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An Implementation on 3ph Inverter for Distributed Generation System: Adaptive Voltage Control and P-Q Control of the System

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Abstract— This paper reviews an adaptive control method of three-phase voltage source (VSI) inverters for stand-alone distributed generation systems (DGSs). The voltage controller includes two control terms: an adaptive compensating term and a stabilizing term. The adaptive compensating control term is combines an adaption control term and a state feedback control term and constructed to avoid directly calculating the time derivatives of state variables. Meanwhile, the stabilizing control term is designed to asymptotically stabilize the error dynamics of the system. Also, a fourth-order optimal load current observer is proposed to reduce the number of current sensors and enhance the system reliability and cost effectiveness. The stability of the proposed voltage controller and the proposed load current observer is fully proven by using Lyapunov theory. The proposed control system can establish good voltage regulation such as fast dynamic response, small steady-state error, and low total harmonic distortion (THD) under sudden load change, unbalanced load, and nonlinear load. Finally, the validity of the proposed control strategy is verified through simulations and experiments on a prototype DGS test bed with a DSP. For a comparative study, the control scheme of feedback linearization for multi-input and multi output is implemented, and its results are presented in this paper.

Key words: Adaptive Control, Distributed Generation (DG) System (DGS), Stand-Alone, Three-Phase Inverter, Robust Control, Load Current Observer, Voltage Control

I. INTRODUCTION

Distributed generation systems (DGSs) using renewable energy sources is eco-friendly (such as wind turbines, photovoltaic arrays, biomass, and fuel cells) are gaining more and more attention in electric power industry to replace existing fossil fuels and reduce global warming gas emissions. Nowadays, the DGSs are extensively used in grid-connected applications, but they are more economical in a stand-alone operation in the case of rural villages or remote islands because connecting to the grid may lead to higher cost and strict environmental regulations regarding greenhouse gas emission [1]–[8].In stand-alone applications, the load-side inverter of the DGS operates analogous to an uninterruptible power supply (UPS) for its local loads. DGSs operate in parallel [9]-[11].

Control of stand-alone DGSs or UPSs has been an attractive research area in recent years. In these applications, the regulation performance of inverter output voltage is evaluated in terms of transient response time, steady-state error, and total harmonic distortion (THD). Furthermore, the quality of inverter output voltage is heavily affected by the types of loads such as sudden load change, unbalanced load, and nonlinear load. In, a conventional proportional–integral (PI) controller has been investigated. However, the output voltage has a considerable amount of the steady-state error, and its THD is not satisfactory in the case of nonlinear load. The H∞ loop-shaping control scheme which is presented in [8] also cannot effectively mitigate the THD of the output voltage under nonlinear load.

Therefore, the load-side inverters require advanced control techniques to achieve excellent voltage regulation performance, particularly under sudden load disturbance, unbalanced load, and nonlinear load. Recently, various advanced control methods have been applied to the load-side inverters in DGS and UPS applications, In a repetitive control is used to regulate UPS inverters, but the general problem with a repetitive control is its slow response and lack of systematical method to stabilize the error dynamics. Feedback linearization control techniques are proposed in [12] and [13].

Although these methods can achieve high performance of the output voltage, the control design techniques seem to be complicated. Two iterative learning control strategies are presented in [14], and these methods are capable of achieving high performance. However, the switching frequency of the inverter is very high, so it results in huge switching losses. In [15], a model predictive control with a load current observer is proposed. Although the control technique is simple, the THD of the output voltage is still high. In [16], another predictive control is proposed, but nonlinear load is not investigated. In [17], a robust PI controller is proposed for an autonomous DG unit. A full set of results is presented in the case of unbalanced RLC load, but the results about nonlinear load are not presented.

Sliding-mode control techniques are applied for inverters in [18]–[21]. In [18], the experimental results show that the output voltage THD is still high undern on linear load. In [19]–[21], although good performance can be obtained, the controller designs are only for single-phase inverters [19], [20], and the results of nonlinear load are not presented [21]. In [6], a robust servomechanism control (RSC) is used to control three-phase inverters of a DGS in stand-alone

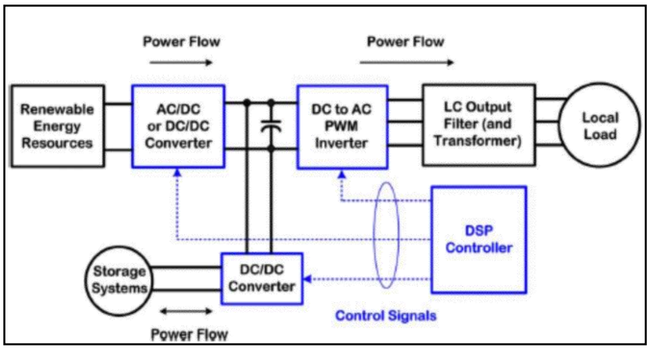

Fig. 1: Configuration of a typical DGS in a stand-alone operation mode

Even though this control technique can achieve good performance, it is quite complicated and needs exact parameter values of an *RLC* load. In [22] and [23], the authors propose the control strategies that consist of an RSC in an outer loop and a sliding-mode control in an inner loop. Even if the simulation and experimental results show good voltage performance, the control approach is complicated.

