Fast Stable Control of Microgrid System Based on Adaptive Non-Singular Terminal Sliding Mode

Yong Xu, Jinxin Zhu, Zhanyang Xu, and Wei Wang

Abstract—**To meet the fast stable requirement of microgrid system, an adaptive voltage control method is proposed in this paper with the aid of non-singular fixed-time terminal sliding mode (TSM) technique. Firstly, by replacing the traditional constant reference signal, an adaptive reference signal is designed for fast tracking of voltage signals. Then, based on this proposed new reference signal, an adaptive non-singular fixed-time terminal sliding mode controller is developed for the control design of the microgrid inverter system, which ensures fast, accurate, and effective tracking of the desired voltage, thereby it improves the stability and anti-interference capability of the microgrid system. Simulation results demonstrate the effectiveness and priority of the proposed strategy.**

Index Terms—**Microgrid inverter; non-singular terminal sliding mode control ; adaptive reference signal; fixed-time control**

I. INTRODUCTION

With the world gets into the new industrial era led by clean energy technologies, the transition from traditional fossil fuels to renewable energy has been an inevitable trend [1, 2]. Solar and wind energy, as renewable energy sources, have received widespread attention from many scholars [3]. Grid-connected inverters are critical components of microgrid power generation systems, which has a crucial role in directly connecting solar and wind power generation units to the grid, and thus their performance directly affects the quality of the final current. As a result, it is of significant theoretical and practical value for the precise control of microgrid systems to research a microgrid inverter control strategy with small steady-state tracking error [4].

Currently, the main control strategies for microgrid inverter systems include: current control, voltage/current control, deadbeat control, repetitive control, and proportional resonant control. Among these, direct current control is simple and easy to implement, but it has the disadvantage of low current tracking accuracy. Even though by introducing grid voltage feedforward control to reduce the steady-state error of output current appropriately, it still cannot improve the power quality issues caused by input voltage disturbances [5]. Voltage/current control can achieve good control effects, but it has the disadvantage of relatively complex control and dual loop parameter adjustment [6]. Deadbeat control has good dynamic performance, but the prediction algorithm relies on system parameters, which significantly affects control accuracy [7]. Proportional resonant control can reduce steady-state error but is limited by bandwidth constraints [8]. Repetitive control is effective for periodic fluctuations but performs poorly for non-periodic fluctuations [9,10].

As a special nonlinear control method, sliding mode control has good adaptability, robustness, and dynamic performance, and it is simple and easy to implement. Therefore, it has been widely studied in the field of grid-connected inverters. Reference [11] proposes an improved exponential reaching law current sliding mode control. Reference [12] uses quasi-sliding mode control for the voltage outer loop and improved fast terminal sliding mode control for the current inner loop. Reference [13] employs a composite control algorithm by combining repetitive control and sliding mode control for grid-connected inverters. Reference [14] proposes an optimized combined reaching law sliding mode control for photovoltaic grid-connected inverters based on grey wolf parameter optimization. However, these studies ignore that the output voltage of microgrid systems is often affected by various factors such as system parameters and power load changes, which leads to uncertain fluctuations in the system output voltage and affects power quality.

To address the above-mentioned issue, an adaptive sliding mode grid-connected inverter control is proposed in this paper. By establishing the system average state dynamic model, an adaptive law is introduced to design the adaptive voltage reference signal. With the aid of this, a disturbance estimation based adaptive sliding mode controller is designed to complete the control design in the grid-connected inverter system. Compared with the existing control methods, the main contributions of this study are twofold, which are as

