# Robust Control of Full Bridge Inverter Based on Improved High-order Sliding Mode Controller

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***Abstract*—It is difficult to adjust the parameters for the controller in the stability control of a full bridge inverter due to its unknown upper bound. To solve this problem, an improved second-order sliding mode twisting algorithm based on adaptive parameter has been proposed and simulated. By adding the adaptive parameter method into the original second-order sliding mode twisting controller, improved controller not only automatically regulates its parameters according to states of system but also fully compensates the uncertainty of upper bound. The simulation in the output control of full bridge inverter illustrates that the system can reach the target value of voltage and current in finite time. Compared with original second-order sliding mode twisting algorithm, this improved algorithm, though under the existence of unknown upper bound, can effetely guarantee the finite-time stability of the system.**

***Keywords—higher order sliding mode, twisting algorithm, adaptive, full bridge inverter***

## I. Introduction

As a typical power electronic device, inverters have been widely used in all walks of life in the national economy, such as AC drive, active filter, photovoltaic power generation and wind power generation. It has become an indispensable equipment in production and life. With the development of society and the progress of science and technology, the performance requirements of inverters become higher and more, particularly, including the fast dynamic and stable robustness output of the inverter under unstable conditions like voltage and frequent load changes. To meet these requirements, Sliding mode control strategy, as a control method with strong applicability to inverters, is more widely used in inverter control.

In reference [1], a controller of full bridge inverter is designed by using the high-order sliding mode super twisting algorithm. The discrete control law is transferred to a higher-order sliding mode surface, which essentially eliminates the influence of the traditional sliding mode chattering. In order to improve the performance of photovoltaic grid connected inverter control system in winter, a single-phase current loop photovoltaic grid connected inverter control system based on improved sliding mode variable structure is designed by using exponential sliding mode variable structure control law and square root sliding mode control law [2]. A sliding mode control method for DC link voltage of Z-source inverter is proposed in paper [3]. A DC link voltage sliding mode controller with the integration of inductance current error, capacitance voltage error and capacitance voltage error as state variables is designed. A direct power control strategy of grid connected inverter in unbalanced and harmonic power grid based on resonant sliding mode is proposed in document [4] that improved the operation performance of grid connected inverter in unbalanced and harmonic power grid by establishing the mathematical model of grid connected inverter in unbalanced and harmonic power grid and taking the sinusoidal output current or stable output active / reactive power as the control goal.

Among the robust control methods against the system uncertainty, the traditional sliding mode control has been widely used because of its remarkable advantages such as invariance to matching uncertainty, simple realization of controller, rapid response, but there remain some shortcomings, such as chattering problem and limitation of relative order. The high-order sliding mode control method takes advantage of the traditional sliding mode control and solves its problems, and it can satisfy the finite time stability of the system. Undoubtedly, a control system with finite time stability is more meaningful.

Although the uncertainty is inevitable in control systems, the idea of adaptive method can estimate the uncertainty or the limit of control parameters online in real time in order to maintain a stable performance, which has great practical significance. Existing sliding mode control methods are robust to the matching uncertainty, but the controller design needs to know the bound of the system uncertainty in advance. For the unmatched uncertainty with unknown upper bound, sliding mode control needs to be combined with other methods to compensate the influence of uncertainty. The sliding mode adaptive control method, which organically combines sliding mode control and adaptive mechanism, is a useful control strategy to solve the problem of parameter uncertainty or time-varying parameter control [5].

The sliding mode adaptive method proposed in reference [6] corrects the control gain according to the amplitude of uncertainty. This method does not overestimate the switching gain so that it reduces the chattering, admittedly, but it needs to know the bound of uncertainty in advance and reduce the control accuracy. In the sliding mode adaptive method proposed in reference [7], although it is unnecessary to know the uncertainty bound in advance, the control gain may be too large, which usually leads to chattering. Literature [8] combines the advantages of the above two methods, uses the method in literature [8] to establish the sliding mode surface, and adopts the method in literature [9] to reduce the control gain, which can reduce the chattering under the unknown bound of uncertainty. The controller in reference [9] whose sliding mode surface is in the form of proportional integral draw lessons from adaptive state feedback to deal with the tracking problem under uncertainty. Reference [10] uses adaptive method to expand the application range of sliding mode observer and reduce the requirements of system for uncertainty. For the nonlinear unmatched uncertain SISO system, a controller based on adaptive multi sliding mode surface is proposed in document [11]. The concept of multiple sliding mode surfaces is used to solve the problem of unmatched uncertainty. The adaptive controller can realize the design of output error convergence and the estimation of boundedness of all signals.

