# PROPOSED SYMMETRICAL 5-LEVEL AC-DC VIENNA RECTIFIER FOR HIGH PERFORMANCE APPLICATION

## ĐỀ XUẤT CHỈNH LƯU VIENNA 5 - MỨC ĐỐI XỨNG CHO CÁC ỨNG DỤNG HIỆU SUẤT CAO

**Phạm Thị Thùy Linh**[1,*]

**ABSTRACT**

Vienna rectifier with reduced number of switches has been receiving wide interest in the past years to improve the input power quality of rectifier systems. In this paper, a review of three phase 3-level Vienna and configuration of 5-level structure from 3-level Vienna topology are presented. Moreover, Phase Opposite Disposition (POD) and Phase Disposition (PD) Pulse Width Modulation (PWM) control are proposed and compared to eliminate the low frequency harmonic in the line current and to achieve unity power factor at the rectifier input terminal. In this paper, the performance and feasibility of the proposed single phase and three phase 5-level Vienna topologies are verified by simulation.

***Keywords***: *Vienna converter, PWM, Phase Opposite Disposition, Phase Disposition, Rectifier.*

**TÓM TẮT**

Chỉnh lưu Vienna với số lượng hạn chế các van bán dẫn đóng/cắt đã và đang nhận được nhiều sự quan tâm chú ý với mục đích cải thiện chất lượng điện năng đầu vào của các hệ thống chỉnh lưu. Trong bài báo này, đánh giá sơ đồ Vienna 3-mức ba pha và cấu trúc sơ đồ Vienna 5 mức từ sơ đồ Vienna 3-mức được trình bày. Thêm vào đó, hai phương pháp điều khiển điều chế độ rộng xung POD và PD được đề xuất và so sánh để giảm các thành phần sóng hài tần số thấp của dòng điện đầu vào và có được hệ số công suất bằng một ở đầu vào của bộ chỉnh lưu. Trong bài báo này, hiệu suất và tính khả thi của các sơ đồ Vienna 5-mức một pha và bap ha được kiểm nghiệm bằng mô phỏng.

***Từ khóa:*** *Bộ biến đổi Vienna; Điều chế độ rộng xung; Vị trí đối pha; Vị trí cùng pha; Chỉnh lưu.*

[1]Khoa CNTĐ, Trường Đại học Điện lực
*Email: linhptt@epu.edu.vn
Ngày nhận bài: 21/12/2017
Ngày nhận bài sửa sau phản biện: 02/02/2018
Ngày chấp nhận đăng: 26/02/2018

### 1. INTRODUCTION

The general trend in power electronics has been to switch power semiconductors at increasingly high frequencies in order to minimize harmonics and reduce passive component sizes. However, the increase in switching frequency increases the switching losses which become significant at high power levels. Several methods for decreasing switching losses and, at the same time improving power quality, have been proposed including constructing resonant converters and multilevel converters. Among these, the topology proposed by Kolar in 1994 called the 3-level Vienna has the additional benefits of reduced controlled switch count in addition to the general the benefits of 3- level converter. This converter is used in telecommunication power system [1], wind turbine systems [2, 3], and power factor correction system [4]. Thus, due to the opportunities of competitive cost reduction, 3-level Vienna is generally considered attractive. In this paper, 3 phase 3 level Vienna is presented in Section II. Then proposed extension 5-level topology is presented in Section III, compared modulation PWM control methods is presented in Section IV. The concluding section presents computer simulations results verifying.

### 2. THREE PHASE 3-LEVEL VIENNA RECTIFIER

One of the realizations of the unidirectional topology with reduced count of controlled switches Vienna Rectifier is show in fig. 1. In each phase leg, only one controlled switch is used. With assumption of continuous conduction mode (CCM), the rectifier pole voltages ($v_{an}$, $v_{bn}$, $v_{cn}$) have a definite sate determined by on/off states of controlled switches and the polarity of line currents at any instant of operation. For instance, if the line current $i_a$ is positive and the controlled switch Tra is off, the voltage between the converter pole A and dc bus midpoint N, van is Vdc/2. The conduction path for this case is illustrated in figure 2a. If the line current ia is positive and the controlled switch Tra is ON, the voltage van is 0 in which case the conduction path is illustrated in Fig 2b. Similarly, if the current ia is negative, the voltage van can be either –Vdc/2 if the switch Tra is OFF or 0 if the switch Tra is ON ass illustrated in Fig 2c and d, respectively. This operating principle also applies to phase legs B and C. To avoid low frequency (lower than the switching frequency) harmonics in line currents, the rectifier phase voltages must be free of low frequency harmonics except for triple harmonics, which may present on the modulation signals to increase the fundamental component without invoking over modulation.

