Improved Adaptive Voltage Control Strategy of Three-Phase Inverters for Stand-Alone Distributed Generation Systems

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***Abstract*—This paper proposes an improved adaptive voltage control of three-phase inverter for stand-alone distributed generation systems (DGs). The proposed voltage controller consists of two control terms: an adaptive compensating control term and a stabilizing control term. The adaptive compensating control term is created for avoiding direct calculation of time derivatives of the state variables. The stabilizing control term is designed for asymptotically stabilizing the error dynamics of the system. Also a fourth-order optimal load current observer is proposed in this paper for enhanced system reliability and cost effectiveness. The stability of the proposed controller and observer is proven using Lyapnov theory. The proposed system can establish good voltage regulation with fast dynamic response, small steady state error and low total harmonic distortions under sudden load changes, unbalanced loads and nonlinear loads. The validity of the proposed control is verified through simulations in MATLAB.**

***Keywords*— Adaptive control, distributed generation (DG) System (DGS), load current observer, stand-alone, three-phase inverter, voltage control.**

I. INTRODUCTION

ENERGY demand growth, environmental issues associated with fossil-fueled power plants, lack of transmission capacity and limitation in constructing new lines, and electricity market deregulation have been driving forces behind the growth of Distributed Generation (DG). DG units often employ non-conventional, clean energy resources such as wind, solar photovoltaic, fuel-cell etc., are gaining more and more attention in electric power industry. Most DG units are interfaced to the grid through power-electronic converters, but they are more economical in a stand-alone mode of operation in the case of rural villages and remote islands since connecting to the grid may cause higher cost [1], [2].

In stand-alone applications, the operation of three phase inverter of the DG is similar to uninterruptible power supply (UPS) for its local loads. In recent years the control of Stand-alone DG or UPS has been an important area of research. The evaluation of regulation performance of inverter output voltage is done in terms of transient response time, steady-state error, and total harmonic distortion (THD). In these applications, the quality of inverter output voltage is highly affected by the types of loads such as sudden load change, unbalanced load, and nonlinear load. Various control techniques have been implemented in these applications yet these control systems does not provide satisfactory performance of the load side inverter of the DG or UPS. Therefore, advanced control methods have to be adopted for excellent voltage regulation of the inverters.

In [3] a new real-time space-vector-based control strategy is presented for three-phase uninterruptible power supply system powering nonlinear and unbalanced loads but the steady state error and THD of the output voltage is not satisfactory in case of nonlinear voltage. In [4] a novel output voltage control scheme for UPS systems using multivariable feedback linearization is implemented. Although, this method can prove good performance at the output voltage, the control technique seems to be highly complicated. A modified stationary reference frame-based predictive current controller is proposed in [5], but nonlinear load is not investigated. A new approach to the sliding-mode control of single-phase uninterruptible-power-supply inverters is introduced in [6]. Even though this control can achieve good performance it is only intended for single phase inverters. The control technique presented in [7] combines an inner discrete-time sliding mode controlled (DSMC) current loop and an outer robust servomechanism controlled voltage loop. The experimental results show good performance but the control method is complicated. In [9]–[11], a repetitive control is used to regulate UPS inverters, but a repetitive control is always associated with its slow response and lack of systematical method to stabilize the error dynamics.

In this paper an advanced adaptive voltage control technique is implemented for a three phase inverter for stand-alone DGs. The adaptive controller is able to maintain consistent performance of the system even in the presence of uncertainty and variations in the plant parameters. The stability of the

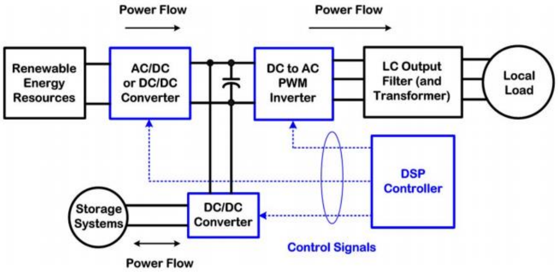


Fig. 1. Typical DG in stand-alone operation

proposed voltage controller and load current observer is proven using Lyapnov stability Theorem. The proposed controller is able to achieve excellent voltage regulation like fast transient behavior, small steady state error and low THD under unbalanced and nonlinear loads. Experiments are done using MATLAB/SIMULINK software and results are found

