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A double closed-loop control of VIENNA rectifier based on sliding-mode of fuzzy approaching law

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Abstract: A novel double closed-loop control of VIENNA rectifier based on sliding-mode of fuzzy approaching law is proposed in this paper. This new control strategy improves dynamic response and steady accuracy of system, chattering phenomenon of the sliding-mode is eliminated. Combined with sliding-mode and fuzzy approaching law, a new type of inner loop power control is proposed to replace traditional current inner ring. Without coordinate transformation and phase-locked-loops(PLL), control algorithm is simple. Under unbalanced three-phase power grid, output voltage still maintains small voltage ripple, network side harmonic suppression and dynamic response perform well. Sliding-mode based on fuzzy approaching law can eliminate the chattering phenomenon of the system, the overshoot produced by load transition can be reduced. The outer ring adopts voltage PI control with real time current compensation, dynamic response performs good and the control algorithm is simple.

1.Introduction[1]

The VIENNA rectifier is commonly used three-level PFC topological structure circuit at present. It has low network side current harmonic component and high power factor. No need for dead-time and voltage stress of each power device is half of output voltage of the direct current (DC)side. It is widely used in fields of communication power and new energy vehicle charging.

The study of VIENNA rectifier is mainly aimed at analysis of the topology model of VIENNA rectifier, optimization of pulse width modulation(PWM) and system control strategy improvement. Mathematical model of VIENNA rectifier was analyzed and traditional double closed-loop control strategy of VIENNA rectifier was introduce[1-4]. The disadvantages of traditional control strategy are slow dynamic response speed and larger overshoot; Double closed-loop control based on sliding-mode to improves dynamic response of VIENNA rectifier. It is difficult to eliminate chattering phenomena and overshoot is huge[5-10]. To solve problems, sliding-mode based on fuzzy approaching law was proposed. The chattering phenomena can be eliminated and advantages of traditional sliding-mode can be retained.

VIENNA rectifier is nonlinear system, traditional double closed-loop control strategy has bad control effect. Based on sliding-mode and fuzzy approaching law, a new double closed-loop control of

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VIENNA rectifier was proposed. The outer ring adopts voltage PI control with real-time current compensation, the power value of inner ring compensation can be obtained quick and dynamic response rate can be improved. It also simplifies selection of PI parameters; The inner ring adopts sliding-mode based on fuzzy approaching law. PLL and coordinate transformation are unnecessary. Control algorithm is simple. Under unbalanced three-phase power grid, output voltage still maintains small voltage ripple, the network side harmonic suppression and dynamic response perform well. Sliding-mode based on fuzzy approaching law can improve dynamic response and steady accuracy of system and eliminate chattering phenomena in wider load range conditions.

2. Power model of VIENNA rectifier

Figure 1 is topological structure of main circuit of three-phase VIENNA rectifier. e_a,e_b,e_c are Power grid three-phase ac power supply; i_a,i_b,i_c are three-phase power grid input side current; R_a,R_b,R_c are topological equivalent three-phase filter resistor, resistance values are all R; L_a,L_b,L_c are three phase filter inductance, inductance value is L; C_1,C_2 are DC side up and down bridge arm filter capacitance, and capacitance value is C; DC side output voltage $U_{dc}=U_{dc1}+U_{dc2}$ .In theory, because C1,C2 has same capacitance value, $U_{dc1}= U_{dc2}$;R_L are DC output side load resistance.

