



Adaptive Voltage Control Based Three Phase Inverter for Standalone Distributed Generation System

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Abstract: A robust adaptive voltage control of three-phase VSI is proposed for a distributed generation system in an unconnected operation. For load-side inverter which considers only the uncertainties of system parameters, the state-space model is established first. The adaptive voltage control technique combines an adaption control term and a state feedback control term. The adaption control part compensates for system uncertainties, whereas the state feedback control part forces the error dynamics to converge exponentially to zero. This algorithm is easy to implement and performances like fast transient response, zero steady-state error, and low THD is guaranteed. The robustness of the closed-loop control system can be found by stability analysis. The performance comparison between adaptive and non adaptive voltage controller under parameter uncertainties is presented using simulation and experimental result to validate the proposed control scheme effectiveness.

Index terms: Adaptive voltage control, distributed generation system (DGS), robust control, stability analysis, standalone operation, uncertainties, voltage source inverter

1. INTRODUCTION

The need for energy is increasing in every year. The electric power is generated by the conventional method such as fossil fuels like coal, oil and natural gas, and nuclear power plant. Due to the combustion of hydrocarbon-rich fossil fuels, the environment is damaged. The carbon hydroxide is emitted in the conventional electric power generation. It produces global warming. So that the electric power generation based on the renewable energy resources are developed.

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 emission[1]-[2].the DGS are interconnected in parallel with the electric utility grid. However, there are some areas where the connection to the grid is impractical and then small scaled standalone DGS are introduced.DGS are operate in parallel with grid or independently. In either operation, a stable operation of each DGS unit is as important as the stability of the parallel operating DGSs. In [3], an adaptive voltage control method

based on the proportional derivative control technique is presented for a pulse width modulation (PWM) inverter operation in an islanded DGS. In [4], an adaptive voltage controller based on the resonant harmonic filters, which measure the capacitor and load current, is introduced to compensate the unbalance and harmonic distortion on the load.

This paper proposes a robust adaptive voltage controller of the three-phase voltage source inverter for a standalone DGS with various types of loads. First, the state space model of the three phase inverter is derived, which considers the uncertainties of system parameter. The proposed adaptive control technique combines an adaption control part and a state feedback control part. The proposed adaptive controller provides good voltage control performance such as fast transient response, small steady state error and low THD under various types of load.

II. SYSTEM MODEL AND CONTROL STRATEGY

Fig. 1 describes a block diagram of a standalone DGS using renewable energy sources which are wind

turbines, solar cells, fuel cells, etc. as shown in fig.1 the DGS are divided into six parts: renewable energy sources, AC to DC converter, three phase inverter, LC filter, transformer and the local load. In this paper a renewable energy source and ac to dc power converter are replaced by a stiff dc voltage source (V_{dc}). The transformer is not used to reduce cost and volume.

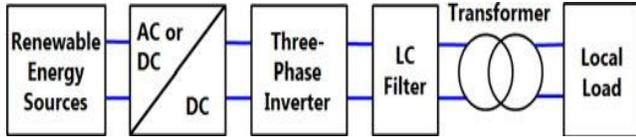


Fig. 1: Block diagram of a standalone DGS using renewable energy sources

The energy storage devices such as batteries, flywheels are used to back up the DG system. 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.

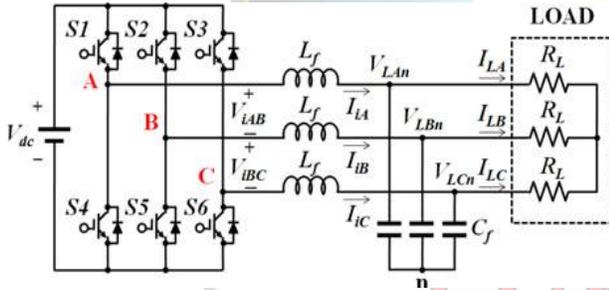


Fig. 2: Three-phase dc to ac inverter with an LC filter in a standalone application.

Fig. 2 shows a schematic diagram of a three phase inverter dc-ac inverter with an LC filter in a standalone application. It consists of a dc voltage source (V_{dc}), a three phase inverter (S1 to S6), an output filter (L_f and C_f), and a three phase resistive load (R_L). The LC filter is very important because it eliminates the harmonic components of the inverter output voltage.

