. 3.2 are balanced. By applying Kirchoff's current law and Kirchoff's voltage law at the *LC* output filter, the following voltage and current equations can be derived:

Load Current Observer Design

The proposed adaptive controller needs load current information. Using the current sensors to measure the load currents (I_L) makes the system more expensive and less reliable. In this section, a linear optimal load current observer is designed to accurately estimate load current information that can heavily affect the controller performance, a fourth- order dynamic model can be obtained as follows:

$$\dot{x} = Ax + Bu \qquad (3.1)$$

Where

$$x = \begin{bmatrix} i_{Ld} \\ i_{Lq} \\ v_{Ld} \\ v_{Lq} \end{bmatrix} \qquad A = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1/C_f & 0 & 0 & \omega \\ 0 & -1/C_f & -\omega & 0 \end{bmatrix}$$

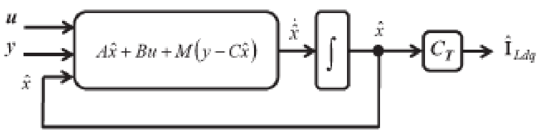

Fig. 3.7 Load current observer

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1/C_f & 0 \\ 0 & 1/C_f \end{bmatrix} \quad u = \begin{bmatrix} i_{id} \\ i_{iq} \end{bmatrix}$$

Then, the load current observer model can be represented as

$$\dot{\hat{x}} = A\hat{x} + My - MC\hat{x} + Bu$$
$$y = Cx \qquad (3.2)$$

$$\hat{\mathbf{I}}_{Ldq} = \begin{bmatrix} \hat{i}_{Ld} \\ \hat{i}_{Lq} \end{bmatrix} = C_T\hat{x}$$

where $\hat{}i_{Ld}$ and $\hat{}i_{Lq}$ are estimates of i_{Ld} and i_{Lq}, respectively, $M \in R^{4\times2}$ is an observer gain matrix, and

$$\hat{x} = \begin{bmatrix} \hat{i}_{Ld} \\ \hat{i}_{Lq} \\ \hat{v}_{Ld} \\ \hat{v}_{Lq} \end{bmatrix} \quad C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad C_T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

Next, the error dynamics of the load current observer can be obtained as follows:

$$\dot{\tilde{x}} = (A - MC)\tilde{x} \qquad (3.3)$$

where $\_x = x - \hat{}x$.

Theorem 2: Consider the following algebraic Riccati equation:

$$AP + PA^{\mathrm{T}} - PC^{\mathrm{T}}R^{-1}CP + Q = 0 \qquad (3.4)$$

where $Q \in R^{4\times4}$ is a symmetric positive semi-definite matrix, $R \in R^{2\times2}$ is a symmetric positive definite matrix, and $P \in R^{4\times4}$ is a solution matrix. Also, assume that the load current observer gain matrix M is given by

$$M = PC^{T}R^{-1} \qquad (3.5)$$

Then, the estimation error converges exponentially to zero.

Proof: Let us define the Lyapunov function as $Vo(\_x) = \_xTX\_x$, where $X = P{-}1$. Its time derivative along the error dynamics (3.29) is given by

$$\begin{aligned} \dot{V}_o(\tilde{x}) &= \frac{d}{dt}\tilde{x}^{\mathrm{T}}X\tilde{x} = 2\tilde{x}^{\mathrm{T}}(XA - XPC^{\mathrm{T}}R^{-1}C)\tilde{x} \\ &= \tilde{x}^{\mathrm{T}}X(AP + PA^{\mathrm{T}} - 2PC^{\mathrm{T}}R^{-1}CP)X\tilde{x} \\ &\le -\tilde{x}^{\mathrm{T}}XQX\tilde{x} \end{aligned} \qquad (3.6)$$

This implies that $\_x$ is exponentially stable.

Remark 3: The proposed fourth-order load current observer is the Kalman-Bucy optimal observer which minimizes the performance index $E(\dot{x}T\_x)$ representing the expectation value of $\_xT\_x$ for the following perturbed model:

$$\dot{x} = Ax + Bu + d \quad y = Cx + v \qquad (3.7)$$

where $d \in R4$ and $v \in R2$ are independent white Gaussian noise signals with $E(d) = 0$, $E_{(v)} = 0$, $E_{(ddT)} = Q$, and $E_{(vvT)} = R$.

IV. SIMULATION RESULTS

The simulation analysis of the there-phase inverter comprises of the DG'S is divided into six parts: an energy source, an ac–dc power converter (wind turbines) or a dc–dc boost converter (solar cells or fuel cells), a three-phase dc–ac inverter, an *LC* output filter, an isolation transformer, and a local load and the simulation circuit shown in figure 4.1. A renewable energy source and an ac–dc power converter or a dc–dc boost converter can be replaced by a stiff dc voltage source (V_{dc}) because this paper focuses on designing a robust adaptive voltage controller under various types of loads such as balanced load, unbalanced load, and nonlinear load. Also, this representation can be acceptable because the front converter (i.e., an ac–dc power converter or a dc–dc boost converter) can rapidly recover the reduced dc-link voltage when a heavy load is suddenly applied.

