Voltage Oriented Controller Based Vienna Rectifier for Electric Vehicle Charging Stations

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ABSTRACT Vienna rectifiers have gained popularity in recent years for AC to DC power conversion for many industrial applications such as welding power supplies, data centers, telecommunication power sources, aircraft systems, and electric vehicle charging stations. The advantages of this converter are low total harmonic distortion (THD), high power density, and high efficiency. Due to the inherent current control loop in the voltage-oriented control strategy proposed in this paper, good steady-state performance and fast transient response can be ensured. The proposed voltage-oriented control of the Vienna rectifier with a PI controller (VOC-VR) has been simulated using MATLAB/Simulink. The simulations indicate that the input current THD of the proposed VOC-VR system was below 3.27% for 650V and 90A output, which is less than 5% to satisfy the IEEE-519 standard. Experimental results from a scaled-down prototype showed that the THD remains below 5% for a wide range of input voltage, output voltage, and loading conditions (up to 2 kW). The results prove that the proposed rectifier system can be applied for high power applications such as DC fast-charging stations and welding power sources.

INDEX TERMS Front-end converters, high power applications, power factor, total harmonic distortion, Vienna rectifier, voltage oriented controller.

I. INTRODUCTION

AC to DC converters with regulated DC output voltage is used as front-end converters for different applications such as electric vehicle chargers, telecommunication applications, welding power sources, data center, and motor drives [1], [2]. The power required for EV charging stations and welding power sources is high, which means that the voltage and current rating at the power converters must be higher than the voltage and current required for other applications such as motor traction [3], [4]. The unidirectional boost rectifier known as Vienna rectifier is used as a front-end converter [5]. This converter is well known for its topological structure advantages such as high efficiency, high power to weight ratio, low total harmonic distortion in the line current, unity power factor at the grid, and the small size of the filter compared to conventional three-phase rectifiers [6]. The Vienna rectifier is ideal for high power applications owing to the high power to weight ratio, high efficiency, and low voltage stress [7], [8].

In recent years, the core of the power electronics systems is the controller unit, which has been subjected to intensive research. The basic controller used in a power converter is a proportional-integral (PI) controller. However, it is challenging to achieve an accurate linear mathematical model of the system required for the PI controller [9]. Moreover, the PI controller often struggles to work satisfactorily under parameter variations, nonlinearity, and load disturbances [10].
In literature, different control methods are used in AC to DC converters for high power applications such as welding power sources and electric vehicle charging stations. The most popular power controllers for EV charging stations are power factor correction controllers (PFC) [11], direct power controller (DPC) [12], voltage-oriented controller (VOC) [13], and their combination DPC-SVM [14]. Voltage oriented controller is commonly used as a power controller for power factor correction in active front-end converters. Table 1 shows the comparison of different controllers.

Table 1 demonstrates the combination of a conventional controller with an intelligent controller can improve the transient analysis of the system and reduce total harmonic distortion in the input current compared to an individual controller. Furthermore, different converters used in the literature are applicable to lower power DC applications and traction applications.

In this paper, a novel design of EV charging system consisting of voltage-oriented controller with a Vienna rectifier (VOC-VR) is proposed for high power applications. The proposed system is a hybrid control structure consisting of voltage-oriented controller with PI controller for the Vienna rectifier, which is used for EV charging stations. Prior designs of AC/DC converters for high power applications employed a hybrid controller using conventional three-phase controlled rectifiers, which requires input and output filters with high rating to mitigate the input current THD [13], [14], [16], [20]. This led to reduced efficiency and power density of the system. To address this issue, a novel design of integrating Vienna rectifier with a VOC and PI controller for high power applications is proposed. Using Vienna rectifier, transient stability is improved, and for an output voltage of 650 V/90 A, the THD is reduced to less than 5%, which satisfies the IEEE-519 standard. The proposed novel design outperforms existing AC/DC power converters for high power applications by significantly reducing the input current THD and increasing the power density.

