MESO-based Robustness Voltage Sliding Mode Control for AC Islanded Microgrid

Hao Pan*, Qingfang Teng and Dangdang Wu
(School of Electrical Engineering and Automation, Lanzhou Jiaotong University, Lanzhou 730070, China)

Abstract: A new modified extended state observer (MESO)-based robustness voltage sliding mode control (SMC) strategy is proposed for an AC islanded microgrid under system uncertainties including system parameter and load variation. First, the disturbance effect on the system is regarded as a lumped uncertainty, and a state space model of the uncertain islanded microgrid system is established. Then, a modified extended state observer is designed to estimate external disturbances and internal perturbation. Finally, considering the lumped uncertainty, a sliding mode controller with a multi-power reaching law is proposed to enable the output voltage of the system to track its reference voltage rapidly and accurately, and to enhance the robustness of the system. The simulation results confirm that the proposed robustness voltage control strategy can perform satisfactory voltage control and demonstrate a strong capability to reject parameter and load variation.

Keywords: Islanded microgrid, modified extended state observer, multi-power reaching law, system uncertainties, robustness voltage sliding mode control

1 Introduction

With the development of photovoltaic, wind, and other distributed power technology, the microgrid has received wide attention from the industries and academia[1-2]. Microgrid is a single control and independent generation system composed of distributed generation (DG), load, energy storage, and control device. It can be operated either under grid-connection mode or islanded mode[3]. For an AC islanded microgrid, the output voltage of the system will fluctuate due to various time-varying disturbances, such as the change of the perturbation of system parameters and power load. The microgrid model does have inherent modeling errors, which cannot meet the requirements of power quality[4-6]. Therefore, research on the control of the islanded microgrid inverter system with strong robustness and low steady-state tracking error has important theoretical significance and engineering value.

At present, to address the voltage deviation issue, the research on disturbance rejection of a microgrid inverter system mainly includes the following methods: artificial intelligence control algorithm[7-9], robust control method[10-11], nonlinear control method[12-17], and disturbance observer (DO)-based control method[18-19]. In Ref. [7], based on the instantaneous power and space vector theory, the particle swarm optimization algorithm is adopted to establish a grid-connected inverter system model including nonlinear links and harmonic disturbance of the power grid to realize anti-interference control. A method using a fuzzy neural network to realize online compensation of external uncertainties caused by DC voltage fluctuation of inverter system is discussed in Ref. [8]. During an unexpected shutdown of the distributed power supply and high nonlinear load, the non-convex condition in the optimization problem was transformed into a convex linear matrix inequality condition in Ref. [9], which is able to adjust the power sharing between the system load voltage and the distributed power supply to achieve good control performance. However, these methods are generally not analytic and hence, difficult to analyze system stability. In Ref. [10], it integrates the optimal transient performance of $H_2$ control and the anti-interference performance of $H_{\infty}$ control, and proposes a mixed optimal control method of $H_2/H_{\infty}$ to resist parameters variations. Although the represent-
ation of this method is simple, the solution process is complicated. In Ref. [11], the Bialternate matrix is used to analyze the stability domain of the hybrid microgrid system with the uncertain parameters of distributed power supply with inverter, and designs the parameters of a power stabilizer to ensure that the microgrid system has a large stability boundary. Ref. [12] uses the unconstrained vector of the continuous control set to predict the change of load current and enhance the anti-disturbance performance of the inverter system against the change of external load. Considering load change, transient short circuit, and unbalanced phase, the model predictive control (MPC) voltage controller is combined with discrete time sliding mode control (SMC) current controller in Ref. [13] to enhance the transient recovery ability of voltage and current. In Ref. [14], SMC strategy is used to predict the harmonic current disturbance and filter the parameter perturbation generated by a nonlinear load in the microgrid system in real time, which realizes the global robust control. According to Ref. [15], the proposed recursive terminal sliding mode control strategy has a strong ability of resisting load variation for a distributed low-voltage microgrid that is in grid-connection mode or islanded mode. However, the redundancy of the MPC method information is high, which increases the complexity of the algorithm. In the sliding mode control method, the selected linear sliding mode surface cannot make the state tracking error converge to zero in finite time and the convergence rate is slow, or the differentials used in the process cannot avoid singularity. Ref. [16] addresses the harmonic distortion due to nonlinear loads and background harmonics, the harmonic impedance reinforcement (HIR) control is proposed for voltage-controlled DG inverters. In Ref. [17], owing to the lack of inertia of an AC/DC inverter system, the unified inertia index is introduced to evaluate the holistic inertia level of the hybrid microgrid, and the global stability and dynamic performance of hybrid microgrid under power disturbance are improved. In Ref. [18], a Kalman estimator-based voltage prediction control method is proposed for the interference of line impedance parameter change, load change, output impedance change, and distributed power supply fault, which is able realize the voltage free deviation control of an AC island microgrid without communication. The active disturbance rejection control (ADRC) method based on the linear extended state observer (ESO) is adopted to realize the robust control of the output current of the grid-connected inverter system in Ref. [19]. However, in the initial stage of the conventional linear ESO action, the estimated initial value of each state variable has a large deviation from the corresponding actual value, which arises the “initial differential peak” phenomenon. For the microgrid inverter system, its model often exhibits inherent modeling error, system parameter perturbation, and uncertain disturbance caused by model mismatch. This has a negative effect on the system performance, but the realization of fast and accurate robust control of the output voltage of the microgrid inverter system still needs to model mismatch the voltage control scheme based on the estimator under the dynamic performance and robustness for further analysis and research.