As shown in Fig. 1, the AC side of the system can be described as three inductors, connected between three phase mains and three dependent voltage sources. For each phase loop the Kirchhoff Voltage Law equation is:

$$L_a\frac{di_a}{dt}=v_{an}-V_{AN}=v_{an}-d_A\frac{v_0}{2}+\varepsilon_a+V_{ON}$$

$$L_b\frac{di_b}{dt}=v_{bn}-V_{BN}=v_{bn}-d_B\frac{v_0}{2}+\varepsilon_b+V_{ON}$$

$$L_c\frac{di_c}{dt}=v_{cn}-V_{CN}=v_{cn}-d_C\frac{v_0}{2}+\varepsilon_c+V_{ON}$$

$$v_0=V^{+}_{\frac{dc}{2}}-V^{-}_{\frac{dc}{2}}$$

$-1 < d_A, b_B, b_C < 1$ are the average duty cycle. Since VON is a zero sequence component, it has no effect on the mains currents and can be further omitted. In case the controller operates, vo has a low value and maybe considered as a small disturbance due to the DC-link unbalance.

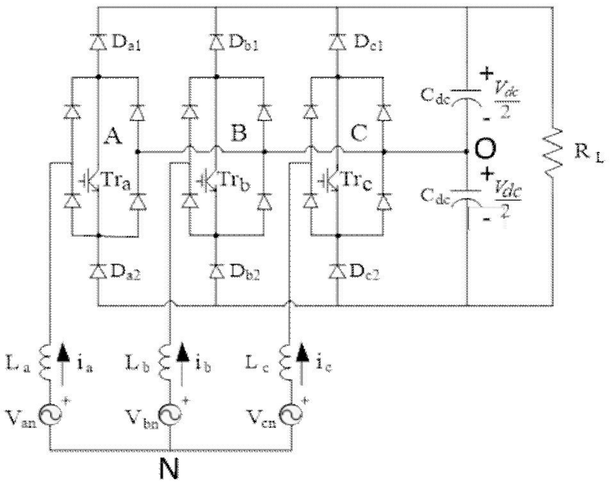



Fig. 1. Three-phase 3-level classical Vienna Rectifier

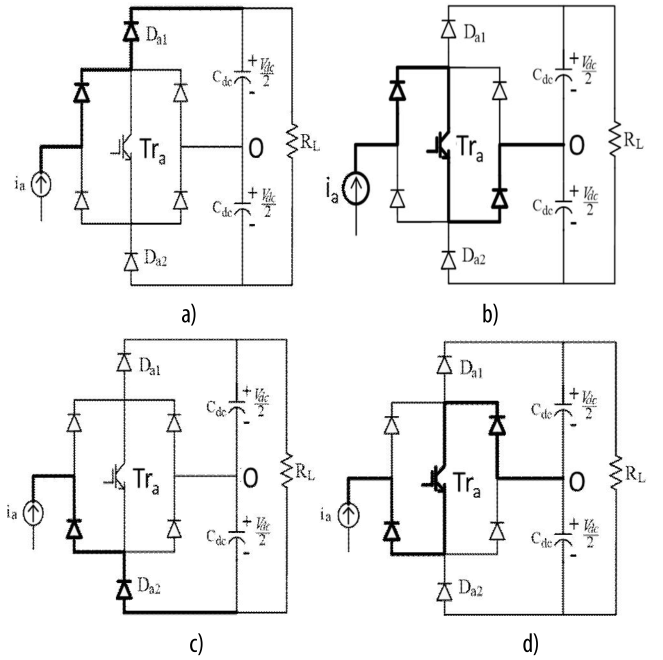



Fig. 2. Conduction paths for phase-leg A when (a) the line current is positive and the controlled switch is OFF; (b) the line current is positive and the controlled switch is ON; (c) the line current is negative and the controlled switch is OFF; (d) the line current is negative and the controlled switch is ON

## 3. EXTENSION 5-LEVEL VIENNA TOPOLOGY FROM 3-LEVEL VIENNA TOPOLOGY

Fig. 3 shows the proposed 5-level extension of the 3-level Vienna thanks to one extra cell for the positive AC conduction and one extra cell for the negative AC conduction. Fig. 3c, shows the 5-level Vienna and connection between DC/4 source and DC/2 source by two diodes. It should be note, in any case, that flying capacitors which are rated only at the switching frequency, must withstand only Vdc/4 and sustain Amps-Second only on a half of AC period. These properties which are very important, allows a very low rating of the flying capacitors, low RMS current and low size compared to the 3-level Vienna topology.

