Research Article

Feedback Linearization and Sliding Mode Control for VIENNA Rectifier Based on Differential Geometry Theory

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Aiming at the nonlinear characteristics of VIENNA rectifier and using differential geometry theory, a dual closed-loop control strategy is proposed, that is, outer voltage loop using sliding mode control strategy and inner current loop using feedback linearization control strategy. On the basis of establishing the nonlinear mathematical model of VIENNA rectifier in d - q synchronous rotating coordinate system, an affine nonlinear model of VIENNA rectifier is established. The theory of feedback linearization is utilized to linearize the inner current loop so as to realize the d - q axis variable decoupling. The control law of outer voltage loop is deduced by utilizing sliding mode control and index reaching law. In order to verify the feasibility of the proposed control strategy, simulation model is built in simulation platform of Matlab/Simulink. Simulation results verify the validity of the proposed control strategy, and the controller has a strong robustness in the case of parameter variations or load disturbances.

1. Introduction

With the development of power electronic technology, three-level pulse width modulation (PWM) rectifiers are widely used in high or medium power converters because of their excellent performance: low switch voltage stress, low input current harmonic distortion, high efficiency, input power factor is unit, and so on [1–7]. Three-phase/switch/level VIENNA rectifier (abbreviated as VIENNA rectifier) is one of the best three-level rectifier, which is proposed in 1994 by Kolar and Zach. Compared with traditional three-level rectifier, such as diode clamping three-level rectifier, VIENNA rectifier has lots advantages, such as small number of power switch tube, simple control circuit, and low design costs, without output voltage bridge arm shoot-through problems. So, more and more scholars and engineers focus their attention on the study of VIENNA rectifier and its control strategy [3–14].

Since VIENNA rectifier is a typical strong coupling nonlinear system, it leads to difficulty in designing the controller. In [8, 9], the mathematical models of large and small signals topology are analyzed in detail, and the controller is designed

by using proportion and integral (PI) algorithm. A control method of input/output accurate linearization is proposed in [10]. State-space average model is established, and PI control algorithm is used in the outer voltage loop; hysteresis control is used in the inner current loop in [11–13]. The control methods described above improved the performance of VIENNA rectifier to some extent. However, there are some disadvantages, such as system excessive dependence on the accurate mathematical model, inconvenience of parameter setting, complicated of control algorithm, and poor dynamic. In order to overcome the above drawbacks, this paper proposes a control strategy which combines feedback linearization control and sliding mode control.

In recent decades, nonlinear control theory has made great progress, especially feedback linearization theory based on differential geometry. In this method, nonlinear system can achieve status or input/output linearization by using a certain nonlinear state transformation or feedback transformation. Feedback linearization control has been applied to three-phase voltage PWM rectifier [14–16], which is a multivariable and strong coupling nonlinear system, and achieved well control effect. All these methods can solve

the problem of decoupling for original nonlinear system and obviously improve static and dynamic performance for three phase rectifier. Yet, this control method depends on an accurate mathematical model and is sensitive to system parameters. Sliding mode control is different from feedback linearization control method. Sliding mode control shows great robustness and stays out of parameter changes when the system is running in the sliding surface. In [17–20], sliding mode control has been applied to the three-phase PWM rectifier and achieved a good result.

The three-phase PWM rectifier is a two-level rectifier, while the VIENNA rectifier is a three-level rectifier. Although their structure is not the same, there are some similarity in control strategy. Learning from the applications of feedback linearization control and sliding mode control for three-phase PWM rectifier, this paper integrates feedback linearization control method and sliding mode control method and eventually establishes a new type of VIENNA rectifier nonlinear control system. That is, sliding mode control is used in the outer voltage loop and state feedback linearization control is used in the inner current loop. At the same time, space vector pulse width modulation (SVPWM) technology is introduced to modulate the output signal of inner currentloop [21]. In order to reduce the chattering phenomenon produced by sliding mode control, index reaching law is adopted to improve the whole approaching process. In order to verify the

correctness and superiority of the proposed control strategy, numerical simulation is done.