In the study, to enhance the islanded microgrid inverter system disturbance rejection performance, an observer-based voltage-SMC scheme with a rejection capability to system uncertainties is proposed. The main contributions of this study are as follows.

1. A modified extended state observer (MESO) is used to estimate system uncertainties. Compared with conventional linear ESO, MESO can make more use of system known information, reduce the estimation burden, and improve the estimation accuracy. Moreover, the convergence of MESO in dynamic estimation will affect the performance of the whole closed-loop control system. In this study, the necessary analysis and proof of convergence are addressed.

2. A sliding mode controller with multi-power reaching law is proposed. The third power term increases the process rate of the system convergence.

3. The combination of MESO and SMC enhances the robustness and reduces chattering. Further, it avoids the use of a current sensor and reduces the influence of current sensor faults.

2 Problem formulation

The structure of the single-phase microgrid inverter system of this study is shown in Fig. 1. The system is composed of a front-stage DG unit, power
inverter, LC filter, and loads. Subscript $i$ refers to the $i^{th}$ microgrid inverter system, and each microgrid system in the islanded mode has the same controller structure. The variables and parameters of each controller are from the local parameters of microgrid. In this study, the subscript $i$ of each part is omitted for the convenience of writing.

In Fig. 1, $U_{\text{DC}}$ represents the voltage on the DC side, which is a constant value. $u_{\text{inv}}$ and $i_{\text{inv}}$ are the output voltage and current of the inverter, respectively. $R_i$, $L_i$, and $C_i$ are the filter resistance, inductor, and capacitor, respectively. $i_c$ is the currents of the filter capacitor. $i_o$ and $u_o$ the output currents and voltages of microgrid. $Z_L/Z_{\text{NL}}$ are the lumped linear and nonlinear loads. $E^*$, $\omega^*$ are the amplitude and frequency of nominal voltage of droop control, respectively. The reference voltage $u_r$ is obtained by droop control. $u \in [-1, 1]$ is the duty ratio of the inverter switch. The relationship between it and $U_{\text{DC}}$ is expressed as $u_{\text{inv}} = u U_{\text{DC}}$.

