An Improved Burst-Mode Control for VIENNA Rectifiers to Mitigate DC Voltage Ripples at Light Load

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***Abstract*—Due to the unidirectional conduction of the diode, a VIENNA rectifier will be operated at over-voltage-protection (OVP) mode as long as the load is light enough. And the output voltage is usually used as the trigger variable in the existing burst-mode control to hold the output, which inducing a very large voltage ripple, otherwise the double line frequency pulsation may lead to false trigging. An improved burst-mode control is proposed with analyzing the dual loop control principle of the rectifier in *dq* frame in detail, where the output of the voltage regulator is employed as the trigger. The control proposed leads to greatly reduced output voltage ripple of the rectifier and works well under grid distortion. Experimental and simulation results are given to verify the effectiveness and advantages of the proposed method.**

Keywords—VIENNA rectifier; light load; improved burst-mode control; output ripples

I. INTRODUCTION

VIENNA rectifier has witnessed a rapid deployment in recent years in telecommunication power supplies, EV chargers, welding power supplies, as well as many types of industrial power supplies due to its remarkable merits such as high efficiency and high-power density, low voltage stresses, low cost and less EMI issue [1-2]. However, when it operates at light load conditions, the inductor currents could fall to zero and enter to a discontinuous operating region due to the unidirectional feature of diodes, which will result in severely distorted input currents and thus high THD.

To mitigate the issue at light load operations, several control methods have been proposed in recent years. In [3], a discontinuous conduction mode (DCM) control method is proposed to realize sinusoidal input currents control. But, the peak and RMS current of DCM are higher than CCM. In order to decrease the peak and RMS current, an improved boundary conduction mode (BCM) control method is presented in [4]. However, both of the two methods need a heavy calculation burden. Transition between the light load and the heavy load is not smooth due to different modulation strategies. Another control method in [5], introducing an adaptive controller, can also correct power factor under light load. Three additional adaptive controllers are needed, which will take up a lot of DSP resources. In addition, the adaptive controller's parameters are difficult to design, usually obtained by simulation or experimental test.

Especially, due to the unidirectional conduction of diodes, when the load is pretty low, the output DC voltage will further increase and exceeds the reference voltage, which will have some potential threats to the operation safety of the power devices due to their high voltage stresses [6]. Burst mode control is a straightforward solution to resolve this issue [7-8]. As for the burst mode, usually a hysteresis control is employed to charge and discharge the output DC link capacitors, resulting in large DC link ripples. Anyway, large output ripples will be introduced by this conventional burst-mode control method and have an adverse effect on voltage ratings of both active power devices and reactive components, as well as the overall efficiency.

In order to mitigate the adverse effect resulting from high DC ripples when operating at burst mode under light load, in this paper, an improved burst mode control method for light load is proposed. By analyzing the dual loop control scheme in dq frame, the voltage regulator and current controller are saturated when the load is pretty low. Therefore, both of the two regulators' output can be used to improve the burst-mode control. After contrast, the method, using the output of voltage regulator as the judgment basis of burst-mode region, can achieve a better control effect and not be affected by grid distortion. Finally, the effectiveness and advantages of the proposed method are verified by experiment.

II. BASIC STRUCTURE AND CONTROL OF VIENNA RECTIFIER

A three-phase VIENNA rectifier is illustrated in Fig. 1, consisting of a three-phase filter in grid side, two split DC link capacitors connected in series, six diodes and three bidirectional switches configured by two back-to-back MOSFETS. Generally, dual loop control scheme in dq frame is employed in VIENNA rectifier as illustrated in Fig. 2.

The outer loop is DC voltage regulator, which is used to control the output DC voltage, and is designed to generate the d-axis reference current. And the inner loop aims at controlling the input current to follow its reference and correct the power factor. In order to reduce the influence of the grid harmonics and distortion, the voltage feedforward control

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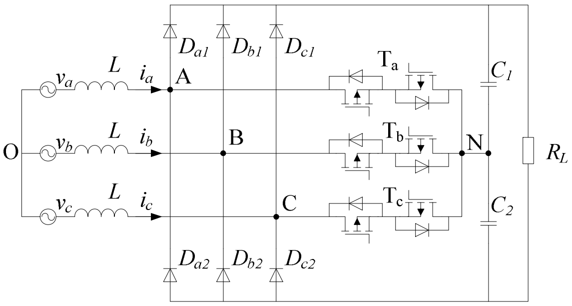