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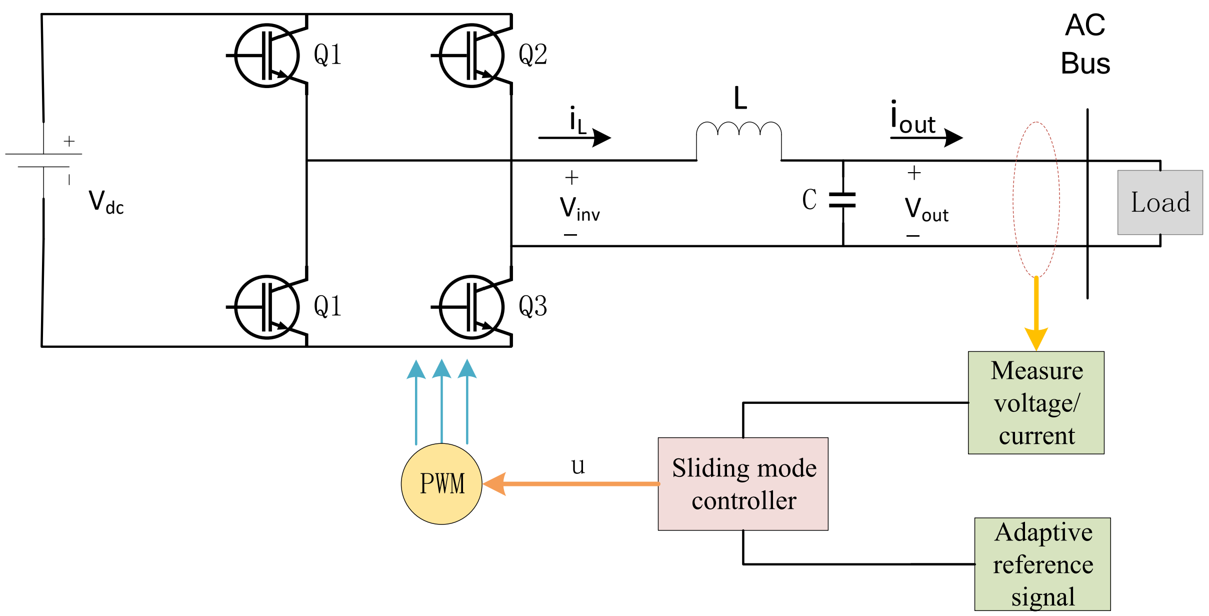

Figure 1 Topology of a microgrid circuit with a single-phase inverter.

follows. 1) To achieve fast tracking of voltage reference signal, an adaptive mechanism is introduced in the design procedure, that is, an adaptive reference signal is designed to replace the traditional constant reference signal in this paper. 2) The idea of active compensation of system uncertainty is employed, based which, an adaptive version of fast terminal sliding mode is developed in this paper to realize the fixed-time tracking.

The rest of this study is organized as follows. Section II presents the system model and preliminary knowledge. The explicit controller design procedure and its corresponding stability analysis are provided in Section III. In Section IV, simulation results are presented to illustrate the effectiveness of this method. Finally, it is concluded this paper.

II. Mathematical Model of Microgrids System

The circuit topology of the single-phase microgrid inverter studied in this article is shown in Figure 1. From Kirchhoff's laws of current and voltage, the state equation of the system in Figure 1 is obtained as follows:

$$L\frac{di_L}{dt}+V_{out}=V_{inv} \tag{1}$$

$$i_L=i_c+i_{out}\,,\quad i_c=C\frac{dV_{out}}{dt} \tag{2}$$

where V_{inv} is the output voltage of the inverter ($V_{inv}=uV_{dc}$), u and is the input controller signal. Combining equations (1) and (2) yields:

$$\frac{d}{dt}\begin{bmatrix}V_{out}\\ i_L\end{bmatrix}=\begin{bmatrix}0 & \frac{1}{C}\\ -\frac{1}{L} & 0\end{bmatrix}\begin{bmatrix}V_{out}\\ i_L\end{bmatrix}+\begin{bmatrix}0\\ \frac{V_{dc}}{L}\end{bmatrix}u+\begin{bmatrix}-\frac{i_{out}}{C}\\ 0\end{bmatrix} \tag{3}$$

where the meanings of electrical parameters can be found in [10].

Definition 1 [15]. Consider the nonlinear system

$$\dot{x}=f(t,x) \text{ with } f(t,0)=0 \tag{4}$$

where $f: R^{+}\times R^{n}\rightarrow R^{n}$ is continuous with respect to x. The equilibrium x=0 of the system is (globally) fixed-time stable if it is globally Lyapunov stable and fixed-time convergent.By``fixed-time convergence," we mean: If, for any initial condition $x(0)\in R^{n}$, there is a bounded settling time T>0 , such that every is defined for $t\in[0,T)$ and satisfies and x(t)=0 for any $t\geq T$.