The adaptive method combined with the traditional sliding mode method has made many achievements and there is also room for application in the high-order sliding mode control method. The existing high-order sliding mode control methods need to know the uncertainty bound of the system in advance, and then select the controller parameters according to the uncertainty bound. In order to solve this problem, many literatures have combined adaptive method with high-order sliding mode control method with advantages and disadvantages. Reference [12] combines the adaptive method with the second-order sliding mode control method to counteract the influence of the uncertainty with unknown upper bound, but it does not give the proof of finite time stability. Reference [13] gives the proof of finite time convergence of the system under the action of the improved controller, but does not consider the prerequisite that the parameters in the finite time stability theorem must be real numbers. In order to reduce system chattering and deal with the problem of unknown uncertain boundary in a class of nonlinear uncertain systems, the combination of adaptive control and high-order sliding mode and the bipolar sigmoid function and controller gain with online adjustable parameters are introduced in paper [14], but the verification in terms of finite time stability is only reflected in simulation rather than theoretical derivation. Literature [15] requires that the uncertainty must meet certain assumptions in order to give the proof of finite time stability. To sum up, the adaptive high-order sliding mode control method needs to overcome the problem of uncertainty item and give a more effective proof of finite time stability. The spiral algorithm of parameter adaptation is proposed in document [16] to realize the parameter self-adjustment and uncertainty compensation in the presence of unknown upper bound uncertainty. His approach is to design an adaptive controller for one parameter and the other parameter appears in its multiple. The proposed adaptive law is discrete, and this method is applied to the control of pneumatic actuator.

In this paper, an improved second-order sliding mode spiral algorithm based on parameter adaptation is proposed. By designing an adaptive parameter controller for the controller parameters of the spiral algorithm, it not only realizes the automatic adjustment of the parameters according to the system state, but also realizes the complete compensation for the uncertainty with unknown upper bound. The improved method is applied to the control of full bridge inverter. Compared with the original spiral algorithm, the proposed algorithm can realize the self-regulation of parameters and ensure the finite time stability of the system in the presence of uncertainty with unknown upper bound..

## II. Full Bridge Inverter Model

Full bridge inverter is a switching power supply topology that converts DC to AC, and its topology diagram is shown in Figure 1.

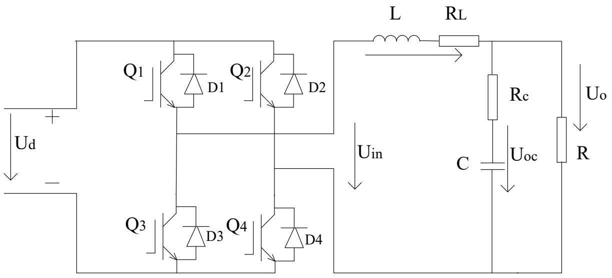


Fig. 1. Topology of full bridge inverter.

The full bridge inverter bridge is composed of four IGBTs divided into two groups of which Q1 and Q4 are in one group while Q2 and Q3 are in the other. Two groups switch on and off alternately, and D1-D4 are freewheeling diodes. $U_{\mathrm{in}}$ indicates voltage source while $L$ is for inductance, $C$ for capacitance and $R$ for equivalent load. $R_L$ and $R_C$ is the parasitic resistance of inductance and capacitance respectively. Respectively, the output AC square wave voltage is obtained by LC low-pass filter to obtain AC sinusoidal output voltage. Because the output filter capacitor voltage and its derivative of the full bridge inverter are continuously measurable, the capacitor voltage and the current on the inductance can be taken as the phase variables to describe the system. The dead time of the switch and the parasitic resistance of inductance and capacitance are ignored. According to Kirchhoff's law of voltage and current, the state equation of the system is:

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{U_{\mathrm{in}}}{L} \\ 0 \end{bmatrix} u \tag{1}$$

where $u \in \{-1,1\}$ represents the on / off state of the two groups of switches respectively. When $u = 1$, Q1 and Q4 are on; When $u = -1$, Q2 and Q3 are on.

