Passivity-Based Control With Active Disturbance Rejection Control of Vienna Rectifier Under Unbalanced Grid Conditions

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This work was supported in part by the Beijing Natural Science Foundation under Grant 3202010/3204040, in part by the National Natural Science Foundation under Grant 51777012, in part by the Natural Science Foundation of Beijing—Education Committee Joint Funding Project under Grant KZ201911232045, and in part by the Key Science and Technology Projects of China Southern Power Grid Corporation under Grant 09900000116.

ABSTRACT In this paper, a practical passivity-based control (PBC) with active disturbance rejection control (ADRC) is proposed to improve performance of the Vienna rectifier under unbalanced grid conditions. In general, the traditional double-loop control based on positive and negative sequence transformation is used in Vienna rectifier under unbalanced grid conditions. However, it could not fundamentally solve the additional time delay caused by the second harmonic filter and loss of performance caused by a linear weighted sum of proportional integral (PI) controller. What’s more, the complexity of the controller is high for the positive and negative sequence currents need to be controlled separately. The PBC is a nonlinear controller based on energy dissipation and it has strong robustness to interference. Further, the line voltage based PBC in inner current loop can deal with the voltage unbalance effectively and easily without negative sequence transformation. To improve the disturbance rejection ability, the ADRC is applied in outer voltage loop, which could overcome PI’s drawbacks of step overshoot and slow response. Under unbalanced grid conditions, the proposed control strategy has good performance, easy implementation and less consuming time with PBC control in inner current loop, and it has strong robustness and fast track performance with ADRC control in outer voltage loop. The detailed mathematical model, control principle and controller design of the Vienna rectifier are thoroughly analyzed. In addition, simulation results based on SIMULINK are also given in the paper. Finally, a downsized 5kW Vienna rectifier prototype is built to validate the correctness and effectiveness of the proposed strategy.

INDEX TERMS Active disturbance rejection control, passivity-based control, unbalanced grid condition, Vienna rectifier.

I. INTRODUCTION

The Vienna rectifier, which was proposed by Johann W. Kolar in 1997, needs only one power switch in one phase, which has no dead time effect and shares only half of the dc voltage stress. What’s more, it can realize perfect sinusoidal current and unity power factor with high reliability and high power-density. Thus, it is widely applied in the unidirectional rectifier, such as active power filter, power factor correction, communication power supply, uninterrupted power supply, electric vehicle charging and new energy power generation [1], [2].

A voltage unbalance often happens in the power system because of unbalanced load or nonlinear load. Here voltage unbalance means unequal voltage magnitudes at the fundamental frequency (under-voltages or over-voltages), harmonic distortion and dc offset injection. In other words, the three-phase voltages are not sinusoidal or unequal in magnitude. According to [3], the voltages unbalance factor of many grids exceeds 3% in the U.S. But the grid voltage
unbalance factor must be less than 2% during a long period of time according to the IEC standard. Excessive voltage unbalance can lead to Vienna rectifier disturbance such as over current, over temperature, output voltage fluctuation and so on. It may even cause the Vienna rectifier to fail to work normally [4]–[6].

In general, the Vienna rectifier is controlled as a positive sequence voltage source [7]–[9], and it works normally under balanced grid conditions. Unfortunately, the control technique of the Vienna rectifier faces the challenge for the negative sequence current, which will be generated under unbalanced grid conditions and threatens the safe operation of the Vienna rectifier. Usually, positive and negative sequence transformations are used in traditional current controllers to detect positive and negative sequence currents. And then two currents controllers are used to regulate the positive and negative currents respectively [10], [11]. Although the sequence currents controllers are effective under unbalanced grid conditions, the controllers suffer from additional time delay caused by second harmonic filter, they are more complex because of the need to calculate and control multi parameters, and they are also easily affected by high order harmonics [12]–[14].