III. Controller Design and Stability Analysis

A. Adaptive Reference Signa (ARS) Design

Unlike previous studies that used a constant amplitude and frequency reference voltage signal, this paper proposes an adaptive reference voltage signal scheme where the amplitude varies according to system conditions. The scheme is expressed as follows:

$$V_{ref}=V_m*\sin(\omega t) \tag{5}$$

$$V_{refnew}=V_{ref}*\beta \tag{6}$$

where the voltage reference signal V_{ref} has an amplitude V_m and angular frequency V_m. And β is defined as:

$$\begin{cases}\beta=1 & if \quad V_{amp}=0\\ \beta=0.7 & if \quad \dfrac{V_m}{V_{amp}}<0.7\\ \beta=1.3 & if \quad \dfrac{V_m}{V_{amp}}>1.3\\ \beta=\dfrac{V_m}{V_{amp}} & if \quad 0.7<\dfrac{V_m}{V_{amp}}<1.3\end{cases} \tag{7}$$

Remark 1: The controller should ensure that the system outputs a fixed voltage w. V_{amp} is the amplitude of the inverter output voltagel. The ARS of voltage is represented by a variable amplitude V_{refnew}. As pointed by Dehghani etal in [10], such ARS amplitude can ensure that the output voltage signal has a low steady-state error and tends to zero, and the amplitude is close to the main amplitude reference signal.

B. Adaptive controller design

In this section, the voltage/current control mode is used to achieve voltage/frequency control of the microgrid system. The deviation between the actual voltage and the reference voltage, and the derivative of the deviation, are selected as new state variables:

$$x_1 = V_{\text{out}} - V_{refnew} \tag{8}$$

$$x_2 = \frac{d}{dt}x_1 = \frac{1}{C}i_C - \frac{d}{dt}V_{refnew} \tag{9}$$

Based on equations (8) and (9), the state-space equation (3) can be rewritten as:

$$\begin{aligned}\frac{dx_1}{dt} &= x_2 \\ \frac{dx_2}{dt} &= -\frac{1}{\text{LC}}x_1 + \frac{V_{\text{DC}}}{\text{LC}}u - \frac{1}{C}\frac{di_{out}}{dt} \\ &\quad -\frac{1}{\text{LC}}V_{ref_new} - \frac{d^2}{dt^2}V_{refnew} + w(t)\end{aligned} \tag{10}$$

where $w(t)$ represents external disturbances such as parameter variations and DC-side voltage fluctuations. Since the total system uncertainty is bounded, it is assumed that the upper bound η, where is $\eta > 0$ is a constant, i.e, $|w(t)| \leq \eta$.

To avoid system singularity and ensure global convergence time, a non-singular fixed-time terminal sliding mode surface function is designed as:

$$\sigma(t) = \text{x}_1 + \Lambda_1 sig^{\gamma_1}(x_1) + \Lambda_2 sig^{\gamma_2}(x_2) \tag{11}$$

where $\Lambda_1 > 0$, $\Lambda_2 > 0$ are controller parameters, $1 < \gamma_2 < 2$, $\gamma_1 > \gamma_2$, $sig^{\gamma_i}(\cdot) = sign(\cdot)|\cdot|^{\gamma_i}$, $sign(\cdot)$ is the standard sign function.

When the system is in the sliding phase $\sigma(t) = 0$, we have:

$$sig(x_2) = -\left(\Lambda_2^{-1}x_1 + \Lambda_1\Lambda_2^{-1}sig^{\gamma_1}(x_1)\right)^{\frac{1}{\gamma_2}} \tag{12}$$

When the system tracking error is near the equilibrium point, i.e., $|x_1| \leq 1$, the high-order term in the sliding mode surface can be ignored, then the sliding mode surface become

$$\sigma(t) = x_1 + \Lambda_2 sig^{\gamma_2}(x_2) \tag{13}$$

one has

$$\text{x}_2 \approx -\Lambda_2^{-\frac{1}{\gamma_2}} x_1^{\frac{1}{\gamma_2}} \tag{14}$$

Due to $1/\gamma_2 < 1$, the system has a fast convergence speed.

When the tracking error of the system is far from the equilibrium point, i.e., $|x_1| > 1$, the convergence time of the system is mainly dominated by high-order terms in the sliding surface. At this point, the sliding mode surface is

$$\sigma(t) = x_1 + \Lambda_1 sig^{\gamma_1}(x_1) \tag{15}$$

then it has

$$x_2 \approx -\Lambda_2^{-\frac{1}{\gamma_2}} \Lambda_1^{\frac{1}{\gamma_2}} x_1^{\frac{\gamma_1}{\gamma_2}} \tag{16}$$

Since, $\gamma_1/\gamma_2 > 1$ the state variables still have a relatively high convergence speed. The two parts together ensure that the system can converge quickly and accurately in a short period of time globally.