2. Physical and Modeling Considerations

In this section, the physical system and the mathematical model of VIENNA rectifier are presented. The main circuit of VIENNA rectifier and its simplified model are shown in Figures 1(a) and 1(b), respectively. The main circuit includes six fast-recovery diodes (D_1 – D_6), three boost inductors, three bidirection power switching tubes (S_a , S_b , and S_c as shown in the dashed box), and two groups of output capacitances. Among them, e_a , e_b , e_c are the AC input power of VIENNA rectifier; C_1 and C_2 are DC side output voltage filter capacitor, and their voltage across, respectively, are V_{C1} , V_{C2} ; R_l is load resistance and the voltage across is V_{dc} , and i_l is the output current; L is the boosting inductor and R is defined as an equivalent resistance of inductor. In order to simplify the system, all the power-switching devices are seen as ideal and switching frequency is much higher than the grid frequency.

The mathematical model of VIENNA rectifier in abc coordinates can be expressed as follows:

$$Z \frac{dX}{dt} = AX + BE, \quad (1)$$

where

$$\begin{aligned} Z &= [L \ L \ L \ C_1 \ C_2], \\ X &= [i_a \ i_b \ i_c \ V_{C1} \ V_{C2}]^T, \\ B &= [1 \ 1 \ 1 \ 0 \ 0], \\ E &= [e_a \ e_b \ e_c \ 0 \ 0]^T, \\ A &= \begin{bmatrix} -R & 0 & 0 & -\left(S_{ap} - \frac{S_{ap} + S_{bp} + S_{cp}}{3}\right) & \left(S_{an} - \frac{S_{an} + S_{bn} + S_{cn}}{3}\right) \\ 0 & -R & 0 & -\left(S_{bp} - \frac{S_{ap} + S_{bp} + S_{cp}}{3}\right) & \left(S_{bn} - \frac{S_{an} + S_{bn} + S_{cn}}{3}\right) \\ 0 & 0 & -R & -\left(S_{cp} - \frac{S_{ap} + S_{bp} + S_{cp}}{3}\right) & \left(S_{cn} - \frac{S_{ap} + S_{bp} + S_{cp}}{3}\right) \\ S_{ap} & S_{bp} & S_{cp} & -\frac{1}{R_l} & -\frac{1}{R_l} \\ -S_{an} & -S_{bn} & -S_{cn} & -\frac{1}{R_l} & -\frac{1}{R_l} \end{bmatrix}. \end{aligned} \quad (2)$$

With Park's transformation, the mathematical model of VIENNA rectifier in d - q coordinates system is given as follows:

$$L \frac{di_d}{dt} = -Ri_d + \omega Li_q - S_{dp}V_{C1} + S_{dn}V_{C2} + e_d, \quad (3)$$

$$L \frac{di_q}{dt} = -\omega Li_d - Ri_q - S_{qp}V_{C1} + S_{qn}V_{C2} + e_q, \quad (4)$$

$$C \frac{dV_{C1}}{dt} = \frac{3}{2}S_{dp}i_d + \frac{3}{2}S_{qp}i_q - i_l, \quad (5)$$

$$C \frac{dV_{C2}}{dt} = -\frac{3}{2}S_{dn}i_d - \frac{3}{2}S_{qn}i_q - i_l, \quad (6)$$

where e_d and e_q are the grid voltage variable in d - q coordinate system; i_d and i_q are the grid current variable in d - q coordinate system. As for S_{dp} , S_{dn} , S_{qp} , and S_{qn} , they are the switching function in d - q coordinate system for

FIGURE 1: Main circuit of VIENNA rectifier and its simplified model.

S_x ($x = a, b, c$). The equivalent circuit of VIENNA rectifier in d - q coordinate system is shown in Figure 2.