The operating states of power circuit are analyzed when the circuit current is positive (Tab. 1). The advantage of this configuration is due to the two redundancy states of the circuit that naturally balance the two voltages of the flying capacitor.

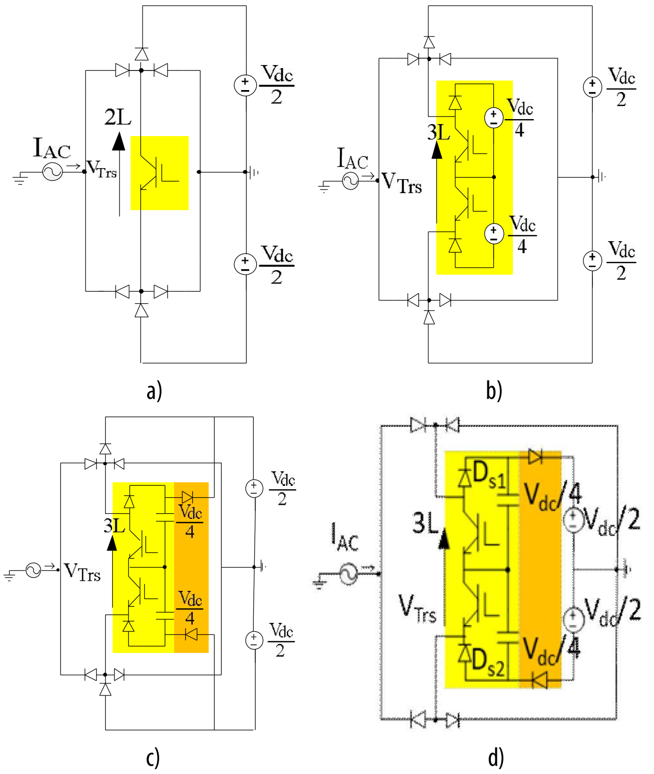
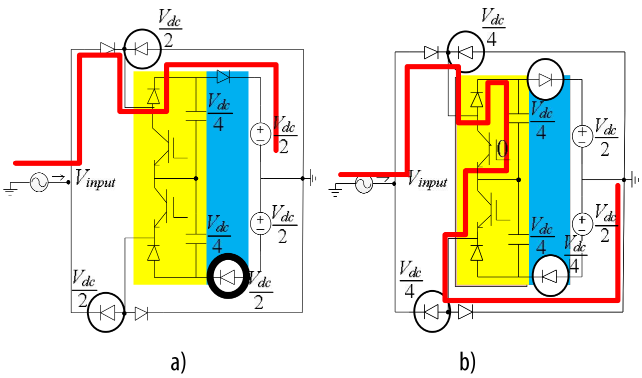
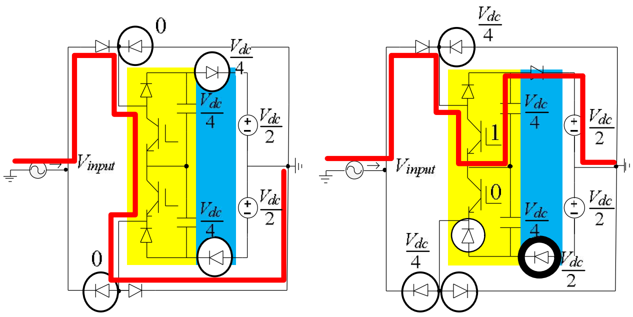



Fig. 3. 5-level Vienna Extension of the 3-level Vienna topology






c) d)

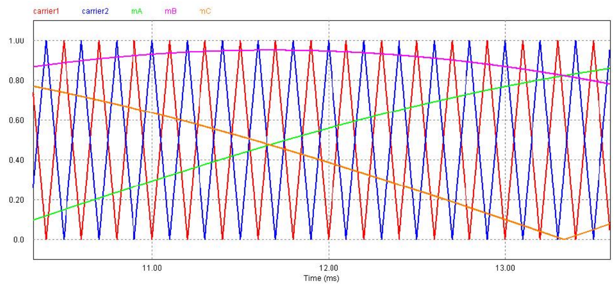
Fig. 4. Illustrates the current flow paths when the circuit current is positive. When the switch Tr1, Tr2 are OFF (a); Tr1 OFF, Tr2 ON (b); the switch Tr1, Tr2 are ON (c); Tr1 ON, Tr2 OFF (d)

