Design and Development of a Three-Level Vienna Rectifier for use in Telecommunications Equipment

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***Abstract*—The three-level Vienna Rectifier has emerged as a highly efficient power conversion solution for telecommunication systems, combining low Total Harmonic Distortion (THD) and high power density. This paper presents the design, modeling, and simulation of a Voltage Oriented Control (VOC) strategy for the Vienna Rectifier, aimed at achieving sinusoidal input currents, a high power factor, and stable DC-link voltage. The simulation was carried out in MATLAB/Simulink, integrating a decoupled control structure with a Phase-Locked Loop (PLL) for grid synchronization and a simplified Space Vector Modulation (SVM) for switching signal generation. Despite challenges with PI controller tuning and numerical solver configuration, the study provides a solid foundation for future research, highlighting advanced tuning methods and hardware validation as critical next steps.**

***Index Terms*—Vienna rectifier, Voltage Oriented Control, Telecommunication Systems, Total Harmonic Distortion, MATLAB/Simulink**

I. INTRODUCTION

Telecommunication systems require efficient and reliable power converters capable of minimizing power losses, reducing harmonic distortions, and ensuring stable voltage supply. The Vienna rectifier has emerged as a robust solution, offering high efficiency and low Total Harmonic Distortion (THD) due to its three-level topology. This topology ensures a compact design with reduced switching losses and stress on components, making it ideal for high-demand applications.

This paper focuses on implementing and simulating a Voltage-Oriented Control (VOC) strategy for the Vienna rectifier. The VOC framework simplifies active and reactive power control using a decoupled approach. This work highlights the theoretical modeling, parameter derivation, and challenges faced during simulation, providing key insights into the rectifier's performance and future improvement opportunities.

II. STATE OF THE ART

The Vienna rectifier, first introduced by Kolar [3], has been widely adopted for its superior performance in high-demand applications such as telecommunications. Its three-level operation allows for reduced harmonic distortion, lower switching losses, and improved efficiency, making it a preferred topology for power factor correction and power quality improvement. Control strategies play a pivotal role in achieving these performance metrics, with various approaches explored in the literature.

Among the most prominent control methods, VOC stands out due to its simplicity and effectiveness in decoupling active and reactive power control. Predictive Control offers higher accuracy and faster dynamic response but comes at the cost of significant computational complexity. Hysteresis Control, although robust and straightforward to implement, suffers from variable switching frequency, which increases switching losses. Space Vector Modulation (SVM) optimizes switching states for high efficiency but requires precise implementation, while Sliding Mode Control (SMC) provides excellent robustness but is computationally demanding.

Table I summarizes the THD values, efficiency, dynamic response, complexity and suitability of these control strategies. This comparison highlights the trade-offs inherent in each method, providing a framework for selecting the most appropriate strategy for specific applications. The references can be found in [4] for VOC, [5] for Predictive Control, [6] for SVM, [4] for Hysteresis Control and [7] for SMC.

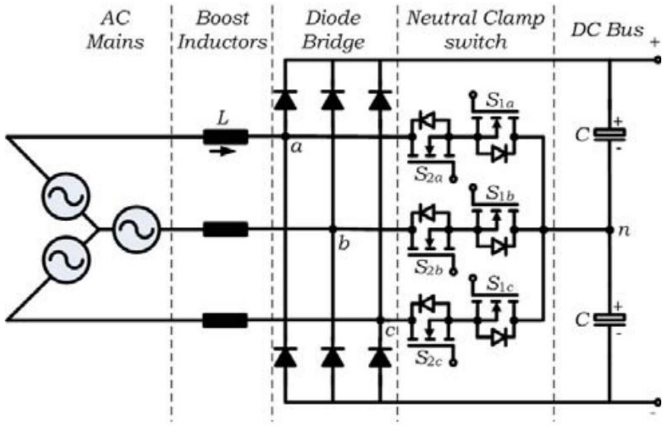

Fig. 1. Vienna rectifier topology [1]

VOC is the predominant strategy for grid-connected applications due to its ability to decouple active and reactive power regulation. Figure 2 shows the control structure used in this study, combining PLL-based synchronization, abc-to-dq transformation, and a decoupled controller. Although other methods, such as Predictive Control and Hysteresis Control, have been explored, VOC remains the most practical and

Control Strategy	THD	Efficiency	Dynamic Response	Complexity	Suitability
VOC	Low (∼2.5 %)	High (∼95 %)	Moderate	Moderate	Grid-connected rectifiers that require a balanced output
Predictive Control	Very Low (<2 %)	Very High (>96 %)	Fast	High	Advanced systems that require an extremely low THD value
SVM	Low (∼3 %)	High (∼95 %)	Moderate	Moderate	Systems designed for efficiency and lower losses
Hysteresis Control	Moderate (∼4.5 %)	Moderate (∼90 %)	Fast	Low	Applications requiring simplicity with less strict THD requirements
SMC	Low (<3 %)	High (∼95 %)	Very Fast	High	Systems requiring robust performance under disturbances