Normally, a double-loop based control strategy is used in Vienna rectifier system, which consists of an outer voltage loop and an inner current loop. For inner current loop, a proportional integral (PI) control is initially used, but it is difficult to realize desired performance for the nonlinear Vienna rectifier [15]. The proportion resonant (PR) control can provide fast dynamic response with high stability, but it is too complex to implement in application [16], [17]. The hysteresis control (HC) and direct power (DP) control have simple control structures and fast dynamic responses, but their switching frequencies are not constant, and it is difficult to design their filters [18], [19]. The predictive control (PC) can eliminate forecast error and minimize resonant behavior, but it has the disadvantage of high sensitivity to parameters and heavy computation burden in application [20]. The dead beat (DB) control is one of predictive controls, and it has fast voltage and current regulation capability, but it also puts forward high requirements for the controller performance [21].

For outer voltage loop, a PI controller is normally used, but it has some weakness such as performance loss in the form of a linear sum and complications brought by the integral control. In this paper, an active disturbance rejection control (ADRC) controller is used in the outer voltage loop to guarantee fast tracking and robustness of the system, line voltages based passivity-based control (PBC) controller is used in the inner current loop to guarantee stability and dynamic performance of the system under unbalanced conditions, and the PBC with ADRC control strategy is thoroughly discussed.

The PBC strategy, which was proposed by R. Ortega and M. Spong in 1989 [22], is a nonlinear control based on energy dissipation, it utilizes energy dissipation to control stability and track given object by means of damping injection. PBC has strong robustness to system parameters deviation and external interference, and it is easily designed and controlled in application. In the electrical application, PBC is used in power conversion system, rectifier, photovoltaic inverter, motor drive, static synchronous compensator, dynamic voltage restorer and dc-dc converter [23]–[27]. Compared with linear control and other nonlinear control strategies, line voltages based PBC control strategy in inner current loop can be easily designed and realized, and be expected to improve Vienna rectifier’s static and dynamic performance under unbalanced grid conditions.

The ADRC strategy, which was proposed by J. Han in 1980s [28], is a nonlinear robust control strategy, it is driven by estimation error and tracking error, and it can actively estimate and compensate internal dynamic changes and external disturbances in real time. In the electrical application, ADRC is used in dc-dc converter, gyroscopes, permanent magnet synchronous motor and flywheel energy storage system [29]–[32]. Compared with PI control strategy, ADRC control strategy in outer voltage loop is expected to provide the desired current for the inner current loop and improve Vienna rectifier’s strong robustness and fast track performance.

In the study, a practical PBC with ADRC control strategy is proposed to improve performance of the Vienna rectifier under unbalanced grid conditions. The Vienna rectifier topology is analyzed thoroughly, and the line voltage based mathematical model in Euler Lagrange (EL) form is deduced. In addition, the passivity characteristic of Vienna rectifier is demonstrated, and the implementation differential equations are given. Further, a PBC with ADRC based controller is designed. Besides, the simulation verification based on SIMULINK is carried out, and the downsized 5 kW prototype experiments further verify the proposed control strategy for Vienna rectifier. The rest of this study is organized as follows. In Section II, the Vienna rectifier topology is introduced and analyzed thoroughly. In Section III, the mathematical model based on EL equation is proposed. In Section IV, the PBC with ADRC based controller is designed according to the EL model. Later in Section V and VI, the results of simulation and prototype experiment are given separately. Finally, Section VII concludes the study.

II. VIENNA RECTIFIER TOPOLOGY ANALYSIS

A. VIENNA RECTIFIER TOPOLOGY

The Vienna rectifier is made up of \( L, R, SW_i, VD_{i1}, \) and \( VD_{i2} \) \((i= a, b, \) and \( c)\), as depicted in the Fig. 1. Where \( L \) and \( R \) are lumped inductor and equivalent resistor, respectively. \( SW_i \) is phase \( i \) bidirectional power switch. \( VD_{i1} \) and \( VD_{i2} \) are phase \( i \) power diodes.