The LC output filter shown in Fig.2 yields the following state equations by using Kirchhoff's voltage law and Kirchhoff's current law:

$$\begin{aligned} \frac{dV_L}{dt} &= \frac{1}{C_f} I_i - \frac{1}{C_f} I_L \\ T_i \frac{dI_i}{dt} &= -\frac{1}{L_f} T_i V_L + \frac{1}{L_f} V_i \end{aligned} \quad (1)$$

The state equations (1) in the stationary abc reference frame can be transformed to the following equations in the synchronously rotating d-q reference frame:

$$\begin{aligned} \dot{V}_{Ld} &= \omega V_{Lq} + k_1 I_{id} - k_1 I_{Ld} \\ \dot{V}_{Lq} &= -\omega V_{Ld} + k_1 I_{iq} - k_1 I_{Lq} \\ \dot{I}_{id} &= \omega I_{iq} - k_2 V_{Ld} + k_3 V_{id} + k_4 V_{iq} \\ \dot{I}_{iq} &= -\omega I_{id} - k_2 V_{Lq} - k_4 V_{id} + k_3 \end{aligned}$$

Where ω is the angular frequency ($\omega=2\pi f$), f is the fundamental frequency of output voltage or current, and

$$k_1 = \frac{1}{C_f}, \quad k_2 = \frac{1}{L_f}, \quad k_3 = \frac{1}{2L_f}, \quad k_4 = \frac{1}{2\sqrt{3}L_f}$$

The reference values of the inverter current in the d-q axis as

$$\begin{aligned} I_{idr}^* &= I_{Ld} - \frac{1}{K_1} \omega V_{Lqr} \\ I_{iqr}^* &= I_{Ld} + \frac{1}{K_1} \omega V_{Ldr} \end{aligned} \quad (3)$$

It should be noted that the output filter capacitance C_f usually satisfies $0 < C_f \ll 1$ i.e., $1 - k_1 < \infty$. Thus we may use the assumption $1 \ll k_1 \pm |\Delta k_1| < \infty$ leading to the following equations:

$$\begin{aligned} I_{idr} &= I_{Ld} - \frac{1}{k_1} \omega V_{Lqr} \approx I_{Ld} - \frac{1}{k_1 + \Delta k_1} \omega V_{Lqr} \\ I_{iqr} &= I_{Lq} + \frac{1}{k_1} \omega V_{Ldr} \approx I_{Lq} + \frac{1}{k_1 + \Delta k_1} \omega V_{Ldr} \end{aligned} \quad (4)$$

From (2) and (3), four state variables are defined as follows:

$$\begin{aligned} x_1 &= V_{Ld} - V_{Ldr}, & x_2 &= V_{Lq} - V_{Lqr} \\ x_3 &= I_{id} - I_{idr}, & x_4 &= I_{iq} - I_{iqr} \end{aligned}$$

Using the above state variables, (2) can be written as,

$$\begin{aligned} \dot{x}_1 &= \omega x_2 + k_1 x_3 \\ \dot{x}_2 &= -\omega x_1 + k_1 x_4 \\ \dot{x}_3 &= \omega I_{iq} - k_2 V_{Ld} + k_3 V_{id} + k_4 V_{iq} \\ \dot{x}_4 &= -\omega I_{id} - k_2 V_{Lq} - k_4 V_{id} + k_3 V_{iq} \end{aligned} \quad (5)$$

In considering the equation (4) and the uncertainties of system parameters, the model (5) becomes

$$\begin{aligned} \dot{x}_1 &= \omega x_2 + k_1 x_3 + \Delta k_1 x_3 \\ \dot{x}_2 &= -\omega x_1 + k_1 x_4 + \Delta k_1 x_4 \\ \dot{x}_3 &= k_3 V_{id} + k_4 V_{iq} + \Delta k_3 V_{id} + \Delta k_4 V_{iq} \end{aligned}$$



$$\omega I_{iq} - (k_2 + \Delta k_2)V_{Ld} + \dot{x}_4 = k_3 V_{iq} - k_4 V_{id} + \Delta k_3 V_{iq} - \Delta k_4 V_{id} - (k_2 + \Delta k_2)V_{Lq} - \omega I_{id} \quad (6)$$