Fig. 1 Topology of VIENNA rectifier

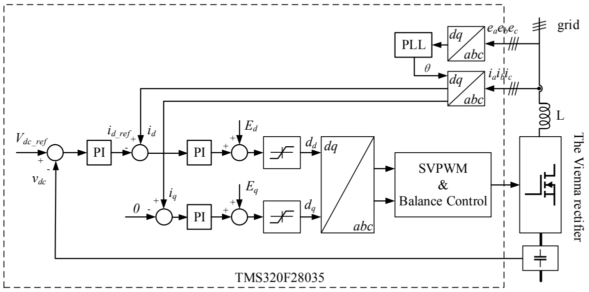


Fig. 2 Basic control system of VIENNA rectifier under DQ synchronous frame

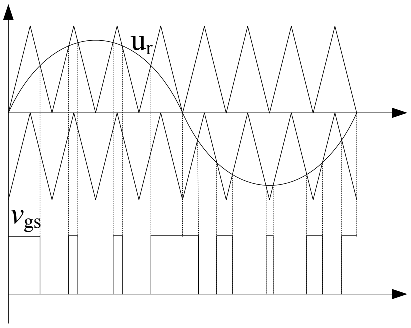


Fig. 3 Carrier cascading principle of three-level system

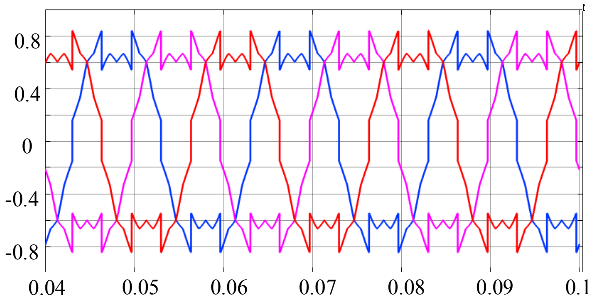
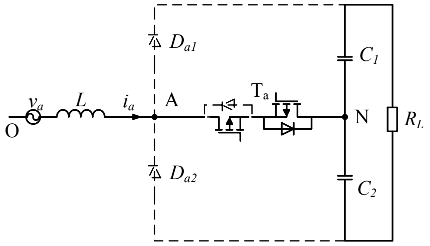


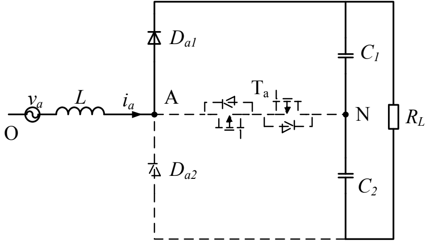
Fig. 4 Modulation waveforms after injecting zero-sequence component

method is employed.

This paper adopts a simplified SVPWM algorithm, injecting a particular zero-sequence component into the three-phase sinusoidal duty cycles, discussed in detail in [9]- [11]. It is essentially a kind of three-level carrier-based cascaded PWM method, as shown in Fig. 3 and Fig. 4.



(a) inductor charging stage



(b) inductor discharging stage

Fig. 5 switching state of single phase

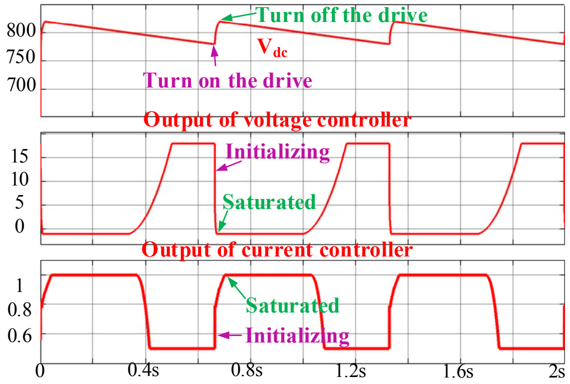


Fig. 6 Key waveforms of the conventional burst-mode control

III. CONVENSIONAL BURST-MODE CONTROL METHOD AND EXISTING PROBLEM

Due to the unidirectional conduction of the diode, the energy can only be transmitted from grid side to DC side. The switching state of single phase in positive half cycle is shown in Fig. 5.

The inductor current will increase when the switches are on, and decrease when the switches are off. It can be seen that the energy will be transmitted to the DC side. When the load is low enough, the input energy transmitted to the DC side will be greater than the energy consumed by load, that will cause the increasing of DC voltage, and eventually, trigger the over-voltage protection.

In order to mitigate the issue, an upper limit for the output voltage is set to turn off drive at either a light load or no load. A lower limit for the output voltage and a delay signal in turn enable the burst mode of the DCM PFC. However, when the upper and lower limits get close to the reference voltage, the sampling noise will lead to false trigging. Due to the unbalance of grid, double-line frequency pulsation exists and may also trigger OVP. Therefore, the upper and lower limits cannot get too close to the reference voltage and lead to large ripples.