For the single-phase LC filter H-bridge inverter in Fig. 1, its mathematical model can be obtained from Kirchhoff’s law as follows

$$\begin{align*}
L_i \frac{di_{\text{inv}}}{dt} &= u_{\text{inv}} - u_o - R_i i_{\text{inv}} \\
C_i \frac{du_o}{dt} &= i_{\text{inv}} - i_o 
\end{align*}$$

(1)

Then, Eq. (1) can be given as

$$\begin{align*}
\dot{u}_o &= -R_i u_o - \frac{1}{L_i C_i} u_o + \frac{u U_{\text{DC}}}{L_i C_i} - \frac{1}{C_i} i_o - \frac{R_i}{L_i C_i} i_o 
\end{align*}$$

(2)

Defining the system state variable as follows

$$\begin{align*}
\dot{x}_1 &= u_r - u_o \\
\dot{x}_2 &= \dot{x}_1 = \dot{u}_r - \dot{u}_o 
\end{align*}$$

(3)

where $u_r$ is the reference, which will be described in detail further.

Considering system uncertainties and external disturbance, from Eqs. (1)-(3), the error state equations can be written as

$$\begin{align*}
\dot{\hat{x}}_1 &= \hat{x}_2 \\
\dot{\hat{x}}_2 &= (f(x) + \Delta f(x)) + (b + \Delta b)u + D = f(x) + bu + D \\
y &= x_1
\end{align*}$$

(4)

where $u$ is the control input, $y$ is the system output, and

$$\begin{align*}
f(x) &= -\frac{1}{L_i C_i} x_1 - \frac{R_i}{L_i} x_2 \\
b &= -\frac{U_{\text{DC}}}{L_i C_i} \\
D &= \frac{R_i}{L_i} \dot{u}_r + \frac{1}{L_i C_i} u_o + \frac{1}{C_i} i_o + \frac{R_i}{L_i C_i} i_o \\
d &= D + \Delta f(x) + \Delta bu
\end{align*}$$

$D$ is external disturbance, and $d$ is voltage lumped uncertainty.

Power calculation and droop control will be discussed in this section to provide a system reference voltage. Each inverter control unit needs to collect local $u_o$ and $i_o$, and send them to the droop control link of each independent control unit for calculating the active power $P$ and reactive power $Q$ of the inverter output. The improved droop control be designed as follows

$$\begin{align*}
E &= E^* - n_1 P - n_2 \frac{dP}{dt} \\
\omega &= \omega^* + m_1 Q + m_2 \frac{dQ}{dt}
\end{align*}$$

(5)

where $n_1$, $m_1$ are the droop coefficients of reactive and active power respectively, $n_2$, $m_2$ are the differential droop control coefficients respectively, and $E$, $\omega$ are the amplitude and angular velocity instructions of the reference output voltage $u_r$ of the inverter respectively.

### 3 Controller design and stability analysis

Here, focus on the problem of the perturbation of system parameters and load disturbance rejection in the islanded microgrid inverter system (Eq. (4)). Fig. 2 is the proposed control block diagram. Its core design
includes MESO and SMC. A MESO is used to estimate lumped uncertainty in a real-time system, and the SMC strategy with multi-power reaching law is used for fast adaptive control of the system considering the complex time-varying disturbance.

3.1 MESO design

Before designing the MESO, the unknown lumped uncertainty \( d \) is extended as a new system state, \( x_3 = d \), then \( q(t) = \ddot{x_3} \), and \( M = \sup_{t \in [0, \infty)} |q(t)| < \infty \) are set.