For three-phase balance power grid, because of $C_1 = C_2 = C$, yield $V_{C1} = V_{C2} = (1/2)V_{dc}$. Assume that

$$\begin{aligned} S_d &= S_{dp} - S_{dn}, \\ S_q &= S_{qp} - S_{qn}. \end{aligned} \quad (7)$$

Thus, (3) and (4) can be rewritten as follows:

$$\begin{aligned} L \frac{di_d}{dt} &= -Ri_d + \omega Li_q - \frac{S_d}{2} V_{dc} + e_d, \\ L \frac{di_q}{dt} &= -Ri_q - \omega Li_d - \frac{S_q}{2} V_{dc} + e_q. \end{aligned} \quad (8)$$

With (5) plus (6), we can obtain

$$C \frac{dV_{dc}}{dt} = \frac{3}{2} (S_d i_d + S_q i_q) - 2i_l. \quad (9)$$

FIGURE 2: Equivalent circuit of VIENNA rectifier in d - q coordinates.

3. Control Goal and Control Strategies

The main control goal for VIENNA rectifier is to make sure that input current waveform is sinusoid and track the input voltage waveform, the power factor is unity, and DC side output voltage stabilized at the given reference voltage. Equations (8)-(9) show that VIENNA rectifier is a strong decoupling nonlinear system. In order to realize the variables decoupling in d - q axis, ensure that input current is sinusoid and tracks input voltage; the feedback linearization technology is used in the inner current loop. At the same time, sliding mode control based on index reaching law is used in the voltage loop to stabilize the output voltage and provide the reference directive current i_d^* for inner current loop.

3.1. Inner Current Loop Controller Design Based on Feedback Linearization. The role of inner current loop is making i_d and i_q keep track of reference directive current i_d^* and i_q^* , respectively, and realizes system unity power factor operation.

3.1.1. Affine Nonlinear Models of VIENNA Rectifier. Select state variables as

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}. \quad (10)$$

Select input variables as

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} S_d \\ S_q \end{bmatrix}. \quad (11)$$

Select output variables as

$$\begin{aligned} y_1 &= h_1 [x(t)] = i_d, \\ y_2 &= h_2 [x(t)] = i_q. \end{aligned} \quad (12)$$

According to (8), we get the affine nonlinear equation for two-input and two-output system as follows:

$$\begin{aligned} \dot{x} &= f(x) + g_1(x)u_1 + g_2(x)u_2, \\ y_1 &= h_1 [x(t)], \\ y_2 &= h_2 [x(t)], \end{aligned} \quad (13)$$

where

$$f(x) = \begin{bmatrix} -\frac{R}{L}i_d + \omega i_q + \frac{1}{L}e_d \\ -\frac{R}{L}i_q - \omega i_d + \frac{1}{L}e_q \end{bmatrix}, \quad g_1(x) = \begin{bmatrix} -\frac{V_{dc}}{2L} \\ 0 \end{bmatrix},$$

$$g_2(x) = \begin{bmatrix} 0 \\ -\frac{V_{dc}}{2L} \end{bmatrix}. \quad (14)$$

For the system which is described in (13), it is nonlinear to state variable $X(t)$ while linear to controlled variable u .

3.1.2. Linearization Processing of VIENNA Rectifier

Lemma 1 (see [22]). Let one assume $B(x) = [b_1, \dots, b_m]$ as a nonsingular matrix and define the following sets:

$$G_0(x) = \{b_1, \dots, b_m\},$$

$$G_1(x) = \{b_1, \dots, b_m, ad_f b_1, \dots, ad_f b_m\},$$

$$\vdots$$

$$G_i(x) = \{ad_f^k : 0 \leq k \leq i, 1 \leq k \leq m\}, \quad i = 0, 1, \dots, n-1. \quad (15)$$

So, the necessary and sufficient conditions for these linearization solutions above are as follows:

- (1) for each $i = 0, 1, \dots, n-1$, the distribution $G_i(x)$ has constant dimension near x ;
- (2) for each $i = 0, 1, \dots, n-1$, the distribution $G_i(x)$ is involution;
- (3) the dimension of $G_{n-i}(x)$ is n .