Fig. 6 depicts the key waveforms of burst mode operations. When the output voltage drops to its lower bound V_L, the controller is enabled and thus the converter starts to transfer energy to the output and brings V_o up. Once Vo rises to its upper limit V_H, the controller is disabled and there are no gating signals. The load power is solely provided by the output energy storage elements. And the power consumption is mainly contributed by the enabled controllers.

Apparently, the conventional burst-mode method can limit the DC voltage and avoid damaging the devices. But it is obvious that the voltage ripple is the range of the DC voltage hysteresis. Therefore, the ripple is large and may have adverse effects on load or the design of DC/DC converters following VIENNA rectifier.

IV. IMPROVED BURST-MODE CONTROL METHOD AT LIGHT LOAD

To mitigate the output ripples introduced by conventional burst-mode control, a low-pass filter and an error amplifier are needed to filter the sampling noise and enlarge the error of output voltage. At light load, the error amplifier will easily get saturated, that can be used to realize the burst-mode control and helpful with reduce the output ripples. The classic proportional integral (PI) controller can be recognized as an error amplifier and low-pass filter, which can be seen from it bode diagram shown in Fig. 7. As shown in Fig. 2, the conventional control loop has two PI controllers, which can be used to realize burst-mode control.

At light load, the output of voltage control loop, which is used as active reference current, will decrease until lower than zero, due to the effect of the voltage PI controller. The effect of active current control loop will cause that the output of the current PI controller, which is used as d-axis duty cycle, gets to the saturation point. The active process at light load is shown as follows:

$$\begin{gathered} v_{dc} > V_{dc\_ref} \rightarrow I_{dref} \downarrow \rightarrow I_{dref} = I_{dref\_\min} \\ \rightarrow d_d \uparrow \rightarrow d_d = d_{d\_\max} \end{gathered} \tag{1}$$

Both of the voltage and current controller will be saturated under light load. From Fig. 6, it can be seen that when working in conventional burst mode, both the outputs of the voltage and d-axis current controller get saturated and their ripples are large.

But at normal load, both the output of voltage PI controller (I_{dref}) and the output of d-axis current controller (d_d) will not get saturated. It is obvious that both of I_{dref} and d_d can be used to realize burst-mode control method.

A. *Using the output of active current controller to realize burst-mode control*

According to the analysis above, the inner d-axis current controller will be saturated at light load. In addition, when the phase RMS voltage is higher than $1/\sqrt{3}$ times of the DC voltage, the inner active current controller will also get into the over-modulation region and have an adverse effect on the system. The drive should also be turned off. Therefore, the output of active current controller can also be used to realize burst-mode control.

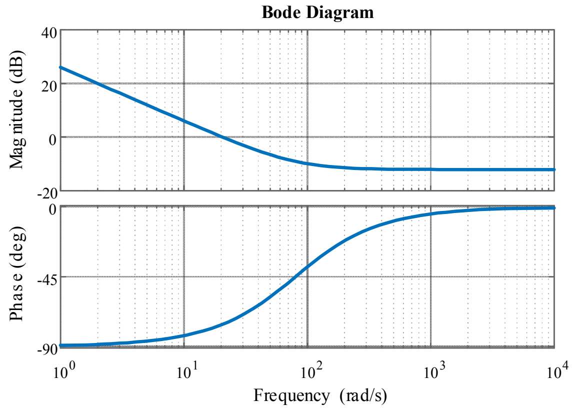


Fig. 7 Bode diagram of PI controller

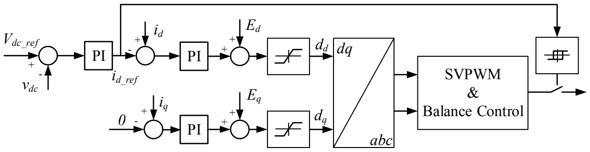


Fig. 8 Block diagram of proposed method

When grid has a serious distortion, the current controller will temporarily get saturated because of the voltage feed-forward control. And then the drive will be turned on by mistake, that will cause the DC voltage increasing and may trigger the over-voltage protection.

On the other hand, when grid is unbalance, this method needs to consider both the positive and negative components and becomes more complex.

B. *Using the output of voltage regulator to realize burst-mode control*

Usually, the output of the DC voltage control loop is used as d-axis active reference current, which reflects the size and direction of energy needed to be transmitted to the DC side. Under light-load, the active reference current will decrease until less than zero. This means that the energy transmitted to DC side is excessive and the drive should be turned off. Therefore, when the reference current I_{dref} drops to its lower bound I_{dref_L}, the drive is turned on and thus the converter starts to transfer energy to the output. Once I_{dref} rises to its upper limit I_{dref_H}, the drive is turned off and there are no gating signals. The load power is supplied by the output capacitors. This method can also reduce output ripples.