Therefore, Eq. (4) can be extended to the following third-order equation of state

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= f(x) + bu + x_3 \\
\dot{x}_3 &= q(t)
\end{align*}
\]

(6)

Eq. (6) is observable to utilize known information. Therefore, MESO can be modified as follows

\[
\begin{align*}
\dot{\hat{x}}_1 &= \ddot{x}_2 + g_1 \left( \frac{x_1 - \hat{x}_1}{\varepsilon^2} \right) \\
\dot{\hat{x}}_2 &= \ddot{x}_3 + g_2 \left( \frac{x_1 - \hat{x}_1}{\varepsilon^2} \right) + f(\hat{x}) + bu \\
\dot{\hat{x}}_3 &= \frac{1}{\varepsilon^2} g_3 \left( \frac{x_1 - \hat{x}_1}{\varepsilon^2} \right)
\end{align*}
\]

(7)

where \( \hat{x}_i \) is the estimate value of \( x_i \), \( \varepsilon > 0 \) is observer gain, \( g_i \) is pertinent chosen functions, and \( i = 1, 2, 3 \).

**Theorem 1**: Considering the MESO of Eq. (7), for the system in Eq. (4), the observation error is ultimately bounded, and satisfies \( |x_i - \hat{x}_i| \leq C_M \), where \( C_M \) is a positive constant about \( \varepsilon \).

**Proof**

**Assumption 1**: \( f(.) \) is Lipschitz continuous, there exists Lipschitz positive constant \( \lambda \), such that \( |f(x) - f(\hat{x})| \leq \lambda \|x - \hat{x}\| \quad \forall x \quad \hat{x} \in \mathbb{R}^3 \).

Let \( \ddot{x}_i = x_i - \hat{x}_i \) (\( i = 1, 2, 3 \)) be the estimation error of MESO, considering Eqs. (6)-(7), it can be obtained as

\[
\begin{align*}
\dot{\ddot{x}}_1 &= \dddot{x}_2 - g_1 \left( \frac{\ddot{x}_1}{\varepsilon^2} \right) \\
\dot{\ddot{x}}_2 &= \dddot{x}_3 - g_2 \left( \frac{\ddot{x}_1}{\varepsilon^2} \right) + \ddot{F} \\
\dot{\ddot{x}}_3 &= q(t) - \frac{1}{\varepsilon^2} g_3 \left( \frac{\ddot{x}_1}{\varepsilon^2} \right)
\end{align*}
\]

(8)

where \( \ddot{F} = f(x) - f(\hat{x}) \).

Let \( z_i = \ddot{x}_i / \varepsilon^2 \) (\( i = 1, 2, 3 \)), then estimate error can be expressed as

\[
\begin{align*}
\ddot{z}_1 &= z_2 - g_1(z_1) \\
\ddot{z}_2 &= z_3 - g_2(z_1) + \ddot{F} \\
\ddot{z}_3 &= \epsilon q(t) - g_3(z_1)
\end{align*}
\]

(10)

Thus,

\[
\dot{z} = Az + BF + PC\epsilon q(t)
\]

(11)

where

\[
\begin{align*}
\dot{z} &= \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}, \\
A &= \begin{bmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}, \\
B &= \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \\
C &= \begin{bmatrix} 0 \end{bmatrix}
\end{align*}
\]

As \( A \) is a Hurwitz matrix, there exists a symmetric positive definite matrix \( P \) with corresponding dimension that satisfies

\[
A^TP + PA = -I
\]

(12)

Defining the Lyapunov function

\[
V_z(z) = z^TPz
\]

(13)

The derivative of \( V_z(z) \) is given by

\[
\frac{dV_z(z)}{dt} = z^TPz + z^TPz = -z^TTz + 2z^TPB\ddot{F} + 2zTPC\epsilon q(t) \leq -\|z\|^2 + 2z^TPB\ddot{F} + 2zTPC\epsilon q(t)
\]

(14)

Obtain as follow\(^{22}\)

\[
\begin{align*}
&\frac{\dot{\lambda}(P)M}{\sqrt{\lambda}(P)} \int_{t_0}^{t} \exp \left[ -\frac{\dot{\lambda}(P) - 2\lambda_{\max}(P)L}{2\lambda_{\min}(P)} \right] \left( t - \tau \right) \right] \right] d\tau
\end{align*}
\]

(15)

Thus,

\[
\|z\| \leq \exp \left[ -\frac{\dot{\lambda}(P) - 2\lambda_{\max}(P)L}{2\lambda_{\min}(P)} \right] (t - t_0)
\]

(16)

Finally, from \( z_i = \ddot{x}_i / \varepsilon^2 \).
where $\lambda_{\max}(P)$ and $\lambda_{\min}(P)$ are the maximum and minimum eigenvalues of the matrix $P$, respectively. Thus, it can be concluded that the estimation error of MESO converges to a constant $C_M$, even zero.