This paper reviews an adaptive voltage controller and an optimal load current observer of three-phase inverters for standalone DGSs. Also, it is analytically proven that the proposed voltage controller and the proposed load current observer are asymptotically stable, respectively. The proposed control method can achieve excellent voltage regulation such as fast transient behavior, small steady-state error, and low THD under sudden load change, unbalanced load, and nonlinear load. For a comparative study, the feedback linearization for multi input and multi output (FL-MIMO) control method in [12] is implemented in this paper. Simulation is done by using Matlab/Simulink software, and experiments are carried out on a prototype DGS test bed with a TMS320F28335 DSP. The remaining part of this paper is organized as follows. Section II describes the DGS in a stand-alone operation and the state-space model of the load-side inverter. The design and stability analysis of the proposed adaptive voltage controller are fully addressed in Section III. Section IV illustrates the proposed load current observer and analyzes its stability. In Section V, the simulation and experimental results are given to evaluate the performance of the proposed control algorithm. Finally, conclusions are drawn in Section VI.

II. SYSTEM DESCRIPTION AND MATHEMATICAL MODEL

Describes a block diagram of a standalone DGS as depicted in Fig. 1, It consists of renewable energy sources (e.g., wind turbines, solar cells, and fuel cells), an ac–dc power converter (wind turbines) or a unidirectional dc–dc boost converter (solar cells or fuel cells), a three-phase dc–ac inverter, an *LC* output filter, a DSP control unit, and a local load. As shown in Fig. 1, a transformer can be used to provide an electrical isolation or boost the output voltage of the three phase inverter, but it may lead to higher cost and larger volume. Also, storage systems such as batteries, ultra-capacitors, and flywheels may be used to generate electric power during the transient (e.g., start-up or sudden load change) and improve their liability of renewable energy sources.

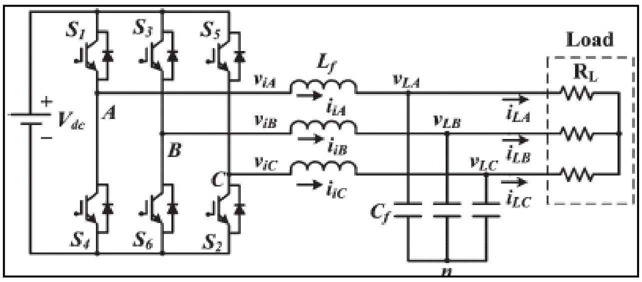

Fig. 2: Schematic diagram of a three-phase inverter with an LC output filter for stand-alone DGSs.

In this paper, we deal with the voltage controller design of the three-phase inverter for stand-alone DGSs that can assure 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 replaced with a dc voltage source (Vdc).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 comprises four parts: a dc voltage source (Vdc), a three-phase pulse-width modulation (PWM) inverter (S1–S6), an output filter (Lf and Cf), and a three-phase load (RL). Note that the LC filter is required to suppress high-order harmonic components of the inverter output voltage due to the PW M action and then provide the load with sinusoidal voltages. The circuit model in Fig. 2 uses the following quantities. The inverter output lines to neutral voltage and phase current vectors are given by Vi = [viAviBviC] TandIi=[iiAiiBiiC]T, respectively. In addition, the load lines to neutral voltage and phase current are represented by the vectors VL=[vLAvLBvLC]T and IL = [iLAiLBiLC]T, respectively. Assume that the three-phase voltages and currents used in Fig. 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:

$$\boxed{\begin{cases} \frac{d\mathbf{V}_L}{dt} = \frac{1}{C_f}\mathbf{I}_i - \frac{1}{C_f}\mathbf{I}_L \\ \frac{d\mathbf{I}_i}{dt} = \frac{1}{L_f}\mathbf{V}_i - \frac{1}{L_f}\mathbf{V}_L. \end{cases}}$$

Under balanced conditions, the aforementioned state equations(1) in the stationary *abc* reference frame can be transformed to the equations in the stationary *αβ* reference frame by using the following expression [2], [3]:

$$\boxed{\mathbf{X}_{\alpha\beta} = x_a e^{j0} + x_b e^{j\frac{2\pi}{3}} + x_c e^{j\frac{4\pi}{3}}}$$

Where Xαβ= xα + jxβ.