The equations of state are listed separately:

$$i_L = -\frac{1}{L} v_C + \frac{E}{L} u \tag{2}$$

$$\dot{v}_C = \frac{1}{C} i_L - \frac{1}{RC} v_C \tag{3}$$

The derivative of formula (3) is:

$$\ddot{v}_C = \frac{1}{C} \dot{i}_L - \frac{1}{RC} \dot{v}_C \tag{4}$$

Substitute formula (4) into formula (2) to obtain:

$$\mathrm{C}\ddot{v}_C + \frac{1}{R}\dot{v}_C + \frac{1}{L} v_C = \frac{E}{L} u \tag{5}$$

Define system state variables $x_1 = v_C, x_2 = \dot{v}_C$ , and rewrite the system state equation as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{1}{R} x_2 - \frac{1}{L} x_1 + \frac{E}{L} u \end{cases} \tag{6}$$

## III. Improved Twisting Algorithm

The uncertainty in system (6) is:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{1}{R} x_2 - \frac{1}{L} x_1 + \frac{E}{L} u + \sigma \end{cases} \tag{7}$$

where $\sigma$ is bounded external interference whose boundary is unknown.

Define sliding surface as $s = x_1 - x_{1d}$ where $x_{1d}$ is the expected value of $x_1$.

Calculate the first and second derivatives of the sliding surface respectively:

$$\dot{s} = \dot{x}_1 - \dot{x}_{1d} \quad (8)$$

$$\ddot{s} = \ddot{x}_1 - \ddot{x}_{1d} = \dot{x}_2 - \ddot{x}_{1d} = -\frac{1}{R}x_2 - \frac{1}{L}x_1 + \frac{E}{L}u + \sigma - \ddot{x}_{1d} \quad (9)$$

Hypothesis $\sigma$ with unknown upper bound $\bar{G} \geq 0$, the estimated value of $\bar{G}$ is $\hat{G}$.

Using the inverse system method, a new control input $v = -\frac{1}{R}x_2 - \frac{1}{L}x_1 + \frac{E}{L}u - \ddot{x}_{1d}$ x is introduced, and a new system is obtained:

$$\begin{cases} \dot{s} = \dot{x}_1 - \dot{x}_{1d} \\ \ddot{s} = v + \sigma \end{cases} \quad (10)$$

The controller designed for the system (10) includes two parts. One is the ideal controller $v_{ideal}$ which is continuous and can ensure the finite time stability when the system uncertainty does not exist. The other part is the compensation controller $v_{com}$, which can fully compensate the system uncertainty and ensure the realization of the system goal together with the ideal controller.

$$v = v_{ideal} + v_{com} \quad (11)$$

Ideal controller $v_{ideal}$ adopts twisting algorithm:

$$v_{ideal} = -r_1\mathrm{sgn}(s) - r_2\mathrm{sgn}(\dot{s}) \quad (12)$$

Adaptive compensation controller $v_{com}$:

$$v_{com} = -\hat{G}\mathrm{sgn}(\dot{s}) \quad (13)$$

The adaptive law satisfies:

$$\dot{\hat{G}} = \beta|\dot{s}| \quad (14)$$

where the estimation error is $\tilde{G} = \bar{G} - \hat{G}$ and $\beta$ is a positive constant.

Define controller as:

$$v = -\hat{r}_1\mathrm{sgn}(s) - \hat{r}_2\mathrm{sgn}(\dot{s}) - \hat{G}\mathrm{sgn}(\dot{s}) \quad (15)$$

where $\hat{r}_1$ and $\hat{r}_2$ represent adaptive parameters respectively, their upper bounds are $r_1$ and $r_2$。 $\hat{G}\mathrm{sgn}(\dot{s})$ is compensation controller ,the adaptive law satisfies:

$$\dot{\hat{r}}_1 = k_1\dot{s}\mathrm{sgn}(s), \dot{\hat{r}}_2 = \dot{\hat{G}} = k_2\dot{s}\mathrm{sgn}(\dot{s}) = k_2|\dot{s}| \quad (16)$$

where $k_1$ and $k_2$ are positive constants.