3.2 MESO-based sliding mode controller design

For the purpose of improving the reaching rate, in this study, a reaching law of multi power is designed as

\[
\dot{s} = -k_l |s|^{\alpha} \text{sgn}(s) - k_2 |s|^{\alpha} \text{sgn}(s) - k_3 |s|^{\alpha} \text{sgn}(s) - k_4 s
\]

such that satisfies Eq. (22), then $v(t)$ can converge to zero in finite time $t_r$, and $t_r$ satisfies Eq. (23)\[25\]

\[
v(t) \leq -a_1 v(t) - b_1 v(t)^{\alpha/\beta} \quad \forall t \geq t_0
\]

where $k_i > 0 (i = 1,2,3,4)$, $w_i > 1$, 0 $< w_2 < 1$.

Traditional sliding mode control has the problem of “chattering”, especially when the system has strong disturbance and uncertainty, “chattering” is more prominent. To effectively weaken the system “chattering”\[24\], based on the MESO, the integral sliding mode surface is designed as

\[
s = \dot{s}_i + \int_0^t \left[ l_0 |x_i|^{\alpha} \text{sgn}(x_i) + l_1 |\dot{x}_i|^{\alpha} \text{sgn}(\dot{x}_i) \right] dt
\]

where $l_0, l_1, \alpha_0$, and $\alpha_1$ are positive constants.

The derivative of Eq. (19) is

\[
\dot{s} = -\frac{1}{L_i C_i} x_i - \frac{R}{L_i} \dot{x}_i + b u + \dot{x}_i + l_0 |x_i|^{\alpha} \text{sgn}(x_i) +
\]

\[
l_1 |\dot{x}_i|^{\alpha} \text{sgn}(\dot{x}_i)
\]

Considering the estimated value of MESO of Eq. (7), the proposed MESO-based SMC law can be expressed as

\[
u = -\frac{1}{b_i} \left[ -\frac{1}{L_i C_i} x_i - \frac{R_i}{L_i} \dot{x}_i + \dot{x}_i + l_0 |x_i|^{\alpha} \text{sgn}(x_i) + l_1 |\dot{x}_i|^{\alpha} \text{sgn}(\dot{x}_i) +
\]

\[
+k_1 |s|^{\alpha} \text{sgn}(s) + k_2 |s|^{\alpha} \text{sgn}(s) + k_4 s
\]

Remark 1: The integral sliding surface (the sign function is included in the integral sign) and continuous control law are designed, effectively weakening the “chattering” problem.

Remark 2: From Eq. (18), based on the single-power reaching law, the power and linear terms are added to the multi-power reaching law, and the parameters $w_i$ are designed according to the situation. To a certain extent, this improves the convergence rate of the system.

Theorem 2: Considering the nonlinear system in Eq. (4), MESO in Eq. (7) and integral sliding mode with multi-power reaching law in Eq. (21), tracking errors ultimately converge to zero in a finite time.

Proof:

Lemma 1: If a continuous function $v(t)$ exists that satisfies Eq. (22), then $v(t)$ can converge to zero in finite time $t_r$, and $t_r$ satisfies Eq. (23)\[25\]

\[
v(t) \leq -a_1 v(t) - b_1 v(t)^{\alpha/\beta} \quad \forall t \geq t_0
\]

where $a_1 > 0$, $b_1 > 0$, $q_1$ and $p_1$ are positive odd constants and $0 < q_1/p_1 < 1$.