The derivative of equation (11) is

$$\begin{aligned}\frac{d\sigma(t)}{dt} &= x_2 + \Lambda_1\gamma_1 diag(|x_1|^{\gamma_1 - 1})x_2 \\ &\quad + \Lambda_2\gamma_2 diag(|x_2|^{\gamma_2 - 1}) \cdot \frac{dx_2}{dt}\end{aligned} \tag{17}$$

When w(t)=0, the equivalent controller is obtained as:

$$\begin{aligned}\frac{dx_2}{dt} &= -\frac{1}{\text{LC}}x_1 + \frac{V_{\text{DC}}}{\text{LC}}u - \frac{1}{C}\frac{di_{out}}{dt} \\ &\quad -\frac{1}{\text{LC}}V_{refnew} - \frac{d^2}{dt^2}V_{refnew}\end{aligned} \tag{18}$$

Based on the selected sliding surface, the controller is designed as follows:

$$u = u_{eq} + u_{est} \tag{19}$$

where u_{eq} is the equivalent controller obtained when the system reaches the sliding surface $\sigma = \dot{\sigma} = 0$. As a robust controller, u_{est} is used to eliminate the impact of system modeling errors and external disturbances on the control quality of the system

The equivalent controller obtained by substituting equation (18) into equation (17) is:

$$\begin{aligned}u_{eq} &= -\Lambda_2^{-1}\gamma_2^{-1}\frac{\text{LC}}{V_{\text{DC}}}\left(x_2 + \Lambda_1\gamma_1 diag(|x_1|^{\gamma_1 - 1})x_2\right) \\ &\quad -\left(|x_2|^{\gamma_2 - 1}(-\frac{1}{V_{\text{DC}}}x_1 - \frac{L}{V_{\text{DC}}C}\frac{di_{out}}{dt}\right. \\ &\quad \left. -\frac{\text{LC}}{V_{\text{DC}}}V_{refnew} - \frac{\text{LC}}{V_{\text{DC}}}\frac{d^2}{dt^2}V_{refnew})\right)\end{aligned} \tag{20}$$

The final control law is:

$$u = u_{eq} - (K_V + \varepsilon)\text{sign}(\sigma) \tag{21}$$

where $K_V > \eta$, $\varepsilon > 0$ the switching gain

Take the Lyapunov function as:

$$V_1 = \frac{1}{2}\sigma^2 \tag{22}$$

Then, the derivative of equation (21) is:

$$\begin{aligned}\frac{d}{dt}V &= -\sigma(\eta + \varepsilon)\text{sign}(\sigma) + w(t)\sigma \\ &\leq -\sigma(\eta + \varepsilon)|\sigma| + |w(t)\sigma| \\ &\leq -\varepsilon|\sigma|\end{aligned} \tag{23}$$

From the stability theory of Lyapunov, the system is finite time stable when $\varepsilon > 0$. That is to say, taking the severe disturbance into account, the controller (21) should be greater than the upper bound of the overall uncertainty of the system, that is $K_V > \eta$. However, in reality, it is difficult to determine the upper bound of uncertainty, so only by taking a sufficiently large value can the system ensure stability. However, due to the variable structure of sliding mode control mainly manifested in the chattering. Excessive switching gain K_V may render severe system chattering, which reduces the robustness of the controller.

Therefore, an adaptive law for estimating the upper bound of system uncertainty is designed as follows:

$$\frac{d}{dt}\hat{\eta}_1 = c_1|\sigma| \tag{24}$$

where $\hat{\eta}_1$ is the estimated value of η_1, and $c_1 > 0$ is the adaptive estimation adjustable coefficient. By adjusting c_1, the rate of change of the estimated value can be altered. Therefore, under unknown external disturbances, replacing $\hat{\eta}_1$ in equation (21) with K_V, the adaptive voltage/current control law can be written as:

$$u = u_{eq} - (\hat{\eta}_1 + \varepsilon)\text{sign}(\sigma) \tag{25}$$

where

$$\begin{aligned} u_{eq} &= -\Lambda_2^{-1}\gamma_2^{-1}\frac{\text{LC}}{V_{\text{DC}}}\left(x_2 + \Lambda_1\gamma_1 diag\left(|x_1|^{\gamma_1-1}\right)x_2\right) \\ &-\left(|x_2|^{\gamma_2-1}\left(-\frac{1}{V_{\text{DC}}}x_1 - \frac{L}{V_{\text{DC}}C}\frac{di_{out}}{dt}\right.\right. \\ &\left.\left.-\frac{\text{LC}}{V_{\text{DC}}}V_{ref_new} - \frac{\text{LC}}{V_{\text{DC}}}\frac{d^2}{dt^2}V_{ref_new}\right)\right) \end{aligned} \tag{26}$$