## IV. Stability Analysis

To prove that the improved stewing algorithm (15) can ensure the finite time stability of system (7) and the adaptive law meets (16).

Proof: Choose Lyapunov function:

$$V_1 = r_1|s| + \frac{1}{2}\dot{s}^2 + \frac{1}{2k_1}\tilde{r}_1^{\,2} + \frac{1}{2k_2}\tilde{r}_2^{\,2} + \frac{1}{2k_2}\tilde{G}^2 \quad (17)$$

The derivation of equation (17) yields:

$$\dot{V}_1 = r_1\dot{s}\mathrm{sgn}(s) + \dot{s}(u+\sigma) + \frac{1}{k_1}\tilde{r}_1\dot{\hat{r}}_1 + \frac{1}{k_2}\tilde{r}_2\dot{\hat{r}}_2 + \frac{1}{k_2}\tilde{G}\dot{\hat{G}}$$

$$= r_1\dot{s}\mathrm{sgn}(s) + \dot{s}\left[-\hat{r}_1\mathrm{sgn}(s) - \hat{r}_2\mathrm{sgn}(\dot{s}) - \hat{G}\mathrm{sgn}(\dot{s}) + \sigma\right] - \frac{1}{k_1}\tilde{r}_1\dot{\hat{r}}_1 - \frac{1}{k_2}\tilde{r}_2\dot{\hat{r}}_2 - \frac{1}{k_2}\tilde{G}\dot{\hat{G}}$$

$$= r_1\dot{s}\mathrm{sgn}(s) - \hat{r}_1\dot{s}\mathrm{sgn}(s) - \hat{r}_2\dot{s}\mathrm{sgn}(\dot{s}) + r_2\dot{s}\mathrm{sgn}(\dot{s}) - r_2\dot{s}\mathrm{sgn}(\dot{s}) - \dot{s}\hat{G}\mathrm{sgn}(\dot{s}) + \dot{s}\sigma - \frac{1}{k_1}\tilde{r}_1\dot{\hat{r}}_1 - \frac{1}{k_2}\tilde{r}_2\dot{\hat{r}}_2 - \frac{1}{k_2}\tilde{G}\dot{\hat{G}}$$

$$\leq \tilde{r}_1\dot{s}\mathrm{sgn}(s) - r_2|\dot{s}| + \tilde{r}_2|\dot{s}| + \bar{G}|\dot{s}| - \hat{G}|\dot{s}| - \frac{1}{k_1}\tilde{r}_1\dot{\hat{r}}_1 - \frac{1}{k_2}\tilde{r}_2\dot{\hat{r}}_2 - \frac{1}{k_2}\tilde{G}\dot{\hat{G}}$$

$$= -r_2|\dot{s}| + \tilde{r}_1[\dot{s}\mathrm{sgn}(s) - \frac{1}{k_1}\dot{\hat{r}}_1] + \tilde{r}_2\left(|\dot{s}| - \frac{1}{k_2}\dot{\hat{r}}_2\right) + \tilde{G}\left(|\dot{s}| - \frac{1}{k_2}\dot{\hat{G}}\right) \quad (18)$$

Hence, when $\dot{\hat{r}}_1 = k_1\dot{s}\mathrm{sgn}(s), \dot{\hat{r}}_2 = k_2|\dot{s}|, \dot{\hat{G}} = k_2|\dot{s}|$ , $\dot{V}_3 \leq -r_2|\dot{s}|$, because $V_3 \geq 0, \dot{V}_3 \leq 0$, $V_1$ is bounded. Then $s$、$\dot{s}$ and $\tilde{G}$ are bounded. Thus, it can be seen that the control input $u$ is bounded, so that $\ddot{s}$ is bounded. That means $s$ and $\dot{s}$ are uniformly continuous, or in another word, square integrable. Since $s$ and $\dot{s}$ are square integrable and $s$,$\dot{s}$ and $\ddot{s}$ are bounded, according to extended Barbalat lemma, we can get $s \to 0$ and $\dot{s} \to 0$. Therefore, the system is asymptotically stable. And $\dot{\hat{r}}_2$ and $\dot{\hat{G}}$ can be seen as an item. In fact, compensation control and adaptive parameter adjustment are realized at the same time.