A Lyapunov function is chosen as $V_2 = (1/2)s^2$. Substituting Eq. (21) in Eq. (20), the derivative of $V_2$ is

\[
\dot{V}_2 = k_i |s|^{\alpha} \text{sgn}(s) - k_2 |s|^{\alpha} \text{sgn}(s) - k_3 |s|^{\alpha} \text{sgn}(s) - k_4 s
\]

\[
\leq -k_i |s|^{\alpha+1} - k_2 s^2 = -2k_i V_2 - 2(|s|^{\alpha+1}/k_1)^2
\]

Therefore, $V_2 \leq 0$, according to Lyapunov stability theory, the control system is stable. Then, from Lemma 1 and Eq. (23), s can converge to zero in a finite time $T$ and satisfies

\[
T = t_0 + \frac{1}{k_i (1-w_0)} \ln \left( \frac{2k_i V_2 (t_0)^{1-w_0}/2 + 2(w_0^{1+w_0})^2 k}{2(w_0^{1+w_0})^2} \right)
\]

where $t_0$ is initial time.

Remark 3: According to Eqs. (24)-(25), the Lyapunov theory is used to demonstrate the validity, and the exact convergence time $T$ is obtained.

4 Simulation analysis

To verify the effectiveness of the proposed control strategy, certain control systems are constructed on the Matlab/Simulink platform, for a single phase 50 Hz islanded microgrid. The proposed control strategy is abbreviated as MPMSC+MESO,
and the system performance is compared with the following controller.

1. MPSMC+ESO strategy: Replace the MESO in this study with a conventional ESO.

2. MPSMC strategy: In the ESO-free sliding mode control strategy, if the sliding surface is consistent with Eq. (21), then for nominal system the sliding mode controller with a multi-power reaching law is designed as

\[
\dot{u} = \frac{1}{b} \left[ -\frac{1}{L_f C_f} x_i - \frac{R_f}{L_f} x_i + \frac{R_f}{L_f} \dot{x}_i + \frac{1}{L_f C_f} u_i + \frac{1}{C_f} i_0 + \frac{R_f}{L_f} i_0 + l_i |x_i|^\alpha \operatorname{sgn}(x_i) + l_i |x_2|^\beta \operatorname{sgn}(x_2) + k_i |s|^\gamma \operatorname{sgn}(s) + k_2 |s|^\gamma \operatorname{sgn}(s + k_\delta s) \right]
\]

where the selection of controller parameters is consistent with that considered in this study.

3. SPSMC+MESO strategy: Based on MESO, the conventional single power reaching law is used in the controller design. The reaching law has the following forms

\[
\dot{s} = -\varphi |s|^\rho - \operatorname{sgn}(s)
\]

where \( \varphi = 0.7, \ \omega = 1.4 \).

The control law can be expressed as

\[
\dot{u} = \frac{1}{b} \left[ -\frac{1}{L_f C_f} x_i - \frac{R_f}{L_f} x_i + \frac{R_f}{L_f} \dot{x}_i + \frac{1}{L_f C_f} u_i + \frac{1}{C_f} i_0 + \frac{R_f}{L_f} i_0 + l_i |x_i|^\alpha \operatorname{sgn}(x_i) + l_i |x_2|^\beta \operatorname{sgn}(x_2) + k_i |s|^\gamma \operatorname{sgn}(s) + k_\delta s \right] + l_i |x_2|^\beta \operatorname{sgn}(x_2) + \varphi |s|^\rho + \operatorname{sgn}(s)
\]

Further, the performance is tested on an islanded microgrid system with the following cases.

### 4.1 Performance of the MPSMC+MESO

The proposed control strategy must enable the system to operate stably. The system output response in steady state are shown in Fig. 3.