B. VIENNA RECTIFIER PRINCIPLE

It is assumed that all the components are ideal. Taking the phase \( i \) for example, when the power switch
SW_i is on, the phase i is clamped to the dc midpoint (point O), and the Vienna ac voltage is equal to 0. When the power switch SW_i is off and the phase current is in positive direction, the power diode VD_i will be on and the Vienna ac voltage is equal to v_{dc1}. When the power switch SW_i is off and the phase current is in negative direction, the power diode VD_i will be on and the Vienna ac voltage is equal to -v_{dc2}. If defining the switching function as S_i, S_i can describe the Vienna rectifier states exclusively.

\[ S_i = \begin{cases} +1 & \text{SW}_i = 0, \ i > 0 \\ 0 & \text{SW}_i = 1, \ i = a, b, c \\ -1 & \text{SW}_i = 0, \ i < 0 \end{cases} \]  

(1)

According to modulation principle and KCL, the Vienna rectifier ac and dc voltages can be expressed as,

\[
\left\{ \begin{array}{l}
v_{ri0} = \frac{S_i v_{dc}}{2} [1 + \text{sgn}(i) \frac{\Delta v_{dc}}{v_{dc}}] \\
C \frac{dv_{dc}}{dt} = \frac{1}{2} \sum_{i=a,b,c} S_i i - v_{dc} \frac{R_i}{R_L} \\
C \frac{d\Delta v_{dc}}{dt} = \frac{1}{2} \sum_{i=a,b,c} \text{sgn}(i) i_i 
\end{array} \right.
\]  

(2)

where \( v_{ri0} \) is the Vienna rectifier ac voltage, \( v_{dc} \) and \( v_{dc} \) are the sum and difference voltages between the upper and lower capacitors, respectively, i.e., \( v_{dc} = v_{dc1} + v_{dc2} \) and \( v_{dc} = v_{dc1} - v_{dc2} \). \( \text{sgn}(x) \) is a sign function, when \( x \geq 0 \), \( \text{sgn}(x) \) is equal to 1, and when \( x < 0 \), \( \text{sgn}(x) \) is equal to -1. It is assumed that the dc capacitor voltages are absolutely balanced due to voltage balance control, then we can get,

\[
\left\{ \begin{array}{l}
v_{ri0} = \frac{S_i v_{dc}}{2} i = a, b, c \\
C \frac{dv_{dc}}{dt} = \frac{1}{2} (S_ai_a + S_bi_b + S_ci_c) - \frac{v_{dc}}{R_L} 
\end{array} \right.
\]  

(3)

III. VIENNA RECTIFIER MATHEMATICAL MODEL

A. ABC COORDINATE MODEL

According to KVL, the Vienna rectifier ac voltages and currents can be expressed as,

\[
\begin{align*}
L \frac{di_a}{dt} + R_{ia} + v_{rao} + v_{ON} &= v_a \\
L \frac{di_b}{dt} + R_{ib} + v_{rbo} + v_{ON} &= v_b \\
L \frac{di_c}{dt} + R_{ic} + v_{rco} + v_{ON} &= v_c
\end{align*}
\]

(4)

where \( v_{ON} \) is the potential difference between dc midpoint (point O) and the ac midpoint (point N).

Considering that \( i_a + i_b + i_c = 0 \) all the time, we can further get,

\[
\begin{align*}
3L \frac{di_a}{dt} + 3R_{ia} + \frac{v_{dc}}{2} (S_{a} - S_{ca}) &= v_{ab} - v_{ca} \\
3L \frac{di_b}{dt} + 3R_{ib} + \frac{v_{dc}}{2} (S_{b} - S_{ab}) &= v_{bc} - v_{ab} \\
3L \frac{di_c}{dt} + 3R_{ic} + \frac{v_{dc}}{2} (S_{c} - S_{bc}) &= v_{ca} - v_{bc}
\end{align*}
\]

(5)

where \( v_{ab}, v_{bc}, v_{ca}, S_{ab}, S_{bc}, \) and \( S_{ca} \) are the line voltages and line switching functions, respectively.