Since the reference current is generated by voltage regulator and not affected by the grid feedforward control, this method will not be affected by grid distortion and it is easily to be realized without any extra cost. Therefore, the method, using the output of voltage regulator to realize burst-mode control, is better than the conventional method and employed in this paper. The block diagram of proposed method is illustrated in Fig. 8.

TABLE I. PARAMETERS OF THE VIENNA PROTOTYPE

Components	**Parameters**
DC capacitor	660uF
Filter inductor	350uH
switching frequency	48kHz
Rated AC line to line voltage (RMS)	380V±20%
Grid frequency	50Hz
Rated DC voltage	800V
Rated output power	15kW

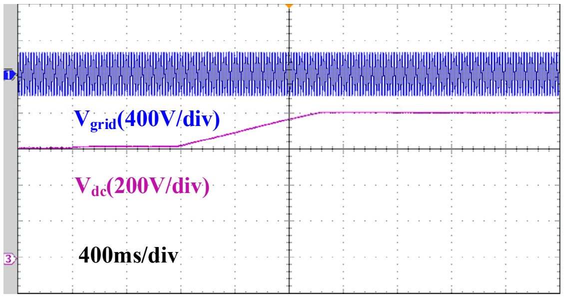


Fig. 9 Waveforms at startup at no-load condition

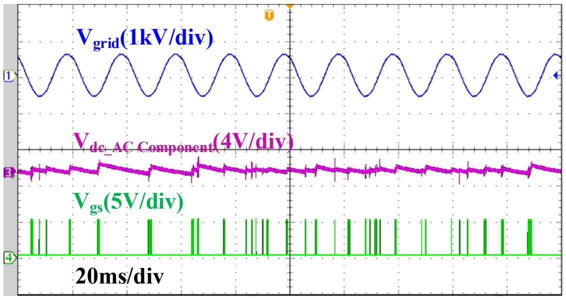


Fig. 10 Waveforms of proposed method at no-load condition

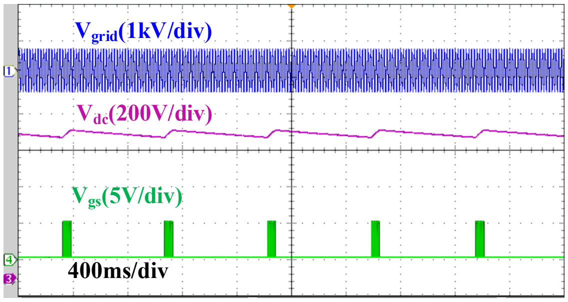


Fig. 11 Waveforms of conventional burst-mode at no-load condition

V. EXPERIMENTAL RESULTS

To verify the proposed method, using the output of voltage regulator to realize burst-mode control, a prototype of 15kW three-phase/level VIENNA rectifier is built. The main circuit is composed of two channel VIENNA rectifiers in parallel and main parameters is listed in Tab. 1. The controller platform is based on TMS320F28035, which has a control law accelerator executing code independently of C28x CPU.

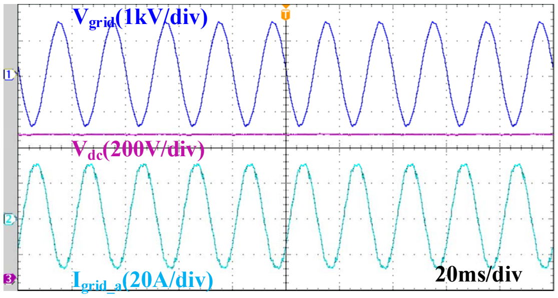


Fig. 12 Steady waveforms at full load

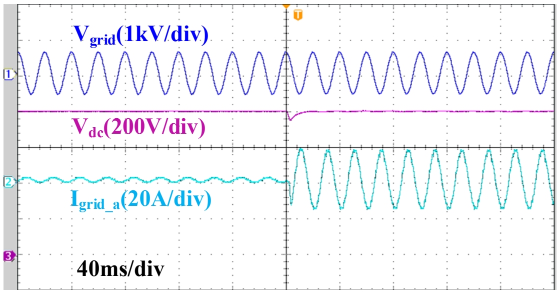


Fig. 13 Experimental waveforms during load step-up change

In order to verify the proposed method, the lower limit for the outer voltage regulator is set as -1A. The drive is turned off when the output of voltage regulator is lower than -0.3A, and turned on when the output of voltage regulator is higher than 0A.