II. SYSTEM CONFIGURATION AND ANALYSIS

The block diagram of typical DGs in stand-alone mode of operation is shown in the Fig. 1. It includes renewable energy resources which may be a wind turbine, solar cell or a fuel cell, an ac-dc power converter for wind turbines or a unidirectional dc-dc power converter in case of solar or fuel cell, a three-phase dc-ac inverter, an LC output filter, a DSP control unit, and a local load. An optional transformer can be used in the system to provide an electrical isolation or boost the output voltage of the three-phase inverter, but this may lead to higher cost and large volume of the overall system. Storage systems such as batteries, ultra capacitors, can also be incorporated to the system to generate electric power during the transients (e.g., start up or sudden load change) and improve the reliability of renewable energy resources.

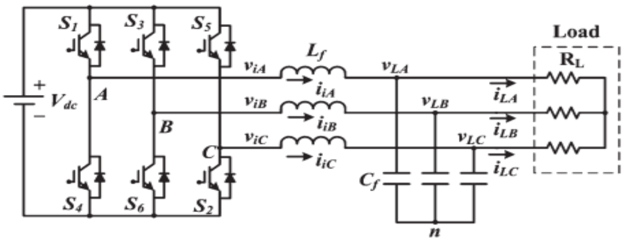


Fig. 2. Circuit diagram of a three phase inverter with LC output filter for stand-alone DGs.

In this paper, we are dealing with a voltage controller design of a three-phase inverter for stand-alone DGs that can promise excellent voltage regulation (i.e. fast transient response, small steady state error, and low THD) under sudden load change, unbalanced load, and nonlinear load. Thus, renewable energy sources and ac–dc power converters or unidirectional dc–dc boost converters can be interchanged with a dc voltage source (V_{dc}). Fig. 2 shows the circuit model of a three-phase inverter with an LC output filter for stand-alone DGSs. As shown in Fig. 2 the system includes mainly four parts: a dc voltage source (V_{dc}), a three-phase pulse-width modulation (PWM) inverter (S1–S6), an output filter (L_f and C_f), and a three-phase load (R_L). Note that the LC filter is necessary to suppress high-order harmonic components of the inverter output voltage due to the PWM action and then deliver the load with sinusoidal voltage.

In this paper, the following assumptions are made to design an adaptive controller and a load current observer.

1) Load voltage and inverter current are available in direct axis and quadrature axis components.

2) The desired load dq-axis voltages (v_{ldq}) and their references are constant, and its derivatives can be set to zero.

3) Load dq-axis current components (i_{ldq}) are unknown, and they change very slowly during the sampling period.

III. ADAPTIVE VOLTAGE CONTROL DESIGN

Based on the system model this section comprises of the adaptive control algorithm and design.

Fig. 3 shows the block diagram of the proposed adaptive control. Note that here dq axis load voltage and inverter current are the state variables, inverter voltage in dq axis is the control input, and load current in dq axis is defined as the disturbance.

First, the errors of the load dq-axis voltages (v_{ld} and v_{lq}) and the inverter dq currents (i_{id} and i_{id}) can be defined as

$$\overline{i_{id}} = i_{id} - i_{idref} \qquad \overline{v_{ld}} = v_{ld} - v_{ldref}$$

$$\overline{i_{iq}} = i_{iq} - i_{iqref} \qquad \overline{v_{lq}} = v_{lq} - v_{lqref}$$