Combining (3), (4), and (5), we can further get,

\[
\begin{align*}
L \frac{di_a}{dt} + R_{ia} + \frac{v_{dc}}{2} (S_{a} - \Delta S) &= v_a - \Delta v \\
L \frac{di_b}{dt} + R_{ib} + \frac{v_{dc}}{2} (S_{b} - \Delta S) &= v_b - \Delta v \\
L \frac{di_c}{dt} + R_{ic} + \frac{v_{dc}}{2} (S_{c} - \Delta S) &= v_c - \Delta v
\end{align*}
\]

(6)

where \( \Delta S \) and \( \Delta v \) are defined zero sequence switching function and zero sequence voltage, respectively.
Then the potential difference \(v_{ON}\) can be described as,

\[
\begin{align*}
\Delta v & = \frac{1}{2} (v_d + v_b + v_c) \\
\Delta S & = \frac{1}{3} (S_a + S_b + S_c)
\end{align*}
\]

(7)

**B. DQ COORDINATE MODEL**

To make the Vienna rectifier operate stably, the synchronous rotation coordinate is adopted. The currents, line voltages, and line switching functions are transformed as follow,

\[
T_1 = \frac{2}{3} \begin{pmatrix} \cos(\omega t) & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\
-\sin(\omega t) & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \end{pmatrix}
\]

(8)

\[
T_2 = \frac{2}{3} \begin{pmatrix} \cos(\omega t + \pi/6) & \cos(\omega t - \pi/2) & \cos(\omega t + 5\pi/6) \\
-\sin(\omega t + \pi/6) & -\sin(\omega t - \pi/2) & -\sin(\omega t + 5\pi/6) \end{pmatrix}
\]

(9)

where \(i_d, i_q, v_d, v_q, S_d,\) and \(S_q\) are dq coordinate currents, line voltages and line switching functions, respectively. \(T_1\) and \(T_2\) are the transformation matrices from abc coordinate to dq coordinate. Combining (6), (8), and (9), we can further get,

\[
\begin{align*}
L \frac{di_d}{dt} + Ri_d - \omega L i_q + \frac{\sqrt{3}}{6} S_d v_{dc} & = \frac{v_d}{\sqrt{3}} \\
L \frac{di_q}{dt} + \omega L i_d + Ri_q + \frac{\sqrt{3}}{6} S_q v_{dc} & = \frac{v_q}{\sqrt{3}} \\
2C \frac{dv_{dc}}{dt} - \frac{\sqrt{3}}{6} S_d i_d - \frac{\sqrt{3}}{6} S_q i_q + \frac{2}{3R_d} v_{dc} & = 0
\end{align*}
\]

(10)

**C. EULER LAGRAN MODEL**

We can further get the mathematical model of the Vienna rectifier in EL form,

\[
M \ddot{x} + JX + RX = V
\]

(11)

where \(M\) is a positive definite symmetric coefficient matrix, i.e. \(M^T = M\). \(J\) is an anti-symmetric coefficient matrix, i.e. \(J^T = -J\). \(R\) is a positive coefficient matrix, i.e. \(R^T = R\), and it satisfies \(R > 0\), which means that the converter has dissipative character. \(X\) is the state variable vector, and \(V\) is the control input variable vector.

\[
M = \begin{pmatrix} L & 0 & 0 \\
0 & L & 0 \\
0 & 0 & 2C/3 \end{pmatrix}, \quad R = \begin{pmatrix} R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & 2/3R_L \end{pmatrix},
\]

(12)

\[
J = \begin{pmatrix} i_d \\
i_q \\
v_{dc} \end{pmatrix}, \quad V = \begin{pmatrix} v_d \\
v_q \\
0 \end{pmatrix}
\]

(13)

**IV. PBC WITH ADRC CONTROLLER DESIGN**

**A. INNER LOOP PBC CURRENT CONTROL**

The PBC control object is that \(X\) converges to \(X^* = (i_d^* i_q^*)^T\), and the error vector \(X_e = X - X^*\) converges to 0, where \(i_d^*, i_q^*\), and \(v_{dc}\) are ac currents and dc voltage variables, respectively. In order to accelerate \(X_e\) converges to 0, the damping injecting matrix \(R_d = \text{diag}(r_{11} r_{12})\) is used, where \(r_{11}\) and \(r_{22}\) are positive damping coefficients. And the mathematical module with state vector \(X\) can be further described by the module with error vector \(X_e\) as,

\[
M \ddot{X}_e + (R C R_d) X_e = V - (M \dddot{X}^* + JX + RX - R_d X_e)
\]