The DG energy sources usually work together with energy storage devices (e.g., batteries, flywheels, etc.) in order to back up the DS systems during the transient, and increase the power quality and reliability. Furthermore, the isolation transformer is not used to reduce cost and volume assuming that the customers need a low voltage ac source (below 600 V) which the DGSs using renewable energy sources can generate without the help of the transformer.

The performance of the proposed observer-based adaptive control system, two kinds of power levels (200-kVA class and 450-VA class) are studied because the 200-kVA unit is a too high power level. In this paper, simulations are performed by using

Matlab/Simulink software; Fig. 5 shows the schematic diagram of the proposed adaptive voltage control approach. As shown in Fig. 5, the inverter currents (I_i) and load output voltages (V_L) are measured with sensors and then transformed to the quantities I_{idq} and V_{Ldq} in the synchronously rotating *dq* reference frame, respectively. On the other hand, the load currents (I_{Ldq}) can be estimated by using the proposed current observer. In this paper, a space-vector PWM technique is utilized to approximate the reference voltages and supply less harmonic voltages to the load. Simulations and experiments are accomplished to demonstrate the transient and steady-state performances of the proposed control algorithm under the following four different cases:

Case 1) balanced resistive load (transient behavior—0% to 100%);
Case 2) balanced resistive load (transient behavior—100% to 0%);
Case 3) unbalanced resistive load (phase *C* opened);
Case 4) nonlinear load (a three-phase diode rectifier)

A. Distributed Generation (Operation for 200kVA)

Considering a 200-VA DG unit, and the system parameters are given in Table 4.1.

Simulation Parameters	Values
DGS rated power	200 kVA
DC link voltage (V_{dc})	600V
Switching & sampling Frequency	4 kHz
Load output voltages ($V_{L, rms}$)	220V
Fundamental Frequency (f)	50Hz
Output filter capacitance (C_f)	500µF
Output filter inductance (L_f)	0.3mH
Non-linear load: L_{load}, C_{load}, R_{load}	0.3mH, 4000µF, 1.2Ω

Table 4.1 Simulation parameters for 200-kVA

As shown in Table 4.1, a three-phase *LC* output filter is designed with L_f = 0.3 mH and C_f = 500 μF, and it has a cutoff frequency of 410.9 Hz. It is well known that, the larger the values of L_f and C_f, the better the filter performance. However, large L_f leads to higher cost and larger volume. Also, large C_f results in larger capacitor current at no load in addition to higher cost. Therefore, there exists a tradeoff when selecting L_f and C_f. In this case, the controller gains and observer gain matrix are selected as follows: $\alpha_d = \alpha_q = 0.1$, $\varphi_{di} = \varphi_{qi} = 1000$, $\delta_d = \delta_q = 1000$, and

$$M = 10^4 \times \begin{bmatrix} -0.3162 & -0.0039 & 3.0955 & -0.0000 \\ 0.0039 & -0.3162 & -0.0000 & 3.0955 \end{bmatrix}^T$$

The waveforms of load voltages (V_L), inverter currents (I_i), load currents (I_L), estimated load currents ($\hat{I}_L$), control inputs (v_{id} and v_{iq}), and load current error ($e_{LA} = i_{LA} - \hat{i}_{LA}$). A 0.726-Ω resistor is used for a balanced resistive load and an unbalanced resistive load. Also, to get the waveforms under nonlinear load in Fig. 10, the following values are chosen: L_{load} = 0.3 mH, C_{load} = 4000 μF, and R_{load} = 1.2 Ω. The transient performance under a balanced resistive load, and the load voltage waveforms are only slightly distorted during the transients and return to steady state within 0.52 ms. The steady-state performance under an unbalanced resistive load and a nonlinear load, respectively. In both figures, the voltage waveforms look quite sinusoidal throughout the time. The proposed observer accurately estimates the load currents under four load scenarios.

Table 4.2 presents the steady-state performance of the simulation results under four different loads for a 200-VA unit. It can be observed from Table 4.2 that the steady-state errors are smaller than 0.31% and the THDs of the output voltages are lower than 0.8% in all cases.

B. Distributed Generation (Operation for 450-VA)

To testify the performance of the proposed control algorithm, the power size is reduced to 450 VA. Accordingly, for comparison, the simulation results are illustrated in this section. Table 4.2 shows the system parameters of a 450-VA unit.

Simulation Parameters	Values
DGS rated power	450 VA
DC link voltage (V_{dc})	280V
Switching & sampling Frequency	5 kHz
Load output voltages ($V_{L, rms}$)	110V
Fundamental Frequency (f)	50Hz
Output filter capacitance (C_f)	6.67µF

Output filter inductance (L_f)	10mH
Non-linear load: L_{load}, C_{load}, R_{load}	10mH, 680μF, 200Ω

Table 4.2 Simulation parameters for 450-VA

As listed in Table4.2, a three-phase *LC* output filter is chosen with L_f = 10 mH and Cf = 6.67 μF, and this filter has a natural frequency (ω_c) of 3872 rad/s. In this case, the controller gains and observer gain matrices are chosen as follows: $\alpha_d = \alpha_q = 20$, $\varphi_{di} = \varphi_q i = 100$, $\delta_d = \delta_q = 100$ for a 450-VA unit, respectively.