Select another Lyapunov function in a small range before the system reaches zero:

$$V_2 = \frac{1}{2}(|s| + |\dot{s}|)^2 \quad (19)$$

The derivative of equation (20) is:

$$\dot{V}_2 = \left(|s| + |\dot{s}|\right)[\dot{s}\mathrm{sgn}(s) - \ddot{s}\mathrm{sgn}(\dot{s})]$$

$$= \left(|s| + |\dot{s}|\right)\left\{\dot{s}\mathrm{sgn}(s) - \left[-\hat{r}_1\mathrm{sgn}(s) - \hat{r}_2\mathrm{sgn}(\dot{s}) - \hat{G}\mathrm{sgn}(\dot{s}) + \sigma\right]\mathrm{sgn}(\dot{s})\right\}$$

$$\leq \left(|s| + |\dot{s}|\right)\left[\dot{s}\mathrm{sgn}(s) + \hat{r}_1\mathrm{sgn}(s)\mathrm{sgn}(\dot{s}) - \hat{r}_2 - \hat{G} + \bar{G}\right]$$

$$= \left(|s| + |\dot{s}|\right)\left[\dot{s}\mathrm{sgn}(s) + \hat{r}_1\mathrm{sgn}(s)\mathrm{sgn}(\dot{s}) - \hat{r}_2 + \tilde{G}\right] \quad (20)$$

Because the system is asymptotically stable, $\dot{s}\mathrm{sgn}(s) + \hat{r}_1\mathrm{sgn}(s)\mathrm{sgn}(\dot{s}) + \tilde{G}$ is bounded. Therefore, there is a constant

$$d = \dot{s}\mathrm{sgn}(s) + \hat{r}_1\mathrm{sgn}(s)\mathrm{sgn}(\dot{s}) - \hat{r}_2 + \tilde{G} < 0 \quad (21)$$

Hence, $\dot{V}_2 \leq -dV^{\eta}, \eta = \frac{1}{2}$.

When the system reaches its origin point, the equation is satisfied. According to the finite time stability theorem, the system (10) is finite time stable in the presence of unknown upper bound uncertainty, and the parameters can be adjusted by themselves.

When $s = x_1 - x_{1d} = 0$ and $\dot{s} = \dot{x}_1 - \dot{x}_{1d} = 0$, we can see $v_c = x_{1d}, \dot{v}_c = \dot{x}_{1d}$. In the equation (3), $\dot{v}_c = \frac{1}{C}i_L - \frac{1}{RC}v_c$, at this time $i_L$ is also stable. The whole system is stable for a finite time.

## V. SIMULATION VERIFICATION

In the simulation, take the system parameters[17] $L = 6.4\text{mH}, R = 44\Omega, E = 450\text{V}, C = 25\mu\text{F}$ . Initial values of state are: controller parameters $k_1 = 1$ , $k_2 = 0.5$ ; the reference value of output voltage is 220sin(t); the initial value of each state is zero; the initial value of parameter is $\hat{r}_1(0) = 120, \hat{r}_2(0) = 90$. The improved algorithm is compared with the existing spiral algorithm, that is to let $v = -r_1\text{sgn}(s) - r_2\text{sgn}(\dot{s})$, The controller parameter is taken as $r_1 = 120, r_2 = 90$, and the initial value of the state is zero. The simulation results are shown in Figure 2-4.

According to Figure 4, the system voltage and current reach the expected value in a limited time, and the proposed improved method performs better than the original method in response time and overshoot.

When disturbance $\sigma = 8\sin{(\text{t})}$ is added to the system, the twisting algorithm has certain robustness. But if the disturbance exceeds its bearing range, the system will diverge, and the improved method can adjust the controller parameters according to the system state to compensate the error caused by the disturbance. The simulation results are shown in Figure 5-7.