(16)

And the line voltages based PBC control equation can be selected as,

\[
V = M \dddot{X}^* + JX + RX - R_d X_e
\]

(17)

According to (10) and (17), we can get the Vienna rectifier PBC control equations as,

\[
\begin{align*}
S_d = v_d - \sqrt{3} \left[ L \frac{du_d^*}{dt} + Ri_d - \omega L i_q - R_{11}(i_d - i_d^*) \right] \\
S_q = v_q - \sqrt{3} \left[ L \frac{du_q^*}{dt} + Ri_q + \omega L i_d - R_{11}(i_q - i_q^*) \right]
\end{align*}
\]

(18)
And then we can further get the line and phase switching function as,

$$\begin{bmatrix} S_{ab} \\ S_{bc} \\ S_{ca} \end{bmatrix} = T_2^{-1} \begin{bmatrix} S_d \\ S_q \end{bmatrix},$$

$$\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} S_{ab} \\ S_{bc} \\ S_{ca} \end{bmatrix}$$

$$\Delta S = \frac{2\Delta v}{v_{dc}}$$

2) DESIGN OF ESO

An ESO module can realize the real-time dc voltage estimation, and the inputs of ESO are input and output of Vienna rectifier, i.e. the $d$ axial current reference $i_d^*$ and dc voltage $v_{dc}$, the outputs of ESO are estimated state and expanded state. The implementation process of ESO is shown as,

$$\begin{cases} e = z_1 - v_{dc} \\ \dot{z}_1 = z_2 - \beta_1 \text{fal}(e, \alpha_2, \delta_2) + bi_d^* \\ \dot{z}_2 = -\beta_2 \text{fal}(e, \alpha_3, \delta_3) \end{cases}$$

where $z_1$ and $z_2$ are the real-time estimation value and the expanded state value, respectively. $e$ is the error between output estimation and input signal. $b$ is a feedback coefficient of the ADRC output. $\beta_1$ and $\beta_2$ are weight coefficients, and $\text{fal}(\cdot)$ is a non-linear smooth function, and its definition is,

$$\text{fal}(e, \alpha, \delta) = \begin{cases} e^{\alpha}, & e > \delta \\ \frac{e^{\delta} - 1}{\delta^{1-\alpha}}, & |e| < \delta \\ -(e^{\alpha}), & e < -\delta \end{cases}$$

where $\alpha$ is a tracking coefficient, which ranges from 0 to 1, and the smaller the tracking coefficient, the faster the tracking speed. $\delta$ is a filter effect coefficient, and the greater filter effect coefficient, the better the filter effect, but the tracking delay time will be increased, so a suitable filter effect coefficient should be selected in the application.

3) DESIGN OF NLSEF

The output of NLSEF is determined by the difference between the reference estimated value and the actual estimated value, i.e.,

$$\begin{cases} e_1 = x_1 - z_1 \\ i_d^* = \beta_3 \text{fal}(e_1, \alpha_4, \delta_4) - \frac{z_2}{b} \end{cases}$$

where $\alpha_4$ and $\delta_4$ are tracking coefficient and filter effect coefficient, respectively, and $\beta_3$ is a weight coefficient.

C. DC BALANCE IMPLEMENTATION

In the previous analysis, it is assumed that the voltages of the upper and lower capacitors are completely balanced, but in fact some dc voltage balance control must be adopted to balance the voltages of the upper and lower capacitors. The zero-sequence voltage injection scheme is used in the study, and the injected voltage can be selected as,

$$v_{zsv} = \text{sgn}(-i_i\Delta v_{dc} C)\Delta v_{dc} C, \quad i = a, b, c$$

where $v_{zsv}$ is the zero-sequence voltage, $\text{sgn}(x)$ is a sign function, when $x \geq 0$, $\text{sgn}(x)$ is equal to 1, and when $x < 0$, $\text{sgn}(x)$ is equal to 0. It can be seen that only when the current direction isn’t consistent with dc voltage difference’s polarity, the zero-sequence voltage is injected, and the magnitude of the zero-sequence voltage is decided by dc voltage difference and capacitance value. Then the Vienna rectifier ac voltages...
can be got, and modulated according to space vector modulation or sinusoidal pulse width modulation to drive the power switches $SW_a$, $SW_b$, and $SW_c$.