III. ADAPTIVE VOLTAGE CONTROLLER DESIGN AND STABILITY ANALYSIS

The control inputs V_{id} and V_{iq} can be defined as two control components

$$V_{id} = V_{id1} + V_{id2}, \quad V_{iq} = V_{iq1} + V_{iq2} \quad (7)$$

Where V_{id1} and V_{iq1} are the feedback control components to stabilize the error dynamics of the system, whereas V_{id2} and V_{iq2} are the nonlinear compensating control components and it is given by,

$$V_{id2} = \frac{-k_4 \omega I_{id} - k_3 \omega I_{iq}}{(k_3^2 + k_4^2)} \quad (8)$$

$$V_{iq2} = \frac{-k_4 \omega I_{iq} + k_3 \omega I_{id}}{(k_3^2 + k_4^2)}$$

Equation (6) can rearrange by using (7) and (8)

$$\begin{aligned} \dot{x}_1 &= \omega x_2 + k_1 x_3 + \Delta k_1 x_3 \\ \dot{x}_2 &= -\omega x_1 + k_1 x_4 + \Delta k_1 x_4 \\ \dot{x}_3 &= k_3 V_{id1} + k_4 V_{iq1} - k_3 f_1(x, t) - k_4 f_2(x, t) \\ \dot{x}_4 &= k_3 V_{iq1} - k_4 V_{id1} + k_4 f_1(x, t) - k_3 f_2(x, t) \end{aligned} \quad (9)$$

Where,

$$\begin{aligned} f_1(x, t) &= a_1 V_{id} + a_2 V_{iq} + a_3 V_{Ld} \\ f_2(x, t) &= a_4 V_{id} + a_5 V_{iq} + a_6 V_{Lq} \end{aligned} \quad (10)$$

In which a_1, a_2, \dots, a_6 are unknown constants

$$\begin{aligned} a_1 &= a_5 = \frac{-k_3 \Delta k_3 + k_4 \Delta k_4}{(k_3^2 + k_4^2)} \\ a_2 &= -a_4 = \frac{k_4 \Delta k_3 - k_3 \Delta k_4}{(k_3^2 + k_4^2)} \\ a_3 &= a_6 = k_2 + \Delta k_2 \end{aligned}$$

The state space form of equation (9) is,

$$\dot{x} = (A + \Delta A)x + B[u - f(x, t)] \quad (11)$$

Where

$$f(x, t) = [f_1(x, t) \quad f_2(x, t)]^T$$

Assuming that there exists a positive definite matrix $P \in R^{4 \times 4}$ satisfying the following inequality

$$(A + \Delta A)^T P + P(A + \Delta A) + Q - 2PBR^{-1}B^T P < 0$$

$$A^T P + PA - 2PBR^{-1}B^T P + Q + \Delta A^T P + P\Delta A < 0 \quad (12)$$

Where, $Q \in R^{4 \times 4}$ and $R \in R^{2 \times 2}$ are positive definite matrices.

The above inequality satisfy if the following inequality holds for some positive ρ

$$A^T P + PA - 2PBR^{-1}B^T P + Q + \rho PEE^T P + \frac{1}{\rho} F^T F \Delta k_1^2 < 0$$

Assume that $|\Delta k_1| \leq$ for some known positive constant, then inequality (12) is satisfied if the following Riccati like inequality has a positive definite solution matrix $P \in R^{4 \times 4}$

$$A^T P + PA - 2PBR^{-1}B^T P + Q + \rho PEE^T P + \frac{1}{\rho} F^T F \zeta < 0 \quad (13)$$

The controller u can make the error dynamics x converge to zero:

$$u = -Kx + W\Pi$$

where $K = R^{-1}B^T P$ is a gain matrix, π is estimated value of π^* , and the adaptive control law is given by,

$$\dot{\Pi} = -\Gamma W^T \sigma$$

Where,

$$W = \begin{bmatrix} V_{id} & V_{iq} & V_{Ld} \\ V_{iq} & -V_{id} & V_{Lq} \end{bmatrix}$$

$$\Gamma = \text{diag}(\gamma_i), \gamma_i > 0, i=1, \dots, 3$$

$$\sigma = B^T P x$$

The Riccati like inequality (13) is equivalent to the following linear matrix inequality (LMI):

$$X > 0$$

$$\begin{bmatrix} AX + XA^T - 2BR^{-1}B + \rho EE^T & X & \zeta XF^T \\ X & -Q^{-1} & 0 \\ \zeta FX & 0 & -\rho I \end{bmatrix} < 0 \quad (15)$$

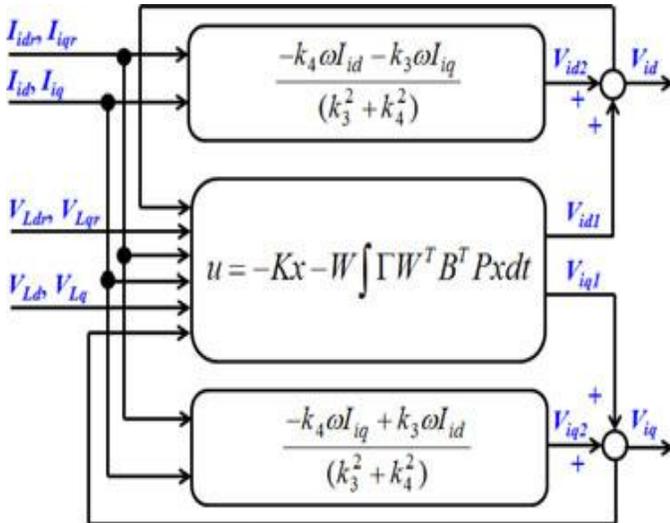


Fig. 3: Adaptive voltage controller.