Fig. 3a and 3b show the duty curve of inverter circuit, and the inverter output voltage, respectively. Fig. 3c and 3d show the output voltage and load current response of the MPSMC+MESO method under resistive load (linear) and RLC load (nonlinear), respectively.

| Tab. 1 | System electrical parameters |
|--------|----------------------------|
| Parameter | Value |
| Inverter switching frequency (kHz) | 10 |
| DC link voltage (V) | 400 |
| Filter inductor (L) (mH) | 3.4 |
| Filter capacitor (C) (µF) | 18 |
| Parasitic resistance (R) (Ω) | 0.2 |
| Linear load (RL) | 38 |
| Nonlinear load (RNL) | (38 Ω + 5 mH)/(2.5 mF) |
| Nominal amplitude \( E' \) | 314.8 |
| Nominal frequency \( \omega^* \) | 311 |

| Tab. 2 | System control parameters |
|--------|----------------------------|
| Parameter | Value |
| Droop parameters \( m_1, n_1, m_2, n_2 \) | 0.002, 0.001, 5, 0.0007, 0.0003 |
| Observer parameters \( \epsilon, G_1, G_2, G_3 \) | 0.7, 0.001, 0.03, 12 |
| Sliding mode parameters \( l_f, l_s, c, \alpha \) | 880, 9/11, 1/200, 23/27 |
| Control law parameters \( k_i, k_1, k_2, k_3, k_4 \) | 0.7, 1.4, 0.1, 0.5, 1000, 0.9 |

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Fig. 3 Output responses of the proposed controller

It can be observed from Fig. 3 that the output voltage of the islanded microgrid inverter system can quickly track its reference input voltage under different load types, and exhibit a steady-state performance.

4.2 Comparison of system parameters perturbation

To compare the fairness and effectiveness, the corresponding control parameters and system parameters are made completely consistent. In view of the limited space, this section only discusses the filters inductance parameters perturbation. Based on the nominal value of 3.7 mH, the filter inductance changes by $\pm 40\%$. Fig. 4 shows the output voltage of different voltage controllers under three inductance parameter values, respectively.

Fig. 4 Output voltages using different voltage controllers

As observed from Fig. 4, when the inductance parameters are perturbed, the output voltage of the controller with MESO is closer to the output voltage under the nominal inductance value, which indicates that the controller with MESO can adapt to the disturbance of the inductance parameters better than the controller without MESO. Comparing Fig. 4b and 4c, the rate of the conventional SPSMC reaching steady state is slower than that of MPSMC with the multi-power reaching law of this study.

4.3 Comparison of load parameters variation

The loads parameters variation is also one of the main factors that affect the robustness of voltage controller because there are load parameters in the system model. As the nonlinear load has a significant effect on the system, the nonlinear load change is studied here. The variation of load is set as

$$Z = \begin{cases} R_{NL}, & 0 \leq t < 0.404 \text{ s} \\ R_{NL} \parallel R_{NL}, & 0.404 \text{ s} \leq t < 0.800 \text{ s} \end{cases}$$  \hspace{1cm} (29)$$

The simulation results for loads parameters variation of the different controllers are illustrated in Fig. 5. Figs. 5a and 5b show the duty ratio curves and steady-state voltage tracking error, respectively. Fig. 5c is the current transient response waveform and the
THD values of the aforementioned different schemes are analyzed in Figs. 5d-5f. To describe the characteristics of the response curve, Tab. 3 lists the performance comparison under different control strategies.

| Algorithms      | Nominal load THD (%) | Load variations Error/V | Load variations THD (%) | Load variations Error/V |
|-----------------|-----------------------|-------------------------|-------------------------|-------------------------|
| SPSMC           | 3.82                  | 4.3                     | 3.82                    | 9.5                     |
| MPSMC           | 3.48                  | 3.5                     | 3.48                    | 8.6                     |
| MPSMC+MESO      | 2.16                  | 2.0                     | 2.16                    | 2.4                     |

When subjected to load disturbance, the duty ratio of the control system without MESO is reduced and cannot be recovered. However, after the introduction of MESO, the duty ratio can be restored to the original amplitude in a short period after the disturbance, as shown in Fig. 5a. The steady-state output voltage tracking error of the different control strategies is significantly different (Fig. 5b). Fig. 5c shows that the MPSMC+MESO can effectively reduce the transient peak value of the output current and shorten its transient adjustment time. As shown in Figs. 5d-5f, all the strategies meet IEEE standard 519-2014 (THD <5%)\cite{26}. In addition, the THD value of proposed strategy is the smallest.