$$v_{r_{io}} = \frac{S_i v_{dc}}{2} + v_{2sni}, \quad i = a, b, c \quad (26)$$

The ADRC control is used in outer voltage loop to generate active reference current $i_d^*$, and the line voltage based PBC control is used in inner current loop to get output voltage reference $v_{r_{io}}$. The PBC with ADRC control diagram of the Vienna rectifier is illustrated in the Fig. 3.

### V. SIMULATION VERIFICATION

To verify the proposed PBC with ADRC control strategy, simulations under balanced and different unbalanced grid conditions are carried out in SIMULINK. The main circuit parameters of the Vienna rectifier are shown in Table 1, and the control coefficients are listed in the Table 2.

#### A. BANLANCED GRID SIMULATION

In the Fig.4, the three-phase grid has balanced voltages with perfect sinusoidal waves, same amplitude and same phase difference. The Vienna rectifier currents are also balanced with perfect sinusoidal waves, same amplitude and same phase difference, and the currents are in phase with their corresponding voltages. The dc voltage is always stable at 800V, and the upper and lower capacitors share the same voltage. It proves that the proposed PBC with ADRC control strategy can operate the Vienna rectifier stably with unity power factor and low total harmonic distortion (THD) under balanced grid condition.
B. UNBALANCED GRID SIMULATION

In the Fig. 5, voltages and currents waveforms under different unbalanced grid conditions are shown. In the Fig. 5a, the three-phase grid has balanced voltages at first. At the time $t_1$, there is a voltage drop of phase A from 220V to 110V, the Vienna rectifier currents are still balanced perfect sinusoidal waves, and the currents amplitudes increase gradually, and the currents are still in phase with corresponding voltages. At the time $t_2$, the voltage of phase A returns to the normal value, and the Vienna rectifier currents restore to the original values gradually. In the transient process, there are some dc voltage fluctuations, and the transient time is less than 0.02s.

In the Fig. 5b., the three-phase grid has balanced voltages at first. At the time $t_3$, the fifth harmonic voltages, whose amplitudes are 10% of the fundamental voltage amplitudes, are injected to the voltages of phase A, B, and C respectively. Then, the Vienna rectifier currents are consistently balanced perfect sinusoidal waves without harmonics, phase shift and amplitude change. At the time $t_4$, the fifth harmonic voltages are reset to 0, and the Vienna rectifier currents have no obvious change. In the transient process, the dc voltages have no any obvious changes, and it means that the grid harmonics have no influence to the Vienna rectifier.

In the Fig. 5c, the grid voltages are balanced at first. At the time $t_5$, the positive dc offset, whose amplitude is 20% of the fundamental voltage amplitudes, is injected to voltage of phase A. Then, the Vienna rectifier currents are consistently balanced perfect sinusoidal waves without dc offset, phase shift and amplitude change. At the time $t_6$, the dc offset is reset to 0, and the Vienna rectifier currents have no obvious change. In the transient process, the dc voltages have only very small fluctuations.

From the simulation results, we conclude that in whether voltage drop, harmonic injection or dc offset unbalanced grid conditions, the proposed PBC with ADRC control strategy can operate Vienna rectifier stably with high power quality and good output performance, the grid currents are always balanced perfect sinusoidal waves with unity power factor and low THD, and the output voltage is always stable at the set value.

C. ADRC SIMULATION

DC voltages waveforms in PI and ADRC control are shown respectively in Fig. 6. At the time $t = 0$, the main circuit breaker is switched on, the power supply is starting to charge the dc capacitor, the dc voltages increase gradually, and the output voltage reaches 360V ultimately. At the time $t = 0.1s$, the soft start resistor is bypassed, the dc voltages increase rapidly, and the output voltage reaches 515V finally. At the time $t = 0.2s$, the controller is starting to operate, and the output voltage begins to increase and be stabilized at 800V after a period of transient time. It can be seen that the PI control has about 0.07s response time with voltage overshoot of 100V, but the ADRC control has only 0.03s response time without voltage overshoot. And it shows that the ADRC control has better performance compared with the PI control.