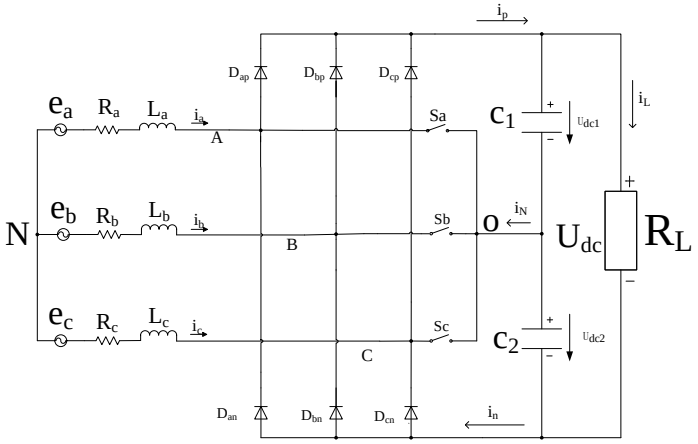


Figure 1 simplified model of the main topology of the VIENNA rectifier

When the grid is in an ideal equilibrium state and the rectifier works in continuous current mode, the following mathematical model is established in the two phase stationary alpha beta coordinate system:

$$\begin{cases} L\dfrac{di_\alpha}{dt} = e_\alpha - R \times i_\alpha - (V_{\alpha N} + V_{NO}) \\ L\dfrac{di_\beta}{dt} = e_\beta - R \times i_\beta - (V_{\beta N} + V_{NO}) \\ C\dfrac{dV_{dc1}}{dt} = s_{\alpha p} \times i_\alpha + s_{\beta p} \times i_\beta - \dfrac{v_{dc}}{R_L} \\ C\dfrac{dV_{dc2}}{dt} = -s_{\alpha n} \times i_\alpha - s_{\beta n} \times i_\beta - \dfrac{v_{dc}}{R_L} \end{cases} \tag{1}$$

When ideal voltage vector in two phase stationary α/β coordinate system rotated ωΔt(Δt approach to zero), to derive nonlinear relationship between e_α and e_β, the following equation can be listed as follows:

$$\begin{cases} \dfrac{de_\alpha}{dt} = -\omega e_\beta \\ \dfrac{de_\beta}{dt} = \omega e_\alpha \end{cases} \tag{2}$$

Taking the derivative of instantaneous active power and reactive power:

$$\begin{cases} L\frac{dP}{dt} = e_\alpha^2 + e_\beta^2 - e_\alpha V_\alpha - e_\beta V_\beta - \omega LQ - RP \\ L\frac{dQ}{dt} = \left(e_\alpha V_\beta - e_\beta V_\alpha\right) + \omega LP - RQ \end{cases} \tag{3}$$

The differential equations of instantaneous active power and instantaneous reactive power are analyzed, both sides of DC side in equation(1) multiplied by V_{dc} (Ideally, the mid-point equilibrium V_{dc1}=V_{dc2}=$V_{dc}/2$):

$$\frac{\left(s_{\alpha p} - s_{\alpha n}\right)i_\alpha + \left(s_{\beta p} - s_{\beta n}\right)i_\beta}{2} V_{dc} = \frac{C}{4}\frac{dV_{dc}^2}{dt} + \frac{V_{dc}^2}{R_L} \tag{4}$$

Ignore the loss in circuit(Equivalent resistance loss of circuit wire, IGBT switching loss, Inductance internal resistance loss and magnetic loss), left side of equation(4) is actually output power of dc side(P_{dc}):

$$P_{dc} = \frac{C}{4}\frac{dV_{dc}^2}{dt} + \frac{V_{dc}^2}{R_L} \qquad (P_{dc} = P = P_{ac}) \tag{5}$$

Based on the derivation of the power model of VIENNA rectifier, the following points can be analyzed:

(1) The active power is one-way flow from the ac side to the dc side, and the reactive power is only flowing in the ac side, in an ideal situation where the loss of the circuit is not considered, the active power of the ac side input is equal to the active power of the dc side output. At the same time, there is a coupling relationship between active power and reactive power, which is reflected in the ac input inductance;

(2) DC side capacitance does not consume power in a switching cycle, providing stable voltage and reducing the effect of output voltage ripple;

(3) The formula (5) can be found that the output side active power can be reflected by the square value of the voltage, Therefore, in designing the double closed loop control circuit and inner ring for power inner ring control, the input of the inner ring should be the output of the outer ring of the voltage multiplied by the load current value of the current moment, Therefore, the internal ring active power is given and the theoretical setting of reactive power is 0.