Thus, the state equations (1) can be transformed to the following:

$$\boxed{\begin{cases} \frac{d\mathbf{V}_{L\alpha\beta}}{dt} = \frac{1}{C_f}\mathbf{I}_{i\alpha\beta} - \frac{1}{C_f}\mathbf{I}_{L\alpha\beta} \\ \frac{d\mathbf{I}_{i\alpha\beta}}{dt} = \frac{1}{L_f}\mathbf{V}_{i\alpha\beta} - \frac{1}{L_f}\mathbf{V}_{L\alpha\beta} \end{cases}}$$

Where VLαβ= [vLα vLβ]T, ILαβ = [iLα iLβ]T, Viαβ =[viα viβ]T, and Iiαβ = [iiα iiβ]T. Next, the state equations in the stationary αβ reference frame can be transformed to the equations in the synchronously rotating dq reference frame from the following formula:

$$\boxed{\mathbf{X}_{dq} = x_d + jx_q = \mathbf{X}_{\alpha\beta} e^{-j\theta}}$$

Where θ(t) =_ t0 ω(τ)dτ+ θ0 is the transformation angle, ω is the angular frequency (ω = 2π · f), and f is the fundamental frequency of voltage or current. Finally, (3) can be transformed to

$$\boxed{\begin{cases} \frac{d\mathbf{V}_{Ldq}}{dt} + j\omega\mathbf{V}_{Ldq} = \frac{1}{C_f}\mathbf{I}_{idq} - \frac{1}{C_f}\mathbf{I}_{Ldq} \\ \frac{d\mathbf{I}_{idq}}{dt} + j\omega\mathbf{I}_{idq} = \frac{1}{L_f}\mathbf{V}_{idq} - \frac{1}{L_f}\mathbf{V}_{Ldq} \end{cases}}$$

Where VLdq= [vLdvLq]T, ILdq= [iLdiLq]T, Vidq=[vid viq]T, and Iidq= [iidiiq]T.

Also, (5) can be rewritten as follows:

$$\boxed{\begin{cases} \dot{v}_{Ld} = \omega v_{Lq} - \frac{1}{C_f}i_{Ld} + \frac{1}{C_f}i_{id} \\ \dot{v}_{Lq} = -\omega v_{Ld} - \frac{1}{C_f}i_{Lq} + \frac{1}{C_f}i_{iq} \\ \dot{i}_{id} = -\frac{1}{L_f}v_{Ld} + \omega i_{iq} + \frac{1}{L_f}v_{id} \\ \dot{i}_{iq} = -\frac{1}{L_f}v_{Lq} - \omega i_{id} + \frac{1}{L_f}v_{iq} \end{cases}}$$

Where vLd,˙vLq,˙iid, and ˙iiqde note the time derivatives of vLd, vLq, iid, and iiq, respectively. Note that

VLdq and Iidq are the state variables, Vidq is the control input, and ILdqis defined as the disturbance. In this paper, the following assumptions are made to design an adaptive controller and a load current observer.

1) vLd, vLq, iid, and iiq are available.
2) The desired load dq-axis voltages vLdrefandvLqref are constant, and its derivatives can be set to zero.
3) iLdandiLq are unknown, and they change very slowly during the sampling period [15].

III. BLOCK DIAGRAM FOR PROPOSED SYSTEM

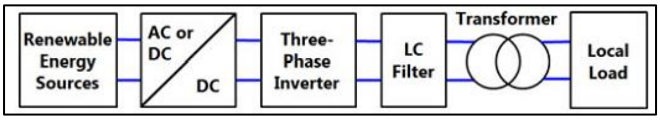

Fig. 3: Block diagram of a standalone DGS using renewable energy sources.

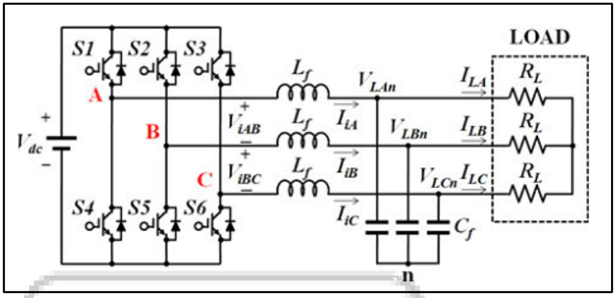

Fig. 4: Schematic diagram of a three-phase dc to ac inverter with an LC filter in a standalone application.

IV. CONCLUSION

This paper will deal with a robust adaptive voltage control strategy of a three-phase inverter for a standalone DG unit. The proposed controller is not only simple to implement, but is also robust to system uncertainties and sudden load disturbances. In addition, the stability of the proposed closed-loop control system has been mathematically proven. To support the validity of the proposed control algorithm, simulations and experiments will have been carried out through a Matlab/Simulink software and a prototype DGS test-bed with a TMS320F28335DSP, respectively.

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