Where v_{ldref}, v_{lqref} are the reference values of v_{ld} and v_{lq}, respectively, and i_{idref}, i_{iqref} are the reference values of i_{id} and i_{iq}, respectively. Again, the i_{idref}, i_{iqref} are given by the equations shown below:

$$i_{dref} = i_{ld} - \omega C_f v_{lq}$$

$$i_{qref} = i_{lq} + \omega C_f v_{ld}$$

The control inputs v_{id} and v_{iq} can be divided into the following two control terms

$$v_{id} = u_{ffd} + u_{fbd}$$

$$v_{iq} = u_{ffq} + u_{fbq}$$

Where u_{ffd}, u_{ffq} are the d and q-axis compensation control terms and u_{fbd}, u_{fbq} are the d- and q-axis feedback control terms to stabilize the error dynamics of the system.

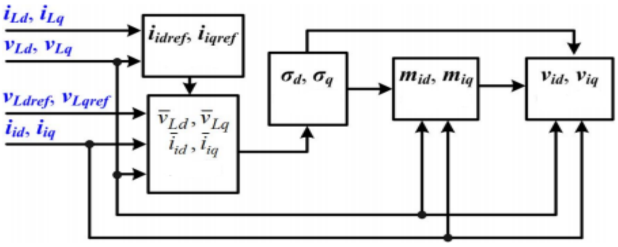


Fig. 3. Block diagram of the proposed control strategy

Assume that c_f is known. Let the compensation control terms (u_{ffd}, u_{ffq}) and the feedback control terms (u_{fbd}, u_{fbq}) be calculated by the following adaptive control laws:

$$u_{ffd} = \sum_{i=1}^{4} m_{di} p_{di} + v_{ld}$$

$$u_{ffq} = \sum_{i=1}^{4} m_{qi} p_{qi} + v_{lq}$$

$$u_{fbd} = -\delta_d \sigma_d$$

$$u_{fbq} = -\delta_q \sigma_q$$

Where,

$$\sigma_d = \bar{v}_{ld} + \alpha_d \bar{i}_{id}$$

$$\sigma_q = \bar{v}_{lq} + \alpha_q \bar{i}_{iq}$$

Where α_d and α_q are positive design constants m_{di} and m_{qi} are the observer gain values and p_{qi}, p_{qi} are the adaptive gains and δ_d, δ_q are the system control parameters.

IV. LOAD CURRENT OBSERVER DESIGN

The proposed adaptive voltage controller requires the load current information using current sensors to measure the load current makes the system more expensive and reliable. Moreover an adaptive control is based on an idea of predicting the uncertain system parameter from the measured system values. Therefore here we are using a linear optimal load current observer to accurately estimate load current information that can heavily affect the controller performance.

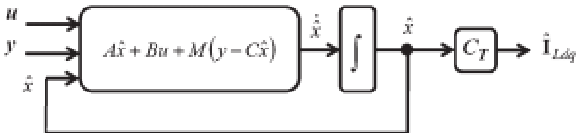


Fig. 4. Block diagram of the proposed load current observer

Remark: This remark details on how the observer gain matrix M is determined. Normally, the observer performance is mostly influenced by the system model if the measurements are excessively noisy and the input noise intensity is small On that note, M is small. This leads to a slow observer. However, if the measurements are good and the input noise intensity is large, the observer relies on the measurement. In this case, M is large, resulting in a fast observer with high bandwidth. Consequently, by assuming that the measurement is good, the fast observer is desirable.

The fig 5 shows the overall block diagram of the system with load current observer. Here the renewable energy source and the converter is replaced by a dc voltage source, the load voltage and inverter current are measured using sensors and transformed in to dq axis components. The resulting values are used by the load current observer for estimating the load current. These signals are processed inside the controller to produce the controlled output inverter voltage in dq-axis components.

The modulation technique used here is SVPW (space vector pulse width modulation). SVPWM treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency. SVPWM technique approximates the reference voltage by a combination of eight switching states including six active state and two zero state. SVPWM is used for better utilization of voltage and low harmonic distortions in the output. The six gate signals produced are supplied to the inverter switches for obtaining the desired regulated voltage at the output.