According to the requirements of exact linearization for nonlinear system, verify the two-input and two-output affine nonlinear system described in (13) as follows:

$$ad_f g_1(x) = \frac{\partial g_1(x)}{\partial x} f(x) - \frac{\partial f(x)}{\partial x} g_1(x) = \begin{bmatrix} 0 \\ -\omega V_{dc} \end{bmatrix},$$

$$ad_f g_2(x) = \frac{\partial g_2(x)}{\partial x} f(x) - \frac{\partial f(x)}{\partial x} g_2(x) = \begin{bmatrix} \omega V_{dc} \\ 0 \end{bmatrix}. \quad (16)$$

From (16), we can obtain this conclusion: the total relative degree $r = 1 + 1 = 2$, which just right equals the system's dimension n . Meanwhile, when $n = 2$, the vector $D = [g_1(X) \ g_2(X) \ ad_f g_1(X) \ ad_f g_2(X)]$ is involution. Hence, it meets the requirements of linearization.

Taking Lie derivative for (13), we can obtain

$$\dot{x}_1 = L_f h_1(x) + L_{g_1} h_1(x) u_1 + L_{g_2} h_1(x) u_2,$$

$$\dot{x}_2 = L_f h_2(x) + L_{g_1} h_2(x) u_1 + L_{g_2} h_2(x) u_2, \quad (17)$$

where

$$L_{g_1} h_1(x) = L_{g_2} h_2(x) = -\frac{V_{dc}}{2L},$$

$$L_{g_2} h_1(x) = L_{g_1} h_2(x) = 0,$$

$$L_f h_1(x) = -\frac{R}{L}i_d + \omega i_q + \frac{e_d}{L},$$

$$L_f h_2(x) = -\frac{R}{L}i_q - \omega i_d + \frac{e_q}{L}. \quad (18)$$

3.1.3. Coordinate Transformation and the Control Law. Select output vector as

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}. \quad (19)$$

According to the definition of relative degree [22], the derivative of two input/output system output functions is

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = \begin{bmatrix} L_f h_1 \\ L_f h_2 \end{bmatrix} + A(x) \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \alpha(x) + A(x) u, \quad (20)$$

where

$$A(x) = \begin{bmatrix} -\frac{V_{dc}}{2L} & 0 \\ 0 & -\frac{V_{dc}}{2L} \end{bmatrix}. \quad (21)$$

In the meanwhile, since the matrix $A(x)$ is invertible, the state feedback control law is given by

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = -A^{-1}(x) \left(\begin{bmatrix} L_f h_1 \\ L_f h_2 \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \right). \quad (22)$$

In order to track the desired value, a new control law is given by [14]

$$v_1 = -k_{10}(y_1^* - y_1)$$

$$v_2 = -k_{20}(y_2^* - y_2). \quad (23)$$

From (20), (22), and (23), the new state feedback control law of the original nonlinear inner current loop is obtained:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = -\frac{2}{V_{dc}} \left(\begin{bmatrix} Ri_d - \omega i_q - e_d \\ \omega i_d + Ri_q - e_q \end{bmatrix} + \begin{bmatrix} -k_{10}(y_1^* - y_1) \\ -k_{20}(y_2^* - y_2) \end{bmatrix} \right). \quad (24)$$

So far, the original nonlinear system is linearization. Meanwhile, the control for inner current loop can be achieved by setting feedback coefficients k_{10} and k_{20} .

3.1.4. Analysis of System Dynamic Stability. Because of the relative degree of (8) being 1 and according to the literature [14], we can get the error dynamic closed-loop system as follows:

$$\dot{e}_1 + k_{10}e_1 = 0, \quad (25)$$

$$\dot{e}_2 + k_{20}e_2 = 0, \quad (26)$$

$$\dot{z} = a(z, e + y^*, \xi), \quad (27)$$

where $\xi = [\dot{y}_1 \ \dot{y}_2]^T$, $e_i = y_i^* - y_i$ ($i = 1, 2$).

Lemma 2. For internal dynamic formula (27), when tracking error e vanishes, that is

$$\dot{z} = a(z, y^*, 0), \quad (28)$$

it is called the zero dynamics [14]. And if a nonlinear system's zero dynamics is asymptotically stable, it is said to be minimum phase.