Thus, it can be observed that the uncertainties, such as filter parameter perturbation and load change, can be estimated by the MESO in real time to realize the adaptive control of the system. Further, the proposed control method has a stronger ability to resist internal and external disturbances.

### 4.4 Comparison of responses under different reaching laws controllers

Fig. 6 shows the response results of the sliding mode controller designed by the conventional single-power reaching law and multi-power reaching law of this study. The condition of sliding surface $s$ with time under different reaching laws is shown in Fig. 6a. Fig. 6b shows the change of state $x_1$ when the 0.404 s load is suddenly changed.

It can be observed from Fig. 6a that it takes a long time from the initial stage to reach the sliding surface by using the single-power reaching law, while the multi-power reaching law has a faster convergence rate. This is because the multi-power reaching law increases the number of adjustable power term
coefficients and the first-order term $k_4s$, which accelerates the convergence rate of the system when it is far away from the sliding mode surface. As shown in Fig. 6b, when the MPSMC controller is adopted, the state $x_1$ converges to equilibrium zero faster than SPSMC after the load changes.

4.5 Comparison of the observation effect based on MESO and conventional ESO

The design of MESO is shown in Eq. (7), if the identified model information is not introduced, i.e., $f(\hat{x})$ terms are removed, it stands for conventional ESO. The comparison of the observation effects between MPSMC+MESO and MPSMC+ESO strategies is shown in Fig. 7.

As observed from Fig. 7, in terms of state estimation error and tracking error index, the MPSMC+MESO system is smaller than the MPSMC+ESO system, and the estimation accuracy of MESO is higher than the conventional ESO system.

5 Conclusions

In this study, a MESO-based robustness voltage SMC scheme for an AC islanded microgrid is proposed. In the presence of system parameter perturbation and load variation, to make the islanded microgrid inverter system still track its reference input well, the aforementioned interference effect is integrated into a lumped uncertainty, which is estimated in real time by a MESO. To improve the response speed and robustness of the system, a sliding mode controller with a multi-power reaching law is designed while considering the lumped uncertainty of MESO reconstruction. The results show that the proposed voltage control strategy enables the inverter system to operate stably and reliably. Further, it resists the internal and external interference of the system, such as filtering parameters and load changes, for the output voltage to exhibit satisfactory dynamic regulation ability and steady-state tracking ability to meet the requirements of power quality. The use of MESO improves the system reliability, saves hardware
costs, and provides a novel control idea and method for the distributed new energy islanded microgrid system.

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**Hao Pan** was born in Gansu Province, China, on October, 1993. He is studying for a master’s degree in electrical engineering at the Lanzhou Jiaotong University, Lanzhou, China. His research interests concern DC-AC inverter control, sliding mode control as well as active disturbance rejection control.

**Qingfang Teng** received the B.S. degree in aviation automation control from Northwestern Polytechnical University, Xi’an, Shaanxi, in 1985. She received the M.S. degree and the Ph.D. degree in traffic information engineering and control from Lanzhou Jiaotong University, Lanzhou, Gansu, in 2003 and 2008. She is currently a professor of control engineering in the Department of Automation and Electrical Engineering. Her research interests include high accuracy control and fault tolerant control for electrical machine.

**Dangdang Wu** was born in Gansu Province, China, on July, 1993. She is studying for a master’s degree in electrical engineering at the Lanzhou Jiaotong University, Lanzhou, China. Her research interests concern energy storage control, sliding mode control as well as active disturbance rejection control.