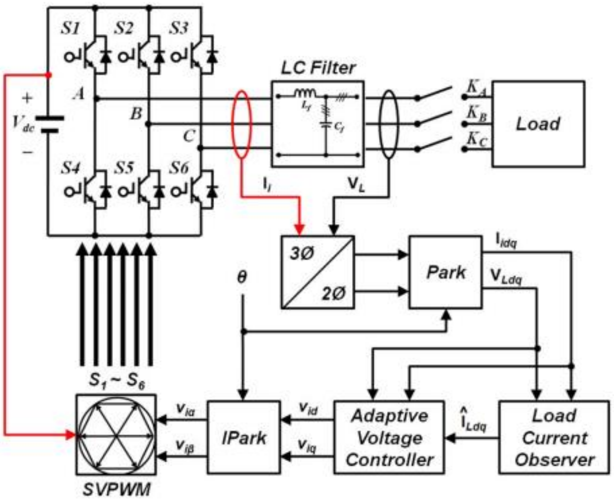


Fig. 5. Overall block diagram of the proposed adaptive control system

V. PERFORMANCE EVALUATION

In this section, simulations and experiments are made, and various results are presented. To evaluate the performance of the proposed observer-based adaptive control system a 200KVA power level unit is studied. In this paper, simulations are performed by using Matlab/Simulink software. Simulations and experiments are accomplished to demonstrate the transient and steady-state performances of the proposed control algorithm under the following cases:

Case 1) balanced load
Case 2) unbalanced load
Case 3) nonlinear load

Fig. 6 shows the nonlinear load circuit that consists of a three-phase full-bridge diode rectifier, an inductor, a capacitor and a resistor.

Consider a 200-kVA DG unit, and the system parameters are given in Table I.As shown in Table I, a three-phase LC output filter is designed with L_f =0.3mH and C_f = 500µF, 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.

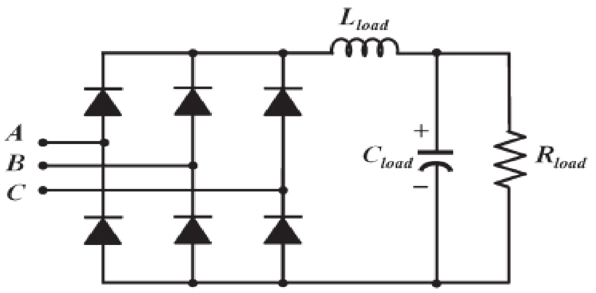


Fig. 6. Nonlinear load circuit with a three phase diode rectifier

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:

α_d, α_q =0.1,

δ_d, δ_q = 1000, and

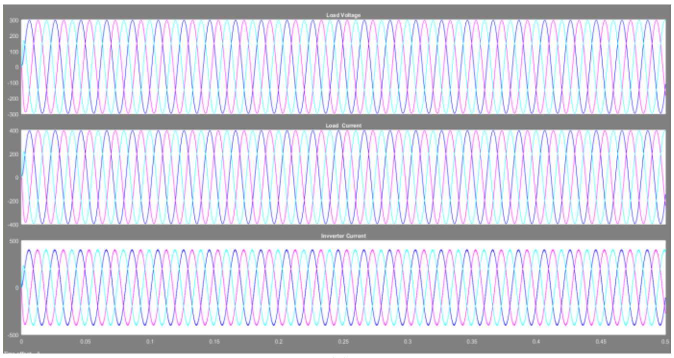
M=

$$\begin{matrix} -0.3162 & -0.0039 & 3.0955 & -0.0000 \\ 0.0039 & -0.3162 & -0.0000 & 3.0955 \end{matrix}$$

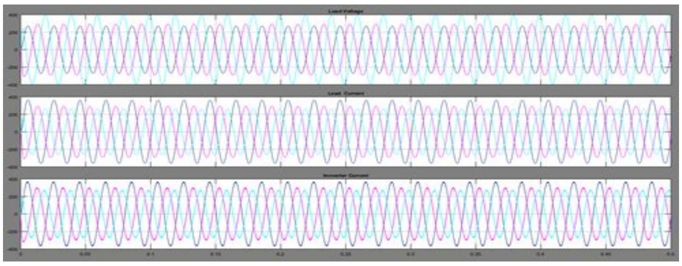
Note that these parameters are chosen through extensive simulation studies with the aforementioned procedure.