Because the power supply is three-phase symmetrical voltage and the rectifier is operated with unity power factor and considered in the steady state, we have $e_d = E_m$, $V_{dc} = V_{dc}^*$, $i_d = I_d^*$ and $i_q = 0$. Therefore, (8) and (9) can be simplified as follows:

$$\begin{aligned} RI_d^* + \frac{S_d' V_{dc}^*}{2} &= E_m, \\ \omega LI_d^* + \frac{S_q' V_{dc}^*}{2} &= 0, \\ \frac{3}{2} S_d' I_d^* &= 2I_l, \end{aligned} \quad (29)$$

where S_d' , S_q' , I_d^* , and I_l represent the steady-state values of the switching functions S_d and S_q , d -axis reference current i_d^* , and output load current i_l , respectively.

By contrast, we find that (29) are the same as (21)–(23) in [14], so the dynamic analysis of VIENNA rectifier can learn from the literature [14].

Transform the original nonlinear system (13) into the linear form of (25)–(27) with $z = x_3 = V_{dc}$. The internal dynamics (27) becomes

$$\begin{aligned} \dot{x}_3 &= -\frac{3L}{2C} \frac{i_d}{V_{dc}} \left[k_{10} (I_d^* - i_d) + \frac{R}{L} i_d + \omega i_q - \frac{E_m}{L} \right] \\ &\quad - \frac{3L}{2C} \frac{i_q}{V_{dc}} \left[-k_{20} i_q + \frac{R}{L} i_q - \omega i_d \right] - \frac{1}{C} i_l. \end{aligned} \quad (30)$$

According to the energy balance and because of the tracking error vector e approaching zero, that is, $i_d \rightarrow I_d^*$ and $i_q \rightarrow 0$, we can get the following zero dynamics equation:

$$\dot{x}_3 = \frac{1}{R_l C x_3} (V_{dc}^{*2} - x_3^2). \quad (31)$$

From (31), we can know the following. For a positive initial dc side output voltage, the steady-state value of x_3 will eventually equal the desired value of V_{dc}^* . So, when using cascaded current mode, the control system is a minimum phase system, and the dynamic is stability. Therefore, we can design a superior performance control system.

3.2. Voltage Loop Controller Design Based on Sliding Mode Control. The role of voltage loop controller is to guarantee output voltage V_{dc} tracking the given reference voltage V_{dc}^* and stable. In the meantime, voltage loop controller provides d -axis reference current i_d^* for the current loop.

For (24), i_d and i_q can be acquired by taking Park's transformation to input currents i_a , i_b , and i_c . For dual closed

loop control system which adopts inner current loop and outer voltage loop, i_d^* is always provided by the outer loop. For three-level PWM rectifier, PI algorithm [23], fractional control algorithm [24], and sliding mode control algorithm [25] are used in the outer voltage loop. Since inner current loop uses feedback linearization control, it brings a shortcoming for this control system; that is, the control system is overreliance on accurate mathematical model. In order to compensate this shortcoming, sliding mode control algorithm is used in the outer voltage loop. One of the biggest advantages for sliding mode control is insensitive to the change of system parameters and having less demand for control system model. In order to avoid chattering, improve the approaching performance, index reaching law is introduced based on sliding mode control which is described in [25].

Let us assume the error between dc output voltage and the given reference voltage as follows:

$$V_e = V_{dc}^* - V_{dc}. \quad (32)$$

Based on the principle of sliding mode control [26, 27], the sliding surfaces can be defined as

$$S_{dc} = V_e + k_3 \int_0^t V_e dt, \quad k_3 > 0. \quad (33)$$

When $S_{dc} = 0$, the system runs in sliding mode surface. Take a derivate on both sides of (33), and because V_{dc}^* is constant, yield

$$\dot{S}_{dc} = -\frac{dV_{dc}}{dt} + k_3 V_e. \quad (34)$$

According to (9), (34) can be rewritten as

$$\dot{S}_{dc} = -\frac{3}{2C} (S_d i_d + S_q i_q) + \frac{2}{C} i_l + k_3 V_e. \quad (35)$$