3. The design of a new closed-loop control system

Traditional current loop control needs to decouple current vector in dq coordinate system to improve power factor of the system. Therefore, additional use of the locking loop tracking technique is required. The direct control of power inner ring greatly simplifies inner ring structure and does not need to use phase-locked loop, so it also has good performances in dealing with unbalanced state of the three-phase power grid; The outer ring adopts voltage PI control with real-time current compensation, dynamic performance response is good and control algorithm is simple. Figure 2 is double closed loop control block diagram of VIENNA rectifier.

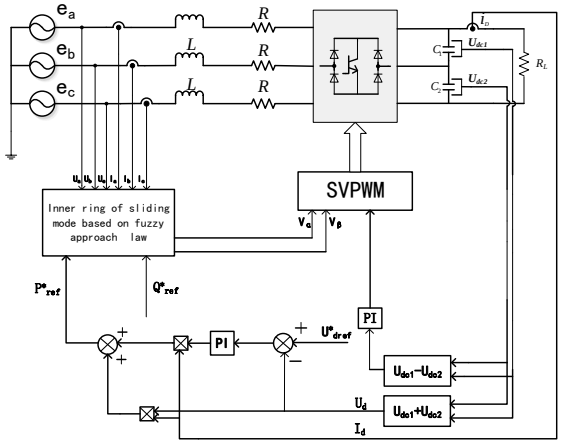


Figure 2 Double closed loop control block diagram of VIENNA rectifier

3.1 Design of sliding controller based on fuzzy approach law

3.1.1 Sliding surface selection. In the dynamic process, the sliding controller is constantly changing according to the current state of the system, the tracking error gradually converges to zero after the system reaches the sliding mode. The input of the sliding controller is the error between the current variable of the system and the ideal reference value. In VIENNA rectifier control system, the active power of inner ring should be close to ideal power P obtained through the output of the outer ring of voltage, and the reactive power value should approach ideal power Q:

$$S = \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} e_P(t) \\ e_Q(t) \end{bmatrix} = \begin{bmatrix} P_{ref} - P \\ Q_{ref} - Q \end{bmatrix} \tag{6}$$

$P_{ref} - P$ is difference value between the active power and ideal value for the inner power ring;$Q_{ref} - Q$ is difference value between the reactive power and ideal value for the inner power ring.

3.1.2 Design of sliding mode controller. The exponential approach to the law is as follows:

$$\frac{dS}{dt} = -\varepsilon sgn(S) - kS \tag{7}$$

ε>0,k>0.The rational choice of k and ε can improve the dynamic characteristics of the system and reduce the chattering phenomenon of the sliding mode controller. In equation (7), sgn(S)can be shown as:

$$sgn(S) = \begin{cases} 1 & S > \lambda \\ \frac{S}{\lambda} & -\lambda \leqq S \leqq \lambda \\ -1 & S < -\lambda \end{cases} \tag{8}$$

Take the derivative of equation (6) and bring the formula (7) into the equation:

$$\frac{dS}{dt} = \frac{d\begin{bmatrix} S_1 \\ S_2 \end{bmatrix}}{dt} = \begin{bmatrix} \frac{dS_1}{dt} \\ \frac{dS_2}{dt} \end{bmatrix} = \begin{bmatrix} \frac{d(P_{ref}-P)}{dt} \\ \frac{d(Q_{ref}-Q)}{dt} \end{bmatrix} = \begin{bmatrix} -K_1 sgn(P_{ref} - P) - K_p(P_{ref} - P) \\ -K_2 sgn(Q_{ref} - Q) - K_q(Q_{ref} - Q) \end{bmatrix} \tag{9}$$

In equation (1), the power mathematical model can be transformed into:

$$L\begin{bmatrix} \frac{dP}{dt} \\ \frac{dQ}{dt} \end{bmatrix} = \begin{bmatrix} -e_\alpha & -e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} + \begin{bmatrix} e_\alpha^2 + e_\beta^2 - RP - \omega LQ \\ -RQ + \omega LP \end{bmatrix} \tag{10}$$