II. VIENNA RECTIFIER

The Vienna rectifier topology includes six active semiconductor switches, either MOSFET or IGBT, and six diodes. The three-phase three-level Vienna rectifier topology is shown in Fig. 1. The voltage stress on each diode and semiconductor switches is $V_{dc}/2$. Three inductors on the input AC side and two capacitors are parallely connected on the DC side. The neutral point of the grid is associated with the neutral point of the DC link. Fig. 2 shows the operation of the three-level Vienna rectifier for the current path of one leg at each mode. The remaining two legs perform the same operation with a 120° phase difference.

In mode 1, when a reference voltage is a positive half cycle and controlled switches (IGBTs/MOSFETs) are OFF, the diode $D_1$ conducts. During this time, the current flows through $V_\text{dc}L_1R_1D_1C_1$ as shown in Fig. 2(a). In mode 2 operation, when a reference voltage is positive half cycle with
controlled switches are ON, switches $S_1S_2$ conducts and current flows through $V_LR_4S_1S_2$ as shown in Fig. 2(b). In mode 3 operations, when a reference voltage is negative half cycle with controlled switches are ON, switches $S_1S_2$ conducts and the current flows through $S_1S_2R_LV_a$ as shown in Fig. 2(c). In mode 4 operation, when a reference voltage is negative half cycle with controlled switches are OFF, the current flows through $C_2V_LR_SV_a$ as shown in Fig. 2(d).

It is observed from Table 2, Vienna Rectifier is applicable for high power applications such as welding power sources, wind energy conversion systems, electric vehicle charging stations, and telecommunication power sources. Different power controllers have been used in Vienna Rectifier for high power applications, such as vector controller, SVPWM controller, predictive controller, and dead-beat controller. The different types of intelligent controllers have been combined with conventional controllers to improve the stability of the system, which increases the complexity of the system. The proposed system consists of Voltage Oriented Controller for Vienna Rectifier (VOC-VR). The proposed system reduces the harmonics in the input source current, improves the power factor at the grid side, and improves the stability of the system.

### III. VOLTAGE ORIENTED CONTROLLER

The operation of AC to DC power converters strongly depends on the implemented control structure. The operation of a voltage-oriented controller is based on dual vector current controllers (DVCC) [31]. Voltage-oriented control is used to mitigate the following problem:

- Output DC voltage ripples
- Total harmonics distortion in the input current
- Input power factor at the grid side

The voltage-oriented controller consists of a voltage controller and a current controller. The current control algorithm has two independent current controllers, which will work in the positive and negative synchronous reference frames (SRF). The positive SRF is used to control the positive current component, which rotates in a clockwise direction, whereas the negative SRF is used to control the negative current component, which rotates in the opposite direction. Since the currents occur as DC values in their frame in SRF, a tracking controller does not need to be built. Due to this advantage, the PI controller is adequate to solve the problems above.

The root of VOC approach is the field-oriented controller (FOC) for induction motors, which offers fast and dynamic responses using current controller loops. The VOC technique used for power electronic converters has been widely known in its theoretical aspects [32]. The pulse width modulation approach is added to the control system to improve the features of the VOC system. The minimization of interference (disturbance) can be done by using the VOC technique. By applying hysteresis Pulse Width Modulation (PWM) technique, the system performance has improved. The variable

### TABLE 2. Vienna rectifier and its applications.

| Ref. | Power Controller | % THD | Power Factor | Application | Remarks |
|------|------------------|-------|--------------|-------------|---------|
| [21] | SVPWM | 3.99 | 0.98 | - | The control technique has strong dynamics of equilibrium. The midpoint fluctuation is minimal, and the current distortion on the source side is eliminated to null. |
| [22] | Conventional PFC Controller | 1.46 | 0.96 | EV Application | The PFC controller is used for low-power applications such as a slow charging station for EVs. |
| [23] | VC based on hysteresis current control | 4 | 0.96 | MEA Application | Vienna Rectifier is used for More Electric Aircraft applications. The conversion efficiency is more than 95%. |
| [24] | Mixed Signal based Control | 4.7 | 0.98 | Onboard EV Charger | The Vienna Rectifier is used for the onboard charger with a 0.99 power factor, 4.7% THD, and 98% efficiency. SiC-based Vienna Rectifier is used for an EV battery charger. This type of design is used for high-power, high-frequency applications. |
| [25] | - | - | 0.98 | EV Battery Charger | The Vienna Rectifier is used for an EV charger with a vector control strategy. High power factor, good dynamic stability, and small midpoint potential fluctuations. |
| [26] | - | - | 0.98 | EV Charger | New Synergetic Vector control is used to reduce the losses in EV chargers. |
| [27] | - | - | 0.99 | EV Charger | The Vienna Rectifier is used for telecommunication applications with sensorless control. |
| [28] | Sensorless Voltage control | 1.5 | - | Wind Energy Applications | The Vienna Rectifier is used as a front-end Wind energy converter. |
| [29] | PC with Space vector | - | - | - | - |
switching frequency of the power converters raises the stress in power switching, resulting in large input and output filters.