TABLE I
COMPARISON OF CONTROL STRATEGIES

widely adopted approach due to its computational simplicity and effectiveness in achieving low THD. [4]

III. OBJECTIVES

The primary objective of this work is to design and simulate a three-level Vienna rectifier optimized specifically for telecommunication systems. To achieve this, the control strategy focuses on delivering sinusoidal grid currents with THD, maintaining stable DC-link voltage regulation, and ensuring a high power factor. The project involves several key steps, starting with the development of a comprehensive MATLAB/Simulink model for the Vienna rectifier, incorporating the VOC strategy. This is followed by the derivation of critical system parameters, including inductance, capacitance, and PI controller gains, based on analytical methods and system requirements. Finally, the work identifies and addresses challenges in controller tuning and system stability, laying the groundwork for future improvements and hardware validation.

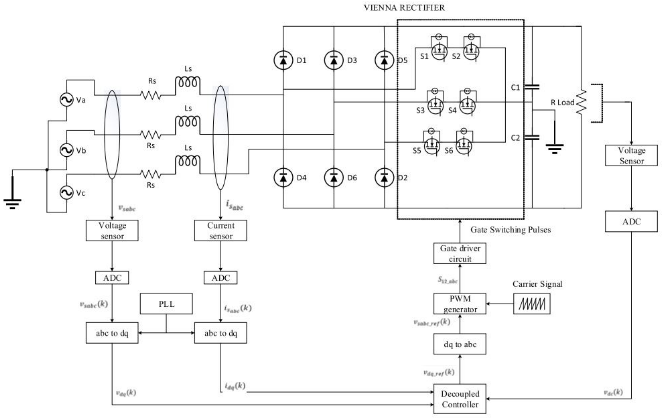

Fig. 2. Overall circuit configuration using VOC [2]

IV. METHOD

The Vienna rectifier topology, shown in figure 1, comprises input inductors, a diode bridge, neutral clamp switches, and DC-link capacitors. Its operation, illustrated in figure 3, involves switching states to generate three voltage levels ($+Vdc/2$, 0, $-Vdc/2$) for each phase. The three modes of operation—positive, zero, and negative current paths—enable efficient power conversion with reduced harmonic distortion.

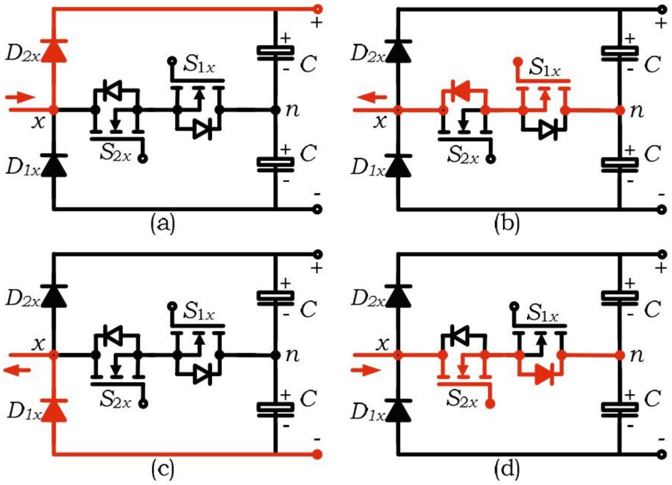

Fig. 3. Different states of a phase-leg, (a) positive half cycle with switch OFF, (b) negative half cycle with switch ON, (c) negative half cycle with Switch OFF, (d) positive half cycle with switch ON [1]

The simulation model, depicted in figure 4, was implemented in MATLAB/Simulink and divided into three main subsystems: measurement, control, and power stage. The VOC framework includes a PLL for grid synchronization, abc-to-dq transformation, and PI controllers for d-axis and q-axis current regulation. The PWM generator uses simplified Space Vector Modulation (SVM) for switching signal generation.

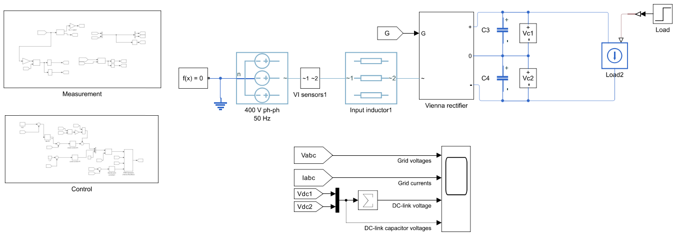

Fig. 4. Simulink model of Vienna rectifier with VOC control

Key parameters were derived based on system specifications. The inductance and capacitance values were calculated using equations 1 and 2 respectively, where Δi_L is the ripple current, f_s is the switching frequency, V_M is the peak source voltage, D is the duty cycle, ΔV_C is the ripple capacitor voltage and V_{dc} is the DC link voltage.