## 4. THREE PHASE 5-LEVEL VIENNA RECTIFIER AND MODULATION STRATEGY IN 5-LEVEL OPERATION

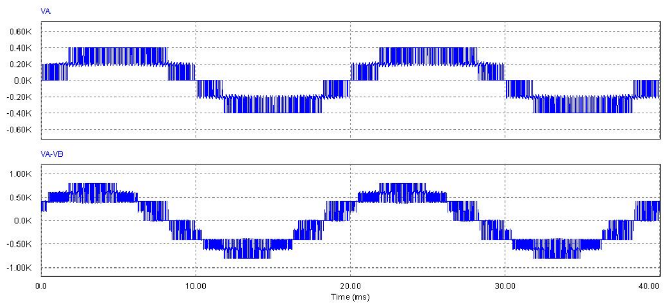
The Vienna rectifier keeps all general advantages with the respect to the Power Factor Correction (PFC) multi-level converter with exception that it is unidirectional converter which implies limitations regarding reactive power handling. However, due to the presence of the inductor on the AC side the electromagnetic interference (EMI) capacitor needed to comply with the harmonic requirements is small. Moreover, this rectifier is by nature 5-level converter which allows smaller values of input inductance.

Switching methods for the Vienna rectifier were proposed in [2, 5, 6, 7, 8, 9].These methods satisfy the important requirement for normal operation of the Vienna rectifier: the sign of the current should be the same as the sign of the voltage [1, 2, 5, 6, 7, 8, 9]. Therefore, the Vienna rectifier has a limitation in its power factor variation. Among these switching methods, the hysteresis switching methods are proposed for controlling the input currents as sinusoidal waveforms. In [1, 2] the sinusoidal reference current and its hysteresis band are used to operate the switching device. However, the hysteresis switching methods do not guarantee a constant switching frequency in the input voltage. Therefore, these methods make it difficult to design the input filter. Pulse width modulation methods have been proposed as solution for the problem of hysteresis switching methods. This method ensures a constant switching frequency.

The modulation consists in providing the input AC voltage with the minimum THD and the balancing management of the two flying capacitors. In 5-level operation, two carriers have to be used. A first approach is shown in Fig. 5a) and consists in extending the 3-level modulator with two others interleaved carriers phase-shifted of π (named Opposite Phase Disposition carriers). This solution can be used if the natural balancing property is realized through an additional input filter tuned at the switching frequency. Here, this approach is not matching with a fault-handling strategy because the reduction of the apparent frequency in fault mode creates a resonance with the input filter that is tuned at the same frequency. A solution can be to use a low frequency active balancing by controlling the different duty cycles. Even if the balancing is realized, Fig. 5b) shows that this first solution gives a non-optimized leg-leg voltage due to the phase variation ±π of the voltage harmonic at the apparent switching frequency when the modulation level crosses {-½, 0, ½}. However, Fig. 6 shows a second interesting solution (named Phase-Disposition carriers) owing to four stacked carriers that exhibit in Fig. 8 an optimized leg – leg waveform due to the suppression of the voltage harmonic at the apparent switching frequency in leg-leg connection. In this second solution, the voltage balancing is more complex that the phase-shifted strategy. A state machine has to be introducing [10] but it will not be detailed in this paper.




a)




b)

Fig. 5. a) POD Modulation PWM control b) Simulation results of 5-level leg voltage and 9-level leg-leg voltage with POD PWM control

Table 1. Analyzes the operating states of power circuit when the circuit current is positive

| $Ctrl\_Tr_1$ | $Ctrl\_Tr_2$ | $V\_Tr_1$ | $V\_Tr_2$ | $V\_Ds_1$ | $V\_Ds_2$ | $V_{input}$ | CdVc1/dt | CdVc2/dt |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | Vdc/4 | Vdc/4 | 0 | Vdc/2 no switch | Vdc/2 | 0 | 0 |
| 0 | 1 | Vdc/4 | 0 | Vdc/4 switch | Vdc/4 no switch | Vdc/4 | $+I_{AC}$ | 0 |
| 1 | 1 | 0 | 0 | Vdc/4 switch | Vdc/4 no switch | 0 | 0 | 0 |
| 1 | 0 | 0 | Vdc/4 | 0 | Vdc/2 no switch | Vdc/4 | $-I_{AC}$ | 0 |