Next, the stability of the proposed control strategy is proven.

The Lyapunov function is modified as:

$$V_1 = \frac{1}{2}\sigma^2 + \frac{1}{2c}\tilde{\eta}_1^2 \tag{27}$$

Then

$$\begin{aligned} \frac{d}{dt}V_1 &= -\sigma(\hat{\eta}_1 + \varepsilon)|\sigma| + |w(t)\sigma| - \tilde{\eta}|\sigma| \\ &= -\sigma(\eta + \varepsilon)|\sigma_1| + |w(t)\sigma| \\ &< -\varepsilon|\sigma| \end{aligned} \tag{28}$$

which means that the system is globally asymptotically stable.

According to the definition of finite-time stability, we only need the system is finite-time convergent to achieve the proof of finite-time stability.

In this case, by noting that

$$V = V_1 - \frac{1}{2c}\tilde{\eta}_1^2 \tag{29}$$

one has

$$\frac{d}{dt}V \le -\frac{1}{2}\varepsilon|\sigma| - \left(\frac{1}{2}\varepsilon - \tilde{\eta}\right)|\sigma| \tag{30}$$

When $\frac{1}{2}\varepsilon - \tilde{\eta} \ge 0$, one has

$$\frac{d}{dt}V \le -\frac{1}{2}\varepsilon|\sigma| \le -\frac{1}{4}\varepsilon V^{\frac{1}{2}} \tag{31}$$

which means that the systems is globally finite-time stable with the settling time

$$t_1 \le \frac{8\text{V}^{\frac{1}{2}}(0)}{\varepsilon} \tag{32}$$

When $\varepsilon/2 - \tilde{\eta} < 0$, equation (28) implies that we can find a finite time t_2 converge to convex set $\Theta = \{V \le \rho\}$,where $V \le \rho \Rightarrow \tilde{\eta} \le \varepsilon/2$. When it enter in convex set Θ, one has

$$\begin{aligned} \frac{d}{dt}V &\le -\frac{1}{2}\varepsilon|\sigma| \\ &\le -\frac{1}{4}\varepsilon V^{\frac{1}{2}} \end{aligned} \tag{33}$$

the system is finite-time convergent with the settling time $t_1 + t_2$ .Therefore, the adaptive sliding mode controller designed in this section can ensure finite time stability of the system.

IV. SIMULATION RESULTS AND ANALYSIS

To verify the effectiveness of the proposed control strategy, a single-phase 50Hz island microgrid control system is built on the Matlab/Simulink platform.

Select system control parameters, $\Lambda_1 = 6$ $\Lambda_2 = 5$, $\gamma_1 = 3$, $\gamma_2 = 1.6$, $c_1 = \varepsilon = 2$, $w = 2\sin t$ and electrical parameters as shown in Table 1.

TABLE I
System electrical parameters

parameter	Value
Inverter switching frequency f	10 kHZ
DC voltage V_{dc}	400 V
Filter inductance L	3.5 mH
Filter capacitor C	18 μF
Reference voltage amplitude V_m	311 V
Reference voltage frequencyf	314 $\text{rad} \cdot s^{-1}$
Linear load R_L	20 Ω
Nonlinear Load R_{NL}	18 Ω ‖ 3.5 mF

The output response of the system under the control strategy in this article is shown in Figures 2 and 3. The results show that although stable output voltage tracking of microgrid inverter system can be achieved based on both constant reference signals and adaptive reference signals, but the control scheme based on adaptive reference signals has better speed and steady-state performance.