The output of power inner ring controller is V_α and V_β, therefore, equation(11) can be obtained:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = -\begin{bmatrix} e_\alpha^2 + e_\beta^2 - RP - \omega LQ \\ -RQ + \omega LP \end{bmatrix}\begin{bmatrix} -e_\alpha & -e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} + L\begin{bmatrix} \frac{dS_1}{dt} \\ \frac{dS_2}{dt} \end{bmatrix}\begin{bmatrix} -e_\alpha & -e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1}$$

$$= \begin{bmatrix} \frac{e_\alpha(F_1 - DS_1) + e_\beta(F_2 - DS_2)}{e_\alpha^2 + e_\beta^2} \\ \frac{e_\beta(F_1 - DS_1) - e_\alpha(F_2 - DS_2)}{e_\alpha^2 + e_\beta^2} \end{bmatrix} \tag{11}$$

which：

$$\begin{cases} F_1 = e_\alpha^2 + e_\beta^2 - RP - \omega LQ \\ F_2 = -RQ + \omega LP \\ DS_1 = L\left(-K_1 sgn(P_{ref} - P) - K_p(P_{ref} - P)\right) \\ DS_2 = L(-K_2 sgn(Q_{ref} - Q) - K_q(Q_{ref} - Q)) \end{cases}$$

The control parameters K_1,K_2,K_p,K_q are all positive. In terms of control effect, selecting the larger K_p,K_q can improve the response speed of the system; Under the condition of system stability,

choosing the smaller K_1,K_2 can reduce the chattering phenomenon generated by the system when it enters sliding surface.

3.1.3 The design of sliding mode controller based on fuzzy approaching law. By analyzing the character of sliding mode controller and experimental data: Under the premise of stable system, the larger K_p,K_q will strengthen the robustness of the system. However, it is easy to generate large the chattering phenomenon, which is not conducive to the dynamic response of the system; On the contrary, the smaller K_p,K_q can reduce the steady state performance of the system and generate the voltage ripple, but can effectively eliminate the chattering phenomenon of the system.

In this paper, the sliding mode controller based on fuzzy approaching law was proposed. The state of sliding mode S_1 is the input of the fuzzy controller, the K_p value of response is directly estimated by the value of S_1. Based on the above ideas, a one-dimensional fuzzy controller can be established. The parameter K_p can be adjusted according to the value of S_1. The specific control block diagram is shown in figure 3.

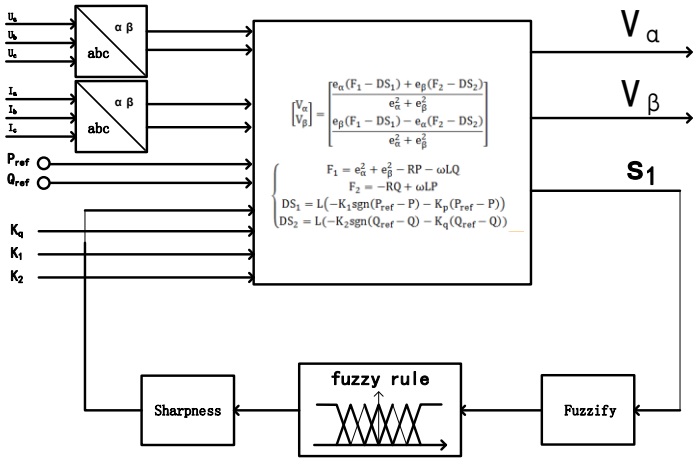
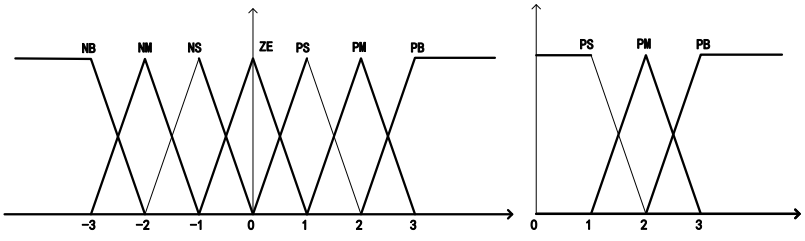