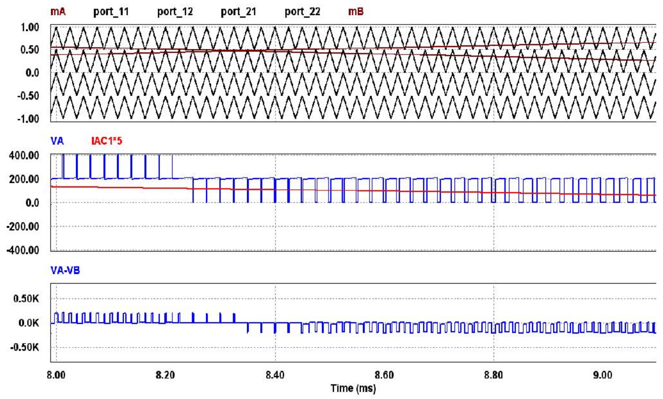



Fig. 6. PD Modulation PWM control and simulation results of leg input voltage and input current IAC and leg-leg input voltage

## 4. SIMULATIONS

The simulations are performed to verify the performance of the proposed three- phase 5-level Vienna. For simulation purposes a 4kW 5-level Vienna system simulation has been conducted using PSIM software. The simulation parameters are listed in Tab. 2.

Simulation results are shown in Fig. 7 and Fig. 8. Obviously, the phase current remains sinusoidal and in phase with the voltage. The voltage unbalance is very low with zero average (Fig. 8) and the 5-level output voltage one leg and 9-level output voltage leg-leg are stable and accurate (Fig. 8). Fig. 7 and Fig. 8 show the current and voltage waveforms when the PD modulation PWM control using state machine is applied. The main advantage of this structure is that the line current is sinusoidal and power factor is unity.

Table 2. Simulation parameters

| Parameter | Value |
|---|---|
| Supply network | 230 V/ 50 Hz |
| Input inductor | 160mH |
| Each output capacitor | 2400 µF |
| Each flying capacitor | 40 µF |
| Nominal load | 40 Ω |
| Total output voltae | 800 V |
| Each DC link source | 400 V |
| Switching frequency | 40 kHz |

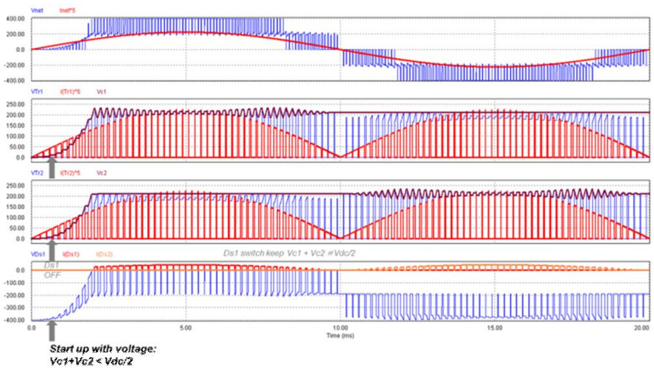



Fig. 7. Typical simulated waveforms for start-up regime of 4kW 5-level Vienna

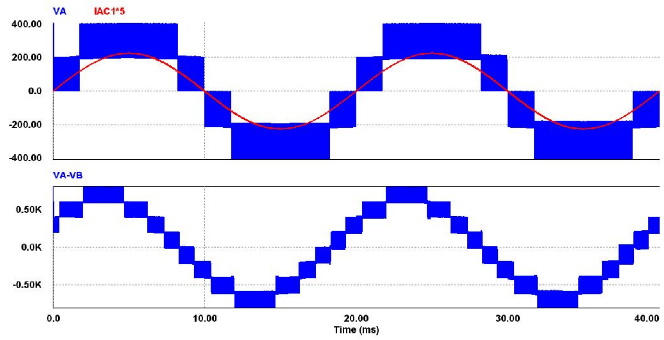



Fig. 8 Simulation results of one leg input voltage and input current $I_{AC}$ and leg-leg input voltage with PD modulation PWM control using state machine

## 6. CONCLUSIONS

This paper is aimed to reduce the number of fully controlled semiconductor switch of 5-level Vienna rectifier. Then the three phase 5-level Vienna rectifier is introduced. The proposed POD and PD PWM control are presented and compared. The input current shaping, multi-level input voltage and output voltage regulation are simulated by PSIM software to verify the results.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