Usually, there are load parameters in the system model, and the variation of load parameters is also one of the main factors affecting the robustness of voltage controllers. Due to the significant impact of nonlinear loads on the system, it is necessary to study the changes in nonlinear loads. The mathematical expression for load variation is:

$$\text{Z} = \begin{cases} R_{NL}, & 0 \le t \le 0.5 \\ R_{NL} \parallel R_{NL}, & t > 0.5 \end{cases} \tag{34}$$

The simulation results of the changes in system load parameters are shown in Figures 4 and 5. The results show that the control strategy still has good speed and steady-state performance under nonlinear load changes, and it has good resistance to internal and external disturbances.

V. CONCLUSIONS

For the voltage instability problem caused by system parameters and load changes in microgrid, a non-singular fixed-time terminal sliding mode control method for microgrid system has proposed in this paper based on the adaptive reference signal. The simulation results show that the proposed control method can achieve fast, accurate and effective tracking of microgrid voltage, and moreover it possesses good anti-interference ability against changes in the external environment. It confirms that the proposed method can improve the stability and anti-interference ability of the microgrid system.

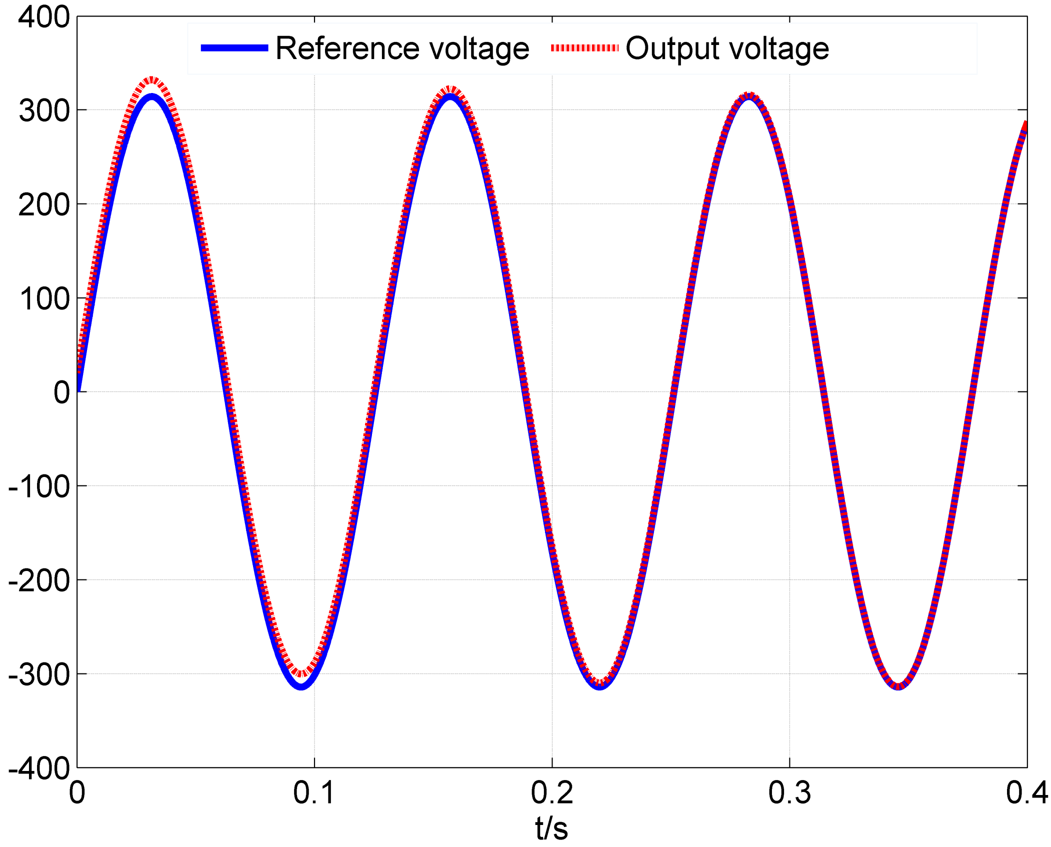

Figure 2 Output response of the system under adaptive reference signal.