VI. EXPERIMENTAL VERIFICATION

In order to further verify the effectiveness of the proposed PBC with ADRC control strategy, a downsized 5 kW Vienna
rectifier prototype is built, as shown in Fig. 7. The main circuit parameters are shown in Table 3, experiments of balanced grid condition and various unbalanced grid condition are also carried out in the prototype.

Fig. 8 gives voltages and current waveforms of the Vienna rectifier under balanced grid condition. The proposed PBC with ADRC strategy can operate the Vienna rectifier stably with perfect sinusoidal current and unity power factor, and stabilize output voltage to drive the load at the same time.

In the Fig. 9a, at the first, the Vienna rectifier operates stably under balanced grid condition. At the time \( t_1 \), there is a voltage drop of phase B from 87V to 40V, i.e. the line voltages \( v_{ab} \) and \( v_{bc} \) change from 150V to 120V, and the line voltage \( v_{ca} \) has no change. It can be seen that the phase current \( i_b \) increases gradually with perfect sinusoidal wave and no phase angle shift. In the Fig. 9b, at the time \( t_2 \), the voltages restore to balanced grid condition, and the phase current \( i_b \) decreases gradually with perfect sinusoidal wave and no phase angle shift. In all these transient processes, the output voltage remains constant to drive the load all the time, and the grid currents are consistently perfect sinusoidal waves with unity power factor.

In the Fig. 10a, at the first, the Vienna rectifier operates stably under balanced grid condition. At the time \( t_3 \), the fifth harmonic voltage, whose amplitude is 20% of the fundamental voltage amplitude, is superposed to voltage of phase B, the THD of line voltages \( v_{ab} \) and \( v_{bc} \) increase, and the THD of line voltage \( v_{ca} \) has no change. It can be seen that the phase currents \( i_a \) and \( i_b \) increase gradually with no fifth harmonic, no phase angle shift and no obvious current THD increase, and the Vienna rectifier currents are also balanced all the time. In the Fig. 10b, at the time \( t_4 \), the fifth harmonic voltage is reset to 0, and the grid voltages have 90°-lead angle shifts at the same time. It can be seen that the phase currents \( i_a \) and \( i_b \) have also 90°-lead angle shifts, the Vienna rectifier currents enter steady state after about 38ms transient process, and the currents begin to increase gradually. In the transient process, the Vienna rectifier currents are always controlled within the rated current range without overcurrent.
And it validates that the proposed solution has not only good steady state performance, but also good transient process performance.

In the Fig. 11a, the Vienna rectifier operates stably under balanced grid condition at first. At the time $t_5$, the dc offset of 25V is superposed to phase B voltage, the line voltage $v_{ab}$ has a negative shift, and the line voltage $v_{ca}$ has no change. It can be seen that the Vienna rectifier currents $i_a$ and $i_b$ are balanced all the time without obvious amplitude change and phase angle shift. In the Fig. 11b, at the time $t_6$, the dc offset is reset to 0, and the Vienna rectifier currents are also balanced all the time without obvious amplitude change and phase angle shift.

From the experimental results, we conclude that the proposed solution can ensure the Vienna rectifier’s stable operation with good output performance and high power quality under whatever balanced grid condition or various unbalanced grid conditions, which includes voltage drop, harmonic distortion and dc offset injection. The experimental results give strong support to the analysis above given and strengthen the simulation results.

VII. CONCLUSION

This study proposes a practical control strategy based on PBC with ADRC for the Vienna rectifier. The proposed control strategy adopts line voltage based PBC in inner current loop and ADRC in outer voltage loop, there is no need of negative sequence transformation, harmonic and dc elements detection under unbalanced conditions, there is only need of instantaneous voltages and currents detections and controls, and the control strategy has the advantage of easy implementation, less consuming time, good performance, strong robustness and fast track performance.

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