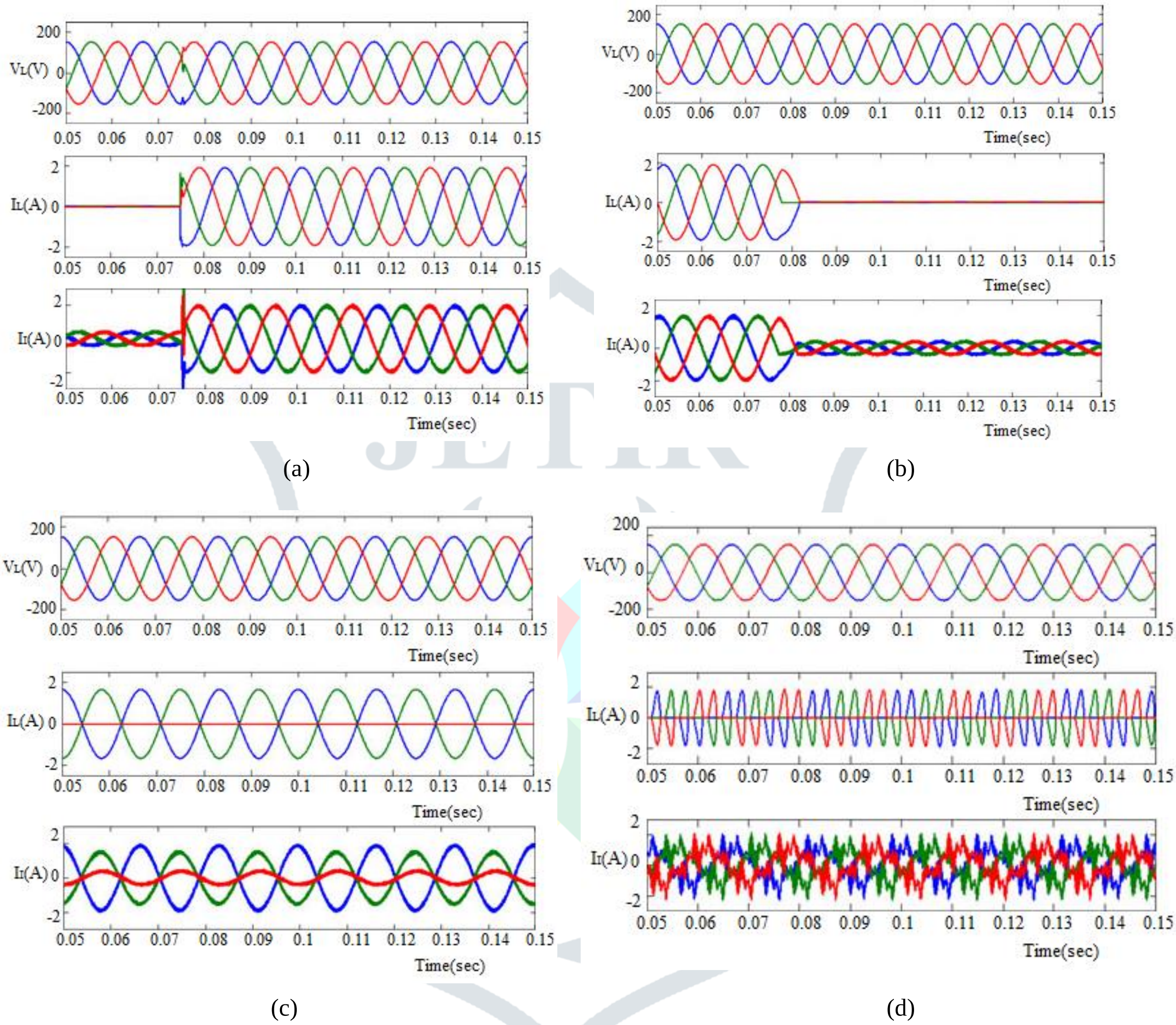

Fig. 4.1 Simulation results of the proposed adaptive voltage controller with 150% uncertainties of system parameters under four different conditions. (a) Balanced resistive load (0% to 100%). (b) Balanced resistive load (100% to 0%). (c) Unbalanced resistive load. (d) Nonlinear load

V. CONCLUSION AND FUTURE SCOPE

A high-performance control strategy for three phase inverter for stand-alone gird connected systems was described that is able to compensate for distortion and unbalance generated by nonlinear and unbalanced loads or by nonlinearity in the inverter. The principle can also be used in any static power supply system like power supplies and ground power units. The voltage-controlled UPS system adapts the inverter reference to achieve sinusoidal balanced output voltages at nonlinear and nonsymmetrical loads by comparing the vectorial output voltages with a circular reference in fixed points on the fundamental period. The implementation of this control strategy on different systems is eased by the low dependency of the output filter parameters.

Future Scope & Extension

Fuzzy logic or Fuzzy based neural network control is used, for high speed control action. Adaptive input membership functions are used, the system is very sensitive to load variations.

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