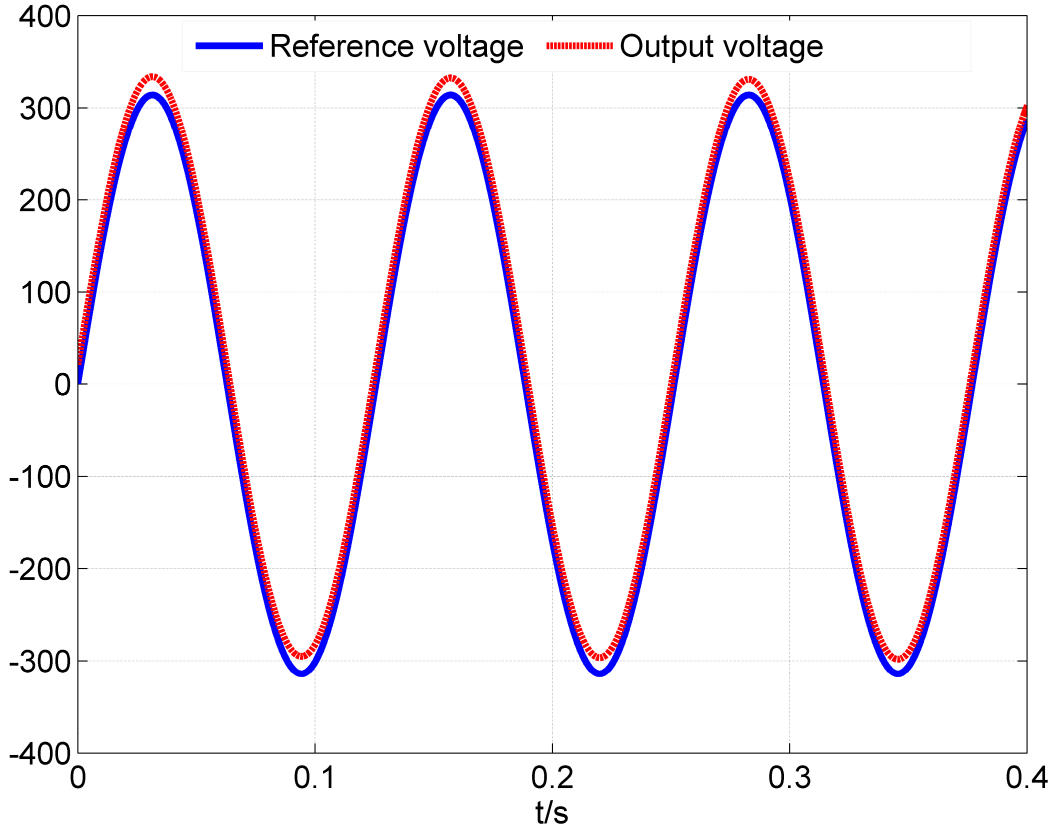

Figure 3 Output response of the system under constant reference signal.