Figure 3 Fuzzy approach law control block diagram

The input variable of the fuzzy controller is S_1,the output variable of the fuzzy controller is K_p. Describe fuzzy subset of language values of input variables as {NB,NM,NS,ZE,PS,PM,PB}, describe fuzzy subset of language values of output variables as {PS,PM,PB}. Membership function curve of input variable is shown in figure 4 (a), and membership function curve of the output variable language value is shown in figure 4 (b).



(a) (b)

Figure 4 Membership function curve

When S_1 deviates from sliding mode surface large, the sliding mode control requires larger K_p to approach sliding mode surface; When S_1 deviates from sliding mode surface small , sliding mode control requires a smaller K_p to approach the sliding mode surface. Therefore, fuzzy rules are formulated as Table 1:

Table 1 Fuzzy rules

S_1	NB	NM	NS	ZE	PS	PM	PB
K_P	PB	PM	PS	PS	PS	PM	PB

3.2 Design of the voltage outer ring

The function of voltage outer ring is mainly to maintain the stability of output voltage, and provide the given active power and reactive power input for the power inner loop control. The capacitance voltage of upper and lower bridges arm were collected, and output voltage of the DC side is obtained, which entered into PI after the difference of the given stable voltage value . The output of PI link is added to the real-time current compensation to get the difference between the real-time power and the given power. The difference of power value and real-time power value can quickly obtain active power of the inner ring of the sliding mode.

4. Simulation and result analysis

In order to verify the effectiveness of dual closed-loop control strategy of VIENNA rectifier, the power electronic simulation model of VIENNA rectifier was established by matlab/simulink simulation, and the simulation analysis was carried out. The simulation parameters are as Table 2:

Table 2 simulation parameters of VIENNA rectifier

The effective value of phase voltage E_{rms}	220V/50Hz
Output bus voltage U_{dc}	750V
filter inductance L_s	0.8mH
The upper and lower bridge arm filter capacitance	$C_{dc1} = C_{dc2} = 2000\mu F$
Max output powerP_{max}	60KW

The switching frequency is 20kHz, and simulation has added mid-point balance control strategy to ensure voltage of upper and lower bridge arm capacitor equal. In outer ring of voltage, PI parameter: $K_{pu} = 4$,K_{iu}=0.02; In power inner ring:Q_{ref}=0,K_1=0.01,K_2=0.1,K_Q=10000,λ_1=λ_2=2000. In traditional double closed loop control strategy, PI parameter of voltage outer ring:$K_{pu} = 4$、K_{iu}=0.02; PI parameter of current inner ring:$K_{pi} = 0.5$,K_{ii}=0.005.

Under the three-phase unbalanced power: In MATLAB simulation, set A phase voltage phase voltage effective value is 175 v, the rest of the two phase voltage RMS voltage is 220 v. Compared with the simulation analysis of the traditional double closed loop PI control system and new double closed-loop control system, the specific simulation waveforms are shown in fig.5 (a) and fig.5 (b).

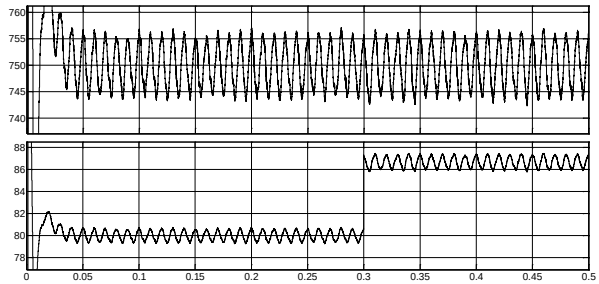


Figure 5(a) voltage and current waveform diagram of diagram traditional double closed loop PI control system