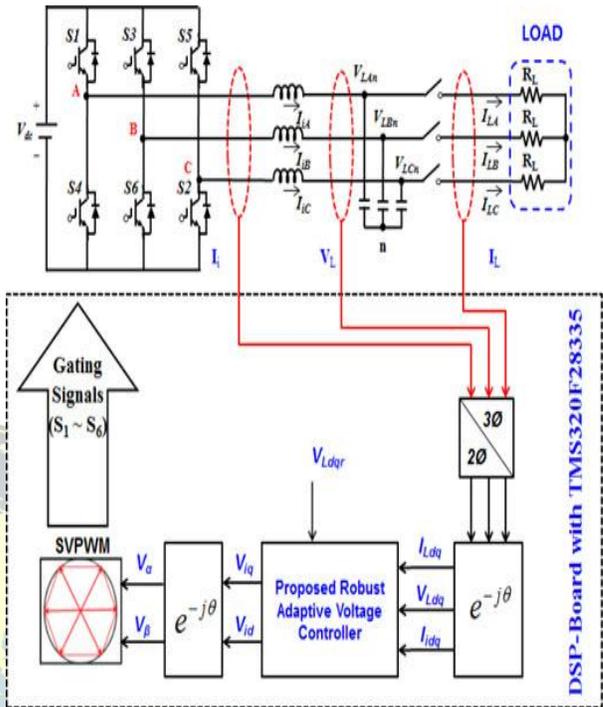


Fig. 4: Proposed adaptive voltage control system

The inverter current, load voltage and load current are feedback to the system. These three phase quantities are transformed to the two phase quantities. Adaptive voltage controller generates the two control inputs (V_{id} and V_{iq}) and these control inputs are given to the SVPWM. Space Vector Pulse Width Modulation implements these two control inputs and produces the gate signal for the inverter as shown in fig 4.

IV. RESULTS AND DISCUSSION

450 VA DG unit is taken to implement this control.

Components	range
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DGS rated power	450VA
DC link voltage	280V
Load output voltage	110V
Output frequency	60Hz
Switching and sampling frequency	5KHz
LC output filter	$L_f = 10\text{mH}, C_f = 6\mu\text{F}$
Resistive load	$R_L = 80\Omega$

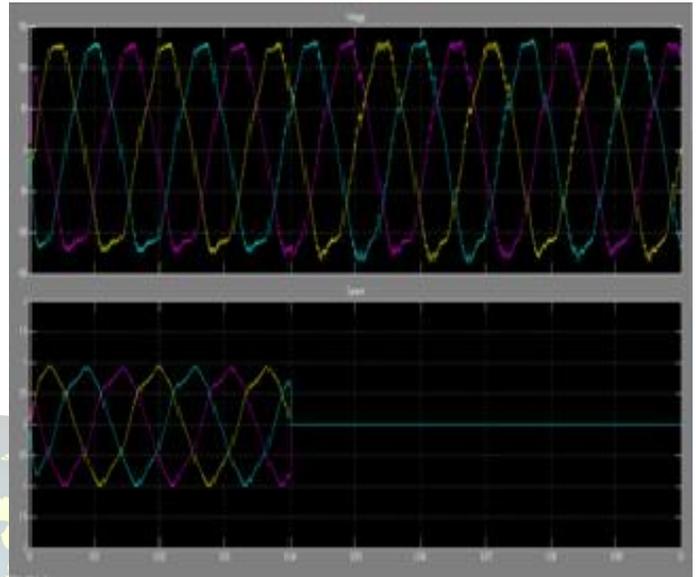


Fig. 6: Simulation results for adaptive voltage controller under a balanced resistive load (100% to 0%)