Fig. 9 depicts the startup transient of the VIENNA rectifier at no-load condition, showing the transition from diode bridge operation to active control mode. The output DC voltage changes from 540V to 800V smoothly. And its ripple is illustrated in Fig. 10, measured with the AC coupler of oscilloscope. The DC voltage stays 800V stably at no-load condition and its ripple is about ±1V.

In contrast, the waveforms of conventional burst-mode method are shown as Fig. 11. It can be seen that the peak-to-peak voltage of output ripple is about 40V, which is much larger than output ripple of the proposed burst-mode control. The proposed control method is verified to be effective at light load.

The full-load steady state oscilloscopes of grid line-to-line voltage, DC voltage and grid current, is shown in Fig. 12. When load steps from no load to half load, typical dynamic waveforms are presented in Fig. 13. The output voltage drops about 50V and its response time is approximately 15ms. The dynamic response process is very smooth, and the state of heavy load is steady. Therefore, the proposed method has no influence on the conventional control at heavy load.

VI. CONCLUSIONS AND FUTURE WORK

This paper proposed an improved burst-mode control method to reduce the output DC voltage ripple at light load or no load. Based on the analysis of conventional control method at heavy load, the proposed method makes full use of the output of voltage regulator, which reflects the size and direction of transmission energy, to realize burst-mode control without additional calculation. The proposed method can mitigate the output ripples, compared with conventional burst-mode control method, and will not affect the conventional control at heavy load. When load steps up, the dynamic response of the output voltage is smooth. Finally, a prototype of 15kW is built. The effectiveness and advantages of the proposed method have been verified by the experimental results. The proposed method can also be introduced to other systems.

REFERENCES

[1] M. L. Heldwein, J. W. Kolar, "Impact of EMC Filters on the Power Density of Modern Three-Phase PWM Converters," IEEE Transactions on Power Electronics, vol. 24. pp. 1577-1588, 2009.

[2] Y. Zhao, Y. Li, and T. A. Lipo, "Forced commutated three level boost type rectifier," IEEE Trans. Ind. Appl., vol. 31, no. 1, pp. 155–161, Jan./Feb. 1995.

[3] Michael Leibl, Johann W. Kolar, Josef Deuringer, "New Current Control Scheme for the Vienna Rectifier in Discontinuous Conduction Mode," IEEE Energy Conversion Congress and Exposition (ECCE), pp.1240–1247, 2014.

[4] Michael Leibl, Moreno Darani, Johann W. Kolar, etc. "New Boundary Mode Sinusoidal Input Current Control of the VIENNA Rectifier," IEEE Energy Conversion Congress and Exposition (ECCE), pp. 201–209, 2015.

[5] Peter Ide, Frank Schafmeister, Norbert Fröhleke, etc. "Enhanced Control Scheme for Three-Phase Three-Level Rectifiers at Partial Load," IEEE Transactions on Industrial Electronics, vol. 52, no. 3, pp. 719-726, 2005.

[6] Yu-Kang Lo, Shang-Chin Yen and Jin-Yuan Lin, "A High-Efficiency AC-to-DC Adaptor with a Low Standby Power Consumption," 2006 37th IEEE Power Electronics Specialists Conference, 2006.

[7] Yen-Shin Lai, Zih-Jie Su, "New Integrated Control Technique for Two-Stage Server Power to Improve Efficiency Under the Light-Load Condition," IEEE Transactions on Industrial Electronics, vol. 62, no. 11, pp. 6944-6954, 2015.

[8] Bernard Keogh, George Young, Hagen Wegner, Colin Gillmor. "Design Considerations for High Efficiency Buck PFC with Half-Bridge Regulation Stage," 2010 Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2010: 1384-1391.

[9] Bin Li, Lijun Hang, Wenxi Yao, et al. "Equivalence of SVM and Carrier-based PWM in Three Phase/Wire/Level VIENNA Rectifier and Unbalanced-Load Ability," 2012 IEEE International Symposium on Industrial Electronics, 2012: 328-333.

[10] Bin Li, Lijun Hang, Leon M. Tolbert, A, et al. "Equivalence of SVM and Carrier-based PWM in Three Phase/Wire/Level Vienna Rectifier for Unbalanced Load," IEEE Transactions on Industrial Electronics, 2012: 988-995.

[11] Lijun Hang, A, Bin Li, Ming Zhang, A, et al. "Equivalence of SVM and Carrier-Based PWM in Three-Phase/Wire/Level Vienna Rectifier and Capability of Unbalanced-Load Control," IEEE Trans-actions on Industrial Electronics, 2014, 61(1): 20-28