TABLE I
SYSTEM PARAMETERS

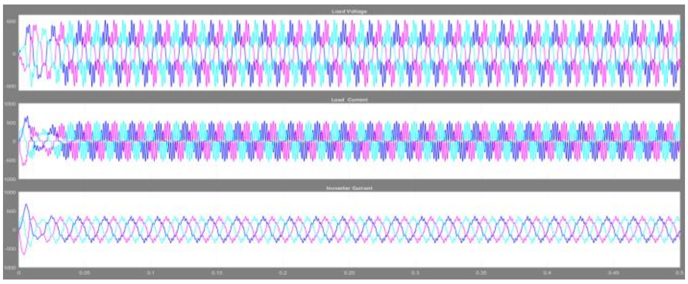
PARAMETERS	Values
DGS rated power	220 kVA
DC-link voltage	600 V
Switching & Sampling frequency	4 kHz
Load output voltages	220 V
Fundamental frequency	60 Hz
Output filter capacitance	500 µF
Output filter inductance	0.3 mH



(a)



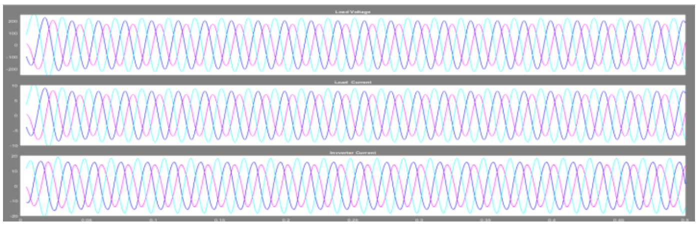
(b)



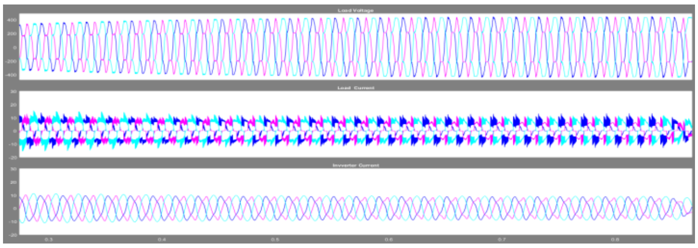
(c)

Fig. 6. Simulation results of the stand-alone DG unit under (a)case 1, (b)case 2 and (c)case 3 respectively for a200kVA unit without any control.

Fig. 6. Shows the steady state performance of the proposed control scheme for a balanced load, unbalanced load, and nonlinear load respectively. Each figure shows the waveforms of the load voltage v_l, load current i_l and inverter current i_i. A .75 ohm resistor is used for a balanced resistive load and an unbalanced load. Also, under nonlinear load the following values are chosen: L_L =0.3mH, C_L = 4000µF, and R_L =1.2Ω. In fig. 6. The voltage and current waveforms are sinusoidal for case 1) balanced load. Under case 2) unbalanced load, the voltage and current waveforms differ their magnitudes in three phases, but the presence of harmonics is minimal. Under case 2) nonlinear load, the waveforms are highly distorted and it contains large amount of harmonics.