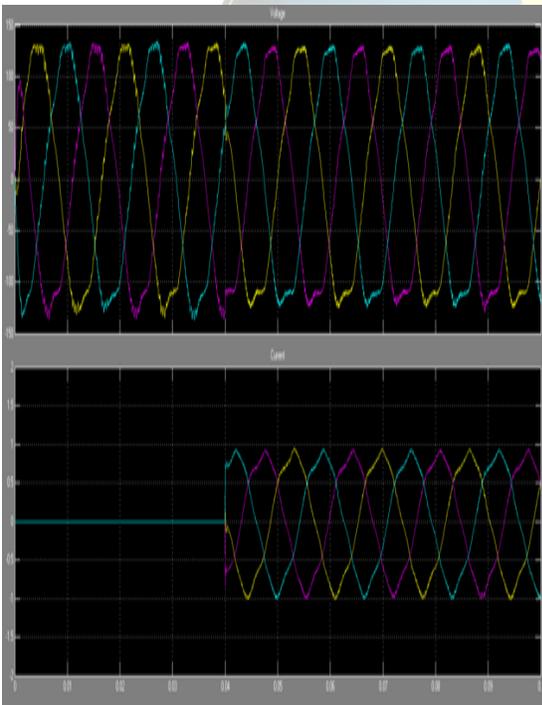


Fig. 5: Simulation results for adaptive voltage controller under a balanced resistive load (0% to 100%).

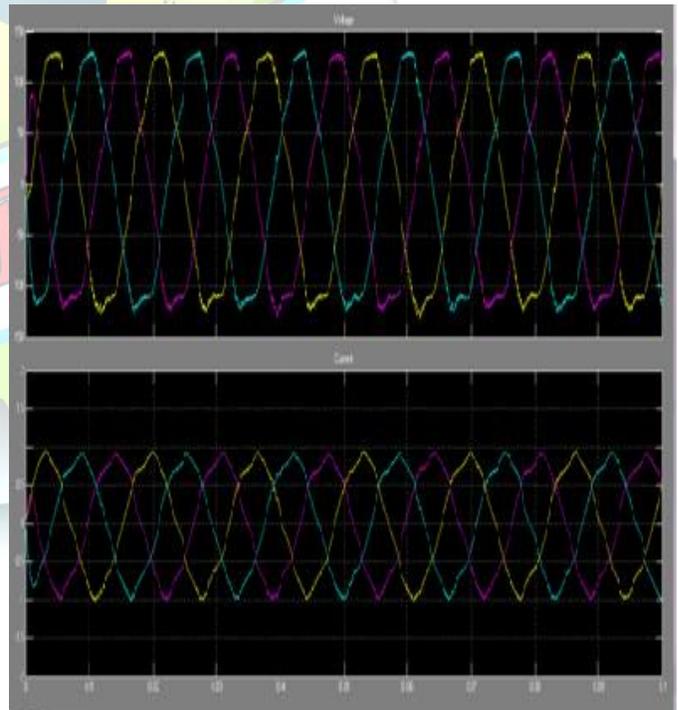


Fig. 7: Simulation results of proposed adaptive voltage controller under balanced resistive load.

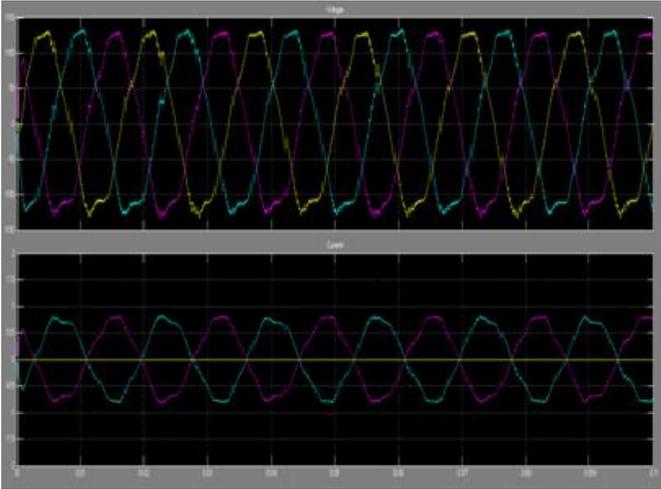


Fig. 8: Simulation results for proposed adaptive voltage controller under unbalanced resistive load.

V. CONCLUSION

This paper has presented a robust adaptive voltage control strategy of a three-phase inverter for a standalone DG unit. The proposed controller is easy and simple to implement. It is robust to system uncertainties and sudden load disturbances. Finally by using Matlab/Simulink software, the simulation was obtained and it is clear from the simulation that the proposed control scheme gives satisfactory voltage regulation performance such as fast dynamic behavior, small steady-state error, and low THD under various loads (i.e., no load, balanced load, unbalanced load, and nonlinear load) in the presence of the uncertainties of system parameters.

ACKNOWLEDGMENT

We thank the lord Almighty for his grace to us. We also thank our parents, friends for their support and encouragement.

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