The proposed approach applies the VOC technology for regulating the charging mechanism with reduced current harmonics in the grid, as shown in Fig. 3. The voltage-oriented controller primarily works in the two-phase αβ0 and dq0 domains where Clark and Park transformation matrices are implemented, as shown in equations (1) and (2), respectively.

\[
\begin{bmatrix}
v_{\alpha} \\
v_{\beta} \\
v_{0}
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
1 & -\frac{1}{2} & \frac{1}{2} \\
0 & \frac{1}{2} & \frac{1}{2} \\
\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0
\end{bmatrix} \begin{bmatrix}
v_{\alpha} \\
v_{\beta} \\
v_{0}
\end{bmatrix}
\]  

(1)

\[
\begin{bmatrix}
v_{d} \\
v_{q}
\end{bmatrix} = \begin{bmatrix}
\sin\theta & \cos\theta \\
-\cos\theta & \sin\theta
\end{bmatrix} \begin{bmatrix}
v_{\alpha} \\
v_{\beta}
\end{bmatrix}
\]  

(2)

TABLE 2. (Continued.) Vienna rectifier and its applications.

| Modulation | Direct Power Control Strategy | High power application |
|------------|-------------------------------|------------------------|
| [30]       | 1.84                          | 6                     |

The current ripple is reduced, and the neutral point voltage is regulated by the offset voltage determined by the Vienna rectifier’s neutral point voltage model. The Direct Power Control Strategy for Wind energy system improves the power factor at the source side and reduces the THD to less than 5% to satisfy the IEEE-519 Standards.

FIGURE 3. The control structure of voltage-oriented controller with PWM technique.

FIGURE 4. Overall domain transformation sequences involved in the voltage-oriented controller technique.

where, \(v_{\alpha}, v_{\beta}, v_{\gamma}\) are the three-phase source voltages in the ABC domain, \(v_{\alpha}^{\prime}, v_{\beta}^{\prime}, v_{\gamma}^{\prime}\) are the source voltages in the \(\alpha\beta0\) and dq0 domains, and \(\theta\) is the operating phase of the power system. A similar transformation approach is applied to convert the three-phase source current \(i_{abc}\) as shown in Fig. 3.

AC side control variables become the DC signals by modifying the transformation technique. The proportional-integral controllers easily eliminate steady-state errors according to the following approaches [13]:

\[
v_{d,ref} = K_p (i_{d,ref} - i_d) + K_i (i_{d,ref} - i_d) dt \quad (3)
\]

\[
v_{q,ref} = K_p (i_{q,ref} - i_q) + K_i (i_{q,ref} - i_q) dt \quad (4)
\]

\(K_p\) and \(K_i\) = PI controller gains

\(i_d\) and \(i_q\) are the input current in the dq0 domain, \(i_{d,ref}\) and \(i_{q,ref}\) are reference signals for \(i_d\) and \(i_q\).

By applying an inverse park transformation, the operation of the Vienna rectifier has been controlled, as shown in Eq. (5); after obtaining the reference voltage \(v_{d,ref}\) and \(v_{q,ref}\) which is used to derive the gate switching pulses \(S_{abc}\). The VOC operation involving the overall domain transformation process is summarized in Fig. 4.

\[