In order to guarantee the system having a good quality in the transition process, especially improving the quality of arrival stage, and eliminating the chattering phenomenon, index reaching law is applied [26]:

$$\dot{S} = -\varepsilon \operatorname{sgn} S - \lambda S \quad \varepsilon > 0, \lambda > 0. \quad (36)$$

According to the literature [26], yield

$$\begin{aligned} S(t) &= \frac{\varepsilon}{\lambda} + \left(S(0) - \frac{\varepsilon}{\lambda} \right) e^{-\lambda t}, \quad S > 0; \\ S(t) &= \frac{-\varepsilon}{\lambda} + \left(S(0) + \frac{\varepsilon}{\lambda} \right) e^{-\lambda t}, \quad S < 0. \end{aligned} \quad (37)$$

From (37), we can obtain

$$t^* = \frac{1}{\lambda} \left(\ln \left(S + \frac{\varepsilon}{\lambda} \right) - \ln \frac{\varepsilon}{\lambda} \right). \quad (38)$$

From (38), it shows that reducing ε and increasing λ can accelerate the approaching process.

From (35) and (36), we can obtain

$$\lambda S_{dc} + \varepsilon \operatorname{sgn}(S_{dc}) - \frac{3}{2C} (S_d i_d + S_q i_q) + \frac{2}{C} i_l + k_3 V_e = 0. \quad (39)$$

Further, (39) can be transformed as follows:

$$\left[\lambda S_{dc} + \varepsilon \operatorname{sgn}(S_{dc}) - \frac{3}{2C} S_q i_q + \frac{2}{C} i_l + k_3 V_e \right] \cdot \frac{2C}{3S_d} - i_d = 0. \quad (40)$$

According to the above assumption, power grid is symmetrical three-phase voltage. When the system is in steady state, yield $i_q = 0, di_q/dt = 0, e_d = \sqrt{3}U_{\text{RMS}}, e_q = 0, V_{dc} = V_{dc}^*$. At the same time, the processing speed of inner loop is faster than the outer loop. Thus, i_d can be seen as constant; yield $di_d/dt = 0$. From (8), the following approximation algorithm can be obtained:

$$\begin{aligned} S_d &\approx \frac{2(e_d - Ri_d)}{V_{dc}}, \\ S_q &\approx -\frac{2\omega Li_q}{V_{dc}}. \end{aligned} \quad (41)$$

From (40) and (41), we can obtain

$$\begin{aligned} i_d &= \frac{CV_{dc}}{3(\sqrt{3}U_{\text{RMS}} - Ri_d)} \\ &\cdot \left[\lambda \left(V_e + k_3 \int_0^t V_e dt \right) + \varepsilon \operatorname{sgn} \left(V_e + k_3 \int_0^t V_e dt \right) \right. \\ &\quad \left. + \frac{2i_l}{C} + k_3 V_e \right]. \end{aligned} \quad (42)$$

When the system is in steady state, $i_d = i_d^*$. So, (42) is rewritten as

$$\begin{aligned} i_d^* &= \frac{CV_{dc}}{3(\sqrt{3}U_{\text{RMS}} - Ri_d)} \\ &\cdot \left[\lambda \left(V_e + k_3 \int_0^t V_e dt \right) + \varepsilon \operatorname{sgn} \left(V_e + k_3 \int_0^t V_e dt \right) \right. \\ &\quad \left. + \frac{2i_l}{C} + k_3 V_e \right]. \end{aligned} \quad (43)$$

As a result, the output of outer voltage loop just is the current instructions i_d^* for the inner loop, which is relevant to the output voltage, output current, valid value of phase voltage, d -axis current i_d , and so on. Besides, i_d^* is irrelevant to the switching function variables.

3.3. Control System Block Diagram. According to the above analysis, we can get the control system block diagram as shown in Figure 3.

FIGURE 3: Control system block diagram.

TABLE 1: Simulation parameters.