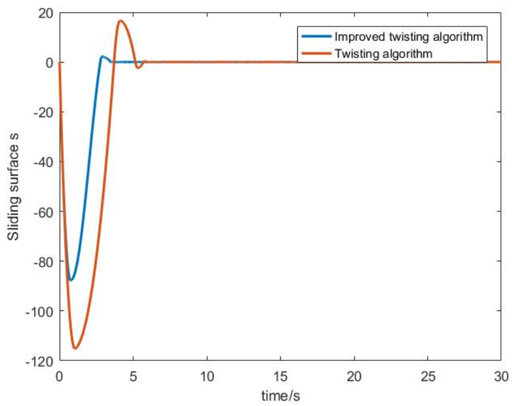


Fig. 2. Voltage errors.

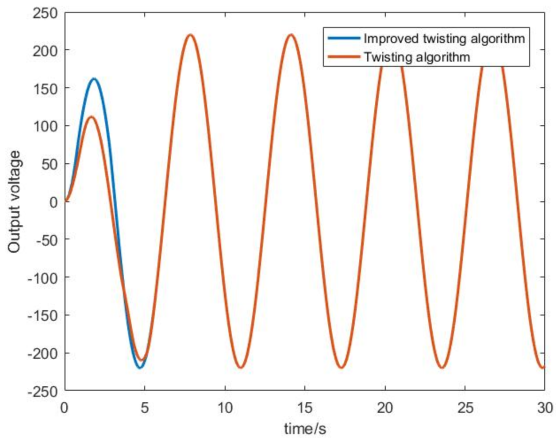


Fig. 3. Output voltages.

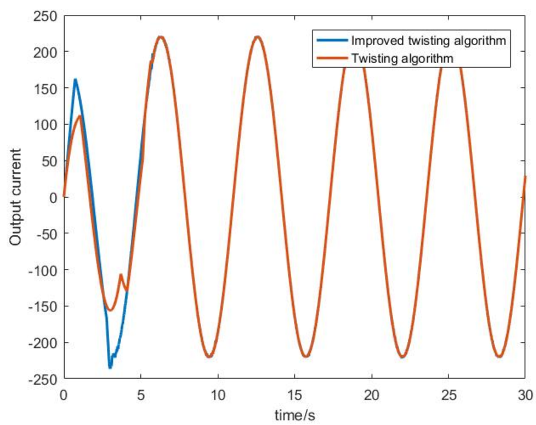


Fig. 4. Output currents

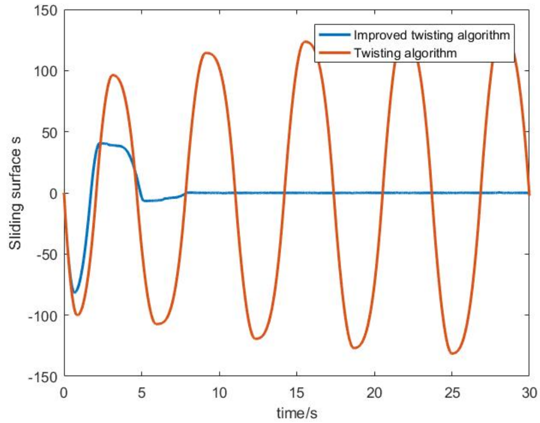


Fig. 5. Voltage errors after adding disturbance.

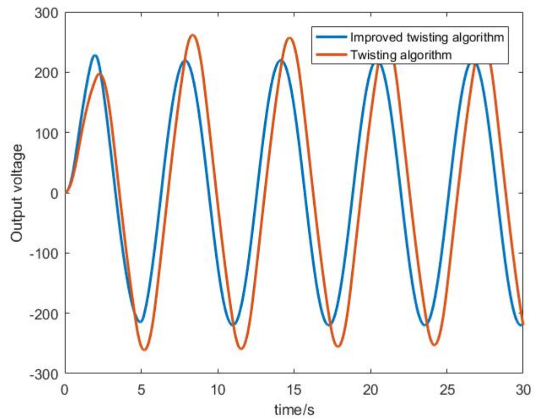


Fig. 6. Output voltages after adding disturbance.

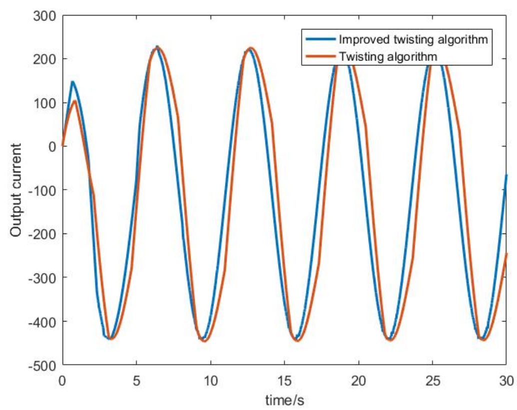


Fig. 7. Output currents after adding disturbance.