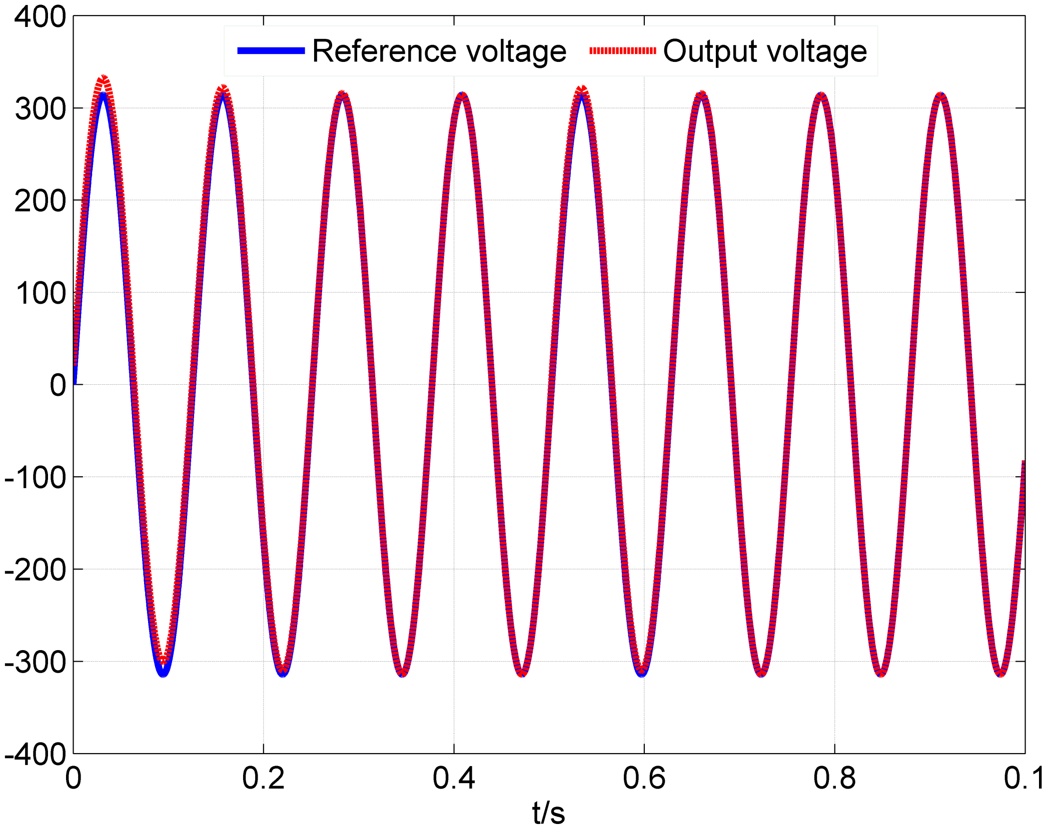

Figure 4 Response of system output voltage.

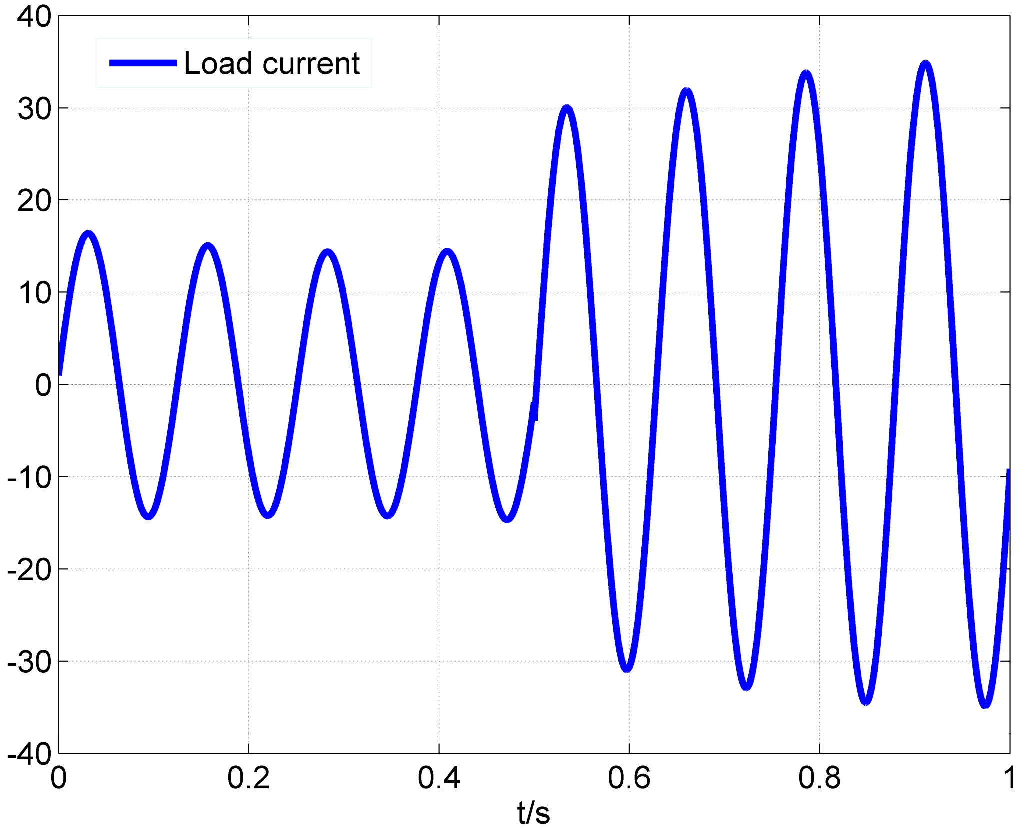

Figure 5 Response of system load current.

VI. Conclusions

For the voltage instability problem caused by system parameters and load changes in microgrid, a non-singular fixed-time terminal sliding mode control method for microgrid system has proposed in this paper based on the adaptive reference signal. The simulation results show that the proposed control method can achieve fast, accurate and effective tracking of microgrid voltage, and moreover it possesses good anti-interference ability against changes in the external environment. It confirms that the proposed method can improve the stability and anti-interference ability of the microgrid system.

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