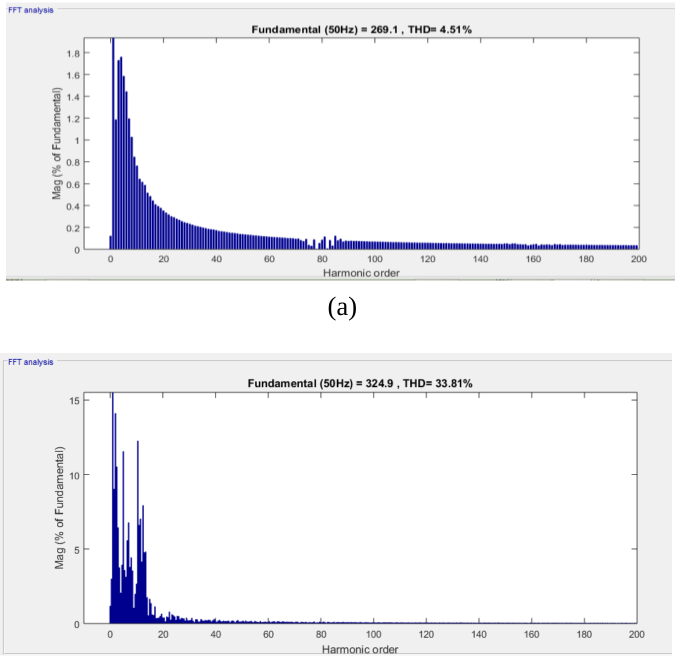


(a)



(b)

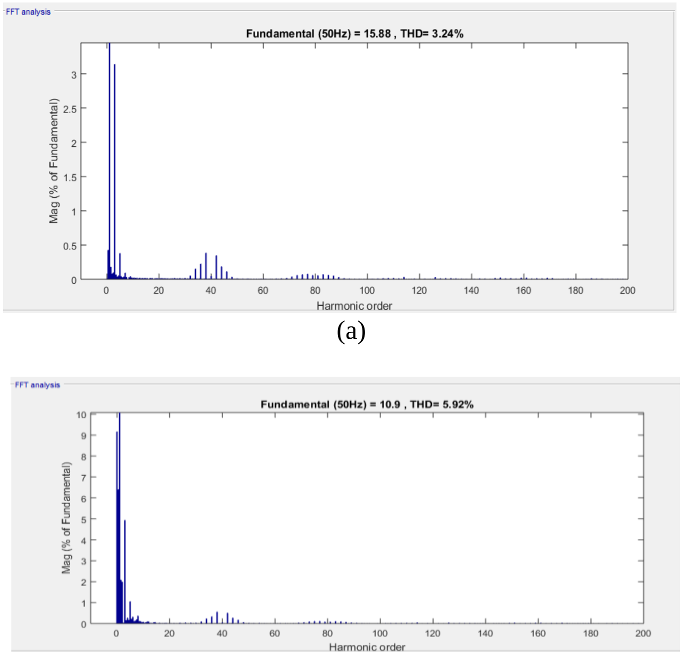
Fig. 7. Simulation results of the proposed control scheme under case2 and case3 respectively..



(b)

Fig. 8. FFT analysis of load current in case of unbalanced load and nonlinear load respectively.

Fig. 7. shows under case2, unbalanced load, the magnitude differences are reduced to a very low level. And under case 3, nonlinear load, the distortions in the load voltage and inverter currents are reduced. The harmonics are also reduced to minimum amount.



(b)

Fig. 9. FFT analysis of load current funder proposed control scheme for unbalanced load and nonlinear load respectively

As shown in the fig. 8. The total harmonic distortion values are 4.51 and 33.81 percentages for unbalanced and nonlinear load respectively, which are very much large values for a regulated output.by applying the proposed control scheme the THD values are reduced to 3.28 and 5.92 percentages in case of unbalanced and nonlinear load respectively as shown in the fig.9. (a) and (b).

VI. CONCLUSION

This paper proposes an enhanced adaptive voltage controller for a three-phase PWM inverter of stand-alone DGSs. Load current was estimated by a fourth-order optimal observer. The stability of the proposed controller and observer was analytically proven by applying Lyapunov stability theory. This adaptive control strategy can achieve more stable output voltage and lower THD than other control techniques under sudden load change, unbalanced load, and nonlinear load. The effectiveness and feasibility of the proposed control strategy were verified through various simulation and experimental results in matlab.

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