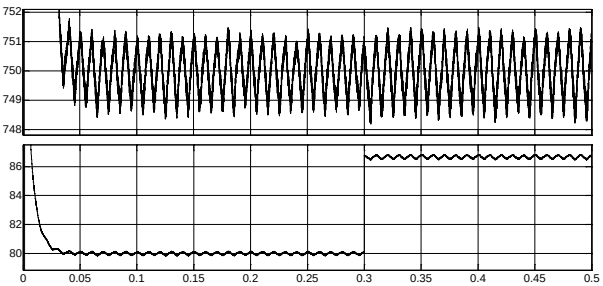
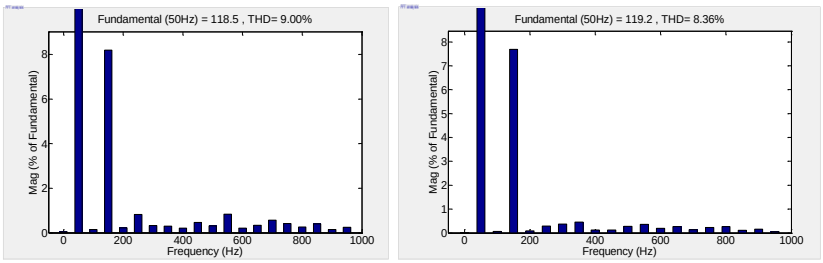


Figure 5(b) voltage and current waveform of new double closed-loop control system

In figure 5 (a), amplitude of voltage vibration is 13V under traditional double closed loop control. In figure 5 (b), voltage ripple can remain in a smaller control range, about 2.5v.



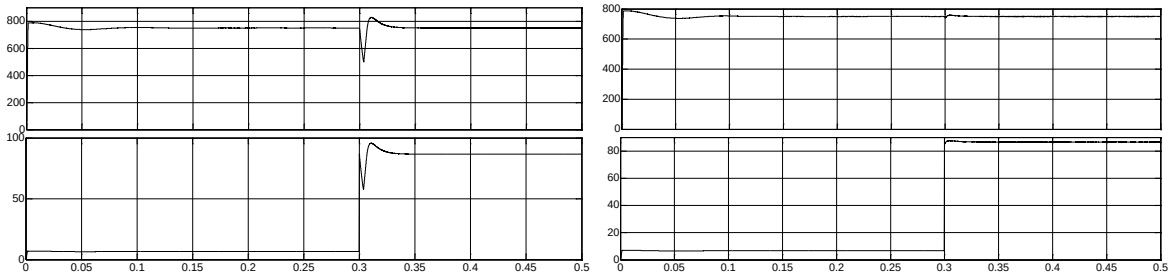
(a) (b)

Figure 6 total harmonic distortion

Figure 6 (a) and (b) are total harmonic distortion(THD)of traditional double closed-loop control strategy and new dual-closed-loop control strategy under unbalanced three-phase power grid. The new dual closed-loop control system has a better effect on harmonic suppression when three-phase power are unbalanced.

As can be seen in Figure 7(a), without using fuzzy approaching law as power inner ring, when t=0.3s, the load increased from 5KW to 65KW. Because of fast approaching speed, the system generates chattering phenomenon, which increases overshoot ,response time, and destroys dynamic response capability of system.

In Figure 7(b), with using fuzzy approaching law as power inner ring, there are no obvious overtones, and no chattering phenomenon.



（a） The inner ring of sliding mode without fuzzy approaching law **(b)**The inner ring of sliding mode with fuzzy approaching law

Figure 7 the load increased from 5KW to 65KW

5. Conclusion

The power mathematical model of the VIENNA rectifier is derived. Based on sliding mode of fuzzy approaching law, the power inner ring is designed to replace the traditional inner ring. Through matlab/simulink simulation, the simulation of the control strategy was completed and the feasibility was verified. The results show that the new double-closed-loop control strategy has better dynamic performance and steady state performance. Especially in the case of unbalanced three-phase power grid, it shows better stable output voltage and the total harmonic distortion(THD). The chattering phenomenon of the sliding mode was solved, better dynamic performance was maintained when the load was fluctuating widely.

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