It can be seen from Figure 7 that when the system disturbance increases to a certain extent, the system has diverged under the original spiral algorithm, while the improved algorithm can still maintain the stability of the system.

**Simulative experiment in application scenario - photovoltaic grid connection:**

The grid connected power generation system is an important direction of solar energy utilization research. The essential task is to control the output voltage of inverter to be consistent with the frequency, phase and amplitude of the grid voltage. At the same time, the output grid connected current is a stable sine wave with less harmonic content and small distortion rate, and its frequency and phase are consistent with that of the grid voltage.

Admittedly, the prerequisite of the conclusion above is that E equals 450 V. However, in real systems, E is hypersensitive to the light intensity and external temperature. Therefore, to verify the superiority of the proposed algorithm, the system is simulated under uncertain light intensity and external temperature. In the simulation, E=500V is set for 1-10s while E=450V for 10-20s and E=350V for 20-30s. The results are shown in Figure 8 to Figure 10.

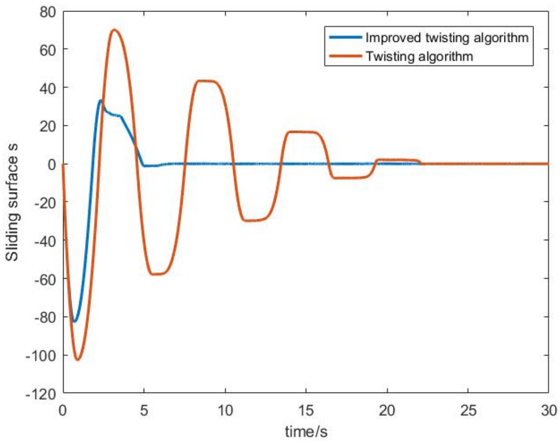


Fig. 8. Voltage errors after adding uncertainty.

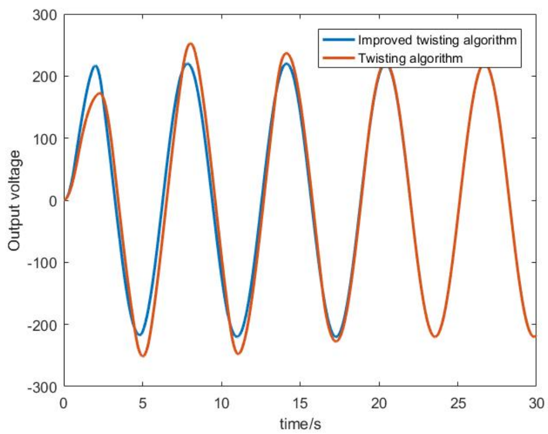


Fig. 9. Output voltages after adding uncertainty.

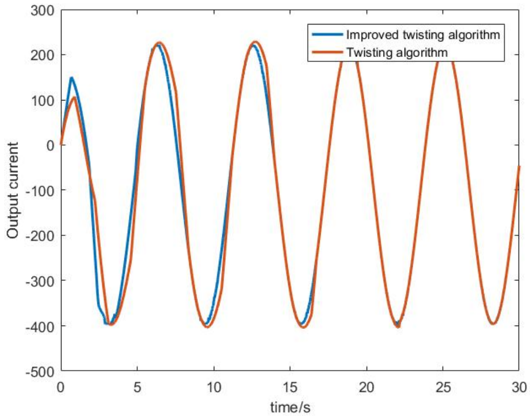


Fig. 10. Output currents after adding uncertainty.

The simulation results demonstrate that when the external input light intensity or temperature changes, the proposed improved method can maintain the voltage and current tracking the given value immediately without impact on the simulation results. By contrast, the original method shows significant fluctuations.