Input phase voltage	$e_{(a,b,c)} = 110 \text{ V}$
Output reference voltage	$V_{dc}^* = 400 \text{ V}$
Boost inductance	$L = 2.8 \text{ mH}$
Line equivalent impedance	$R = 0.1 \Omega$
Output filtering capacitor	$C_1 = C_2 = 680 \mu\text{F}$
Nominal load resistance	$R_l = 100 \Omega$
Power rating	$P = 1.6 \text{ KW}$
Switching frequency	$f = 10 \text{ KHz}$

4. Simulation Results

In order to verify the correctness and superiority of the proposed control method, the simulation model is built in the simulation platform of Matlab/Simulink. The main simulation parameters are given in Table 1. SVPWM algorithm based on two-level space vector is used in modulation methods of VIENNA rectifier. Small positive vector is set as the first vector, by judging the direction of phase load current which is connected to the output neutral point and adjusting relative action time according to the imbalance between small positive and negative vectors. Voltage regulating factor r ($0 < r < 1$) is introduced. The adjustment to vector action time is done so as to realize the midpoint potential balance control.

4.1. System Startup Responses. When the system is started, DC side output voltage rapidly rises from 0 V and stabilizes at reference voltage V_{dc}^* approximately at 0.0035 s, the response waveforms of output voltage are shown in Figure 4. At the same time, it shows that the system has a rapid response, without overshoot and static error. Also, it verifies that using sliding mode control method could force the system running path moving fast to sliding surfaces, thereby accelerating the convergence process of the system.

4.2. System Steady-State Characteristics. When VIENNA rectifier is operating in steady state, input current waveform tracks input voltage waveform very well and shows sinusoid, as shown in Figure 5(a); the active current i_d can well track reference current i_d^* given by outer voltage loop, as shown in Figure 5(b); the reactive current i_q is 0, which means the rectifier operates with unit power factor, as shown in Figure 5(c). The simulation waveforms indicate that the VIENNA rectifier reaches predetermined target.

FIGURE 4: Response waveforms of output voltage when system starts up.

(a)

(b)

(c)

FIGURE 5: Steady-state simulation waveforms.

4.3. Transient Responses to Step Changes in Load. When load suddenly changes, the simulation waveforms are shown in Figure 6. The value of load resistance R_l is changed from $100\ \Omega$ to $200\ \Omega$ at 0.05 s . As shown in Figure 6(a), DC side output voltage rises to about 6 V instantaneously and then reverts to a stable value (400 V) after 0.001 s . Figure 6(b) shows that input current also suddenly changes. However,

(a)

(b)

(c)

FIGURE 6: Transient responses to step changes in load.

input current waveform can correctly track the input voltage waveform and maintain sinusoid. Figure 6(c) shows that active current i_d can correctly track the given active current reference i_d^* . At the same time, the system response time is short. In a word, it shows significant anti-interference capability to external disturbance by using the proposed strategy.

4.4. Transient Responses to Step Changes in the Given Output Reference Voltage. Assuming output voltage value instantaneously declines to 350 V at 0.06 s , the simulation waveforms are shown in Figure 7. From Figure 7(a), output voltage begins to decrease at 0.06 s and stabilized at 350 V after 0.003 s . From Figure 7(b), a -phase input current value is 0 at 0.06 s and lasts about 0.003 s . Since then, it starts to increase rapidly and tracks input voltage and remains sinusoid.

FIGURE 7: Transient responses to step changes in the given output reference voltage.

5. Conclusions

In this paper, a dual closed loop control method, that is, outer voltage loop based on sliding mode control and inner current loop based on feedback linearization, is proposed. Simulation results show that the proposed control strategy has a good control effect. The main contributions of this paper are as follows.

- (i) It presents feedback linearization control strategy for VIENNA rectifier inner current loop such that it solves the linearization problems and realizes d - q axis variable decoupling.
- (ii) It presents sliding mode control strategy for VIENNA rectifier outer voltage loop and introduces the index reaching law such that it solves stability of output voltage, system startup response, and dynamic characteristics.
- (iii) The combination control strategy overcomes the disadvantage that the system is overreliance on the

accurate mathematical models by using feedback linearization control strategy. Meanwhile, the proposed control strategy greatly improves the robustness of the system.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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