$$L = \frac{D \cdot (V_M - V_{dc})}{\Delta i_L \cdot f_s} \tag{1}$$

$$C = \frac{D \cdot (V_m - V_{dc})}{2 \cdot \Delta V_C \cdot L \cdot {f_s}^2} \tag{2}$$

The PI controller gains were tuned using bandwidth α_i and damping factor $\xi = 0.707$.

$$\alpha_i < 2\pi \frac{f_{sw}}{10},\ [1] \tag{3}$$

$$Kp_{id} = Kp_{iq} = \alpha_i L, \quad Ki_{id} = Ki_{iq} = \alpha_i R\ [1] \tag{4}$$

$$Kp_{vdc} \geq C\xi\omega \text{ and } Ki_{vdc} \geq \frac{C\xi\omega}{2},\ [1] \tag{5}$$

V. REALIZATION

The simulation parameters were configured to match telecommunication requirements: a grid voltage of $400\,\mathrm{V}$ (RMS), a frequency of $50\,\mathrm{Hz}$, and a DC-link voltage of $800\,\mathrm{V}$. Inductance and capacitance values were set to $16\,\mathrm{mH}$ and $156\,\mathrm{nF}$, respectively.The PLL ensured accurate grid synchronization, while the PI controllers regulated the d-axis and q-axis currents to achieve decoupled control.

Figure 2 illustrates the complete control framework, integrating the decoupled VOC strategy with PWM generation. The simulation model, as shown in figure 4, incorporated the Vienna rectifier power stage, measurement subsystem, and control subsystem.

VI. RESULTS

The simulation results, shown in figure 5, highlight the system's performance. The grid currents exhibited significant distortion, deviating from the desired sinusoidal form. Fluctuations were also observed in the DC-link voltage and capacitor voltage balancing, indicating challenges in achieving stable operation. These issues were primarily attributed to suboptimal tuning of the PI controllers and limitations of the numerical solver configuration in MATLAB/Simulink.

Fig. 5. Simulink scope of Grid voltages, Grid currents, DC link voltage and DC link capacitor voltage

While the theoretical framework and system design were successfully implemented, the simulation outcomes underscore the need for improved tuning methods and advanced control strategies to achieve the desired performance metrics.

VII. SUMMARY & OUTLOOK

This paper presents the design, modeling, and simulation of a three-level Vienna rectifier with VOC. The work demonstrates the theoretical basis for parameter derivation, system modeling, and control implementation. Despite challenges in simulation stability, the results provide valuable insights into the rectifier's behavior under VOC.

Future work should focus on optimizing PI controller gains using tools such as MATLAB/Simulink's $Closed\,Loop\,PID\,Autotuner$ and exploring adaptive control strategies. Additionally, hardware validation through real-world implementation or Hardware-in-the-Loop (HIL) testing will be essential to evaluate the rectifier's performance under practical operating conditions.

REFERENCES

[1] D. A. Molligoda, J. Pou, C. Gajanayake, and A. Gupta, "Analysis of the vienna rectifier under nonunity power factor operation," in 2018 Asian Conference on Energy, Power and Transportation Electrification (ACEPT). IEEE, 2018, pp. 1–7

[2] G. Rajendran, C. A. Vaithilingam, N. Misron, K. Naidu, and M. R. Ahmed, "Voltage oriented controller based vienna rectifier for electric vehicle charging stations," IEEE Access, vol. 9, pp. 50 798–50 809, 2021.

[3] J. W. Kolar, H. Ertl and F. C. Zach, "Design and experimental investigation of a three-phase high power density high efficiency unity power factor PWM (VIENNA) rectifier employing a novel integrated power semiconductor module," Proceedings of Applied Power Electronics Conference. APEC '96, San Jose, CA, USA, 1996, pp. 514-523 vol.2, doi: 10.1109/APEC.1996.500491.

[4] Cyprich, Pavel and Cyprich, Petr and Strossa, Jan and Damec, Vladislav and Havel, Aleš, "Comparison of Hysteresis Current Control and VOC Control With SPWM and SVPWM Applied to Vienna Rectifier," in 2024 24th International Scientific Conference on Electric Power Engineering (EPE), 2024, pp. 1–6.

[5] Xie, Shiming and Sun, Yao and Su, Mei and Lin, Jianheng and Guang, Qiming, "Op- timal switching sequence model predictive control for three-phase Vienna rectifiers," IET Electric Power Applications, vol. 12, no. 7, pp. 1006–1013, 2018.

[6] A. Sunbul and V. K. Sood, "Simplified svpwm method for the vienna rectifier," in 2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL), 2019, pp. 1–8.

[7] B. KOODALSAMY, V. NARAYANASWAMY, K. KRISHNAMOORTHY, and B. ANANTHAN, "Implementation of vienna rectifier with sliding mode control for electric vehicle charging stations," REVUE ROUMAINE DES SCIENCES TECHNIQUES—SÉRIE ÉLECTROTECHNIQUE ET ÉNERGÉTIQUE, vol. 69, no. 4, pp. 425–430, 2024.