## VI. Conclusion

In order to overcome the influence of full bridge inverter on control performance in the presence of unknown upper bound uncertainty, an improved high-order sliding mode twisting algorithm control strategy is proposed by combining the adaptive algorithm with the twisting algorithm. With designing an adaptive parameter controller for the controller parameters of the twisting algorithm, it not only realizes the automatic adjustment of the parameters according to the system state, but also realizes the complete compensation for the uncertainty with unknown upper bound. When the system uncertainty does not exist, the influences of the improved method and the original twisting algorithm on the system performance do not have differences. When the bound of uncertainty is beyond the tolerance of twisting algorithm, the system diverges under the original method and meanwhile, the improved algorithm can still ensure the finite time stability of the system.

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## References

[1] HUANGFU Yigeng, WANG Yi, et al. A super-twisting al-gorithm of robust high order sliding mode control for full-biedge inverter[J]. Journal of Northwestern Polytechnical University, 2015,3(2):315-319..

[2] HUO Qunhai, KONG Li, WEI Tongzhen. Two modified grid-connected inverter control strategies based on sliding mode variable structure[J]. Electric Power Automation Equipment, 2009, 29(4): 32-35.

[3] WANG Xiaogang, XIAO Liye. Sliding mode control for DC-link voltage of Z-source inverter[J]. Electric Machines and Control, 2015, 19(2): 1-6.

[4] QUAN Yu, NIAN Heng. Resonance-based sliding mode con-trol of grid connected inverters under unbalanced and har-monic grid voltages[J]. Proceedings of CSEE. 2014, 34(9): 1345-1352.

[5] Kochalummoottil J O. Adaptive Second Order Sliding Modes[D]. Huntsville: The School of Graduate Studies of The University of Alabama in Huntsville, 2012.

[6] Lee H, Utkin V. Chattering Suppression Methods in Sliding Mode Control Systems[J]. Annual Reviews in Control, 2007, 31: 179-188.

[7] Huang A C, Chen Y H. Adaptive Multiple-Surface Sliding Control for Nonautonomous Systems with Mismatched Uncertainties[J]. Automatica, 2004, 40(l): 1939-1945.

[8] Plestan F, Shtessel Y, Bregeault V, Poznyak A. New Methodologies for Adaptive Sliding Mode Control[J]. International Journal of Control, 2010, 83(9): 1907-1919.

[9] Fei J T. A Class of Adaptive Sliding Mode Controller with Integral Sliding Surface[C]. International Conference on Mechatronics and Automation, 2009: 1156-1161.

[10] PU Ming, WU Qingxian, JIANG Changsheng, et al. Appli-cation of adaptive second-order dynamic terminal sliding mode control to near space vehicle[J]. Journal of Aerospace Power, 2010, 25(5): 1169-1176.

[11] Chang Y T, Cheng C C. Adaptive Sliding Mode Control for Plants with Mismatched Perturbations to Achieve Asymptotical Stability[J]. International Journal of Robust and Nonlinear Control, 2006, 17(9): 880-896.

[12] ZHAO Zhanshan, ZHANG Jing, SUN Liankun, et al. Design of self-adaptive sliding mode controller with finite time convergence[J]. Journal of Shandong University , 2012, 42(4): 74-78.

[13] Li P, Zheng Z Q. Robust Adaptive Second-Order Sliding-Mode Control with Fast Transient Performance[J]. IET Control Theory and Applications, 2012, 6(2): 305–312.

[14] ZHAO Zhanshan, ZHANG Jing, SUN Liankun. Higher order sliding mode control with self-tuning law for a class of un-certain nonlinear systems[J]. Control and Design, 2011, 26(8): 1277-1280.

[15] Shtessel Y, Edwards C, Spurgeon S K, Kochalummoottil J. Adaptive Continuous Finite Reaching Time Control and Second Order Sliding Modes[C]. International Workshop on Variable Structure Systems, 2010: 5126-5131.

[16] Taleb M, Levant A, Plestan F. Pneumatic Actuator Control: Solution Based on Adaptive Twisting and Experimentation[J]. Control Engineering Practice, 2013, 21: 727-736.

[17] HOU Bo, MU Anle, DONG Fengbin, et al. Backstepping Sliding Mode Control Strategy of Single-Phase Voltage Source Full-Bridge Inverter[J]. Transactions of China Elec-trotechnical Society, 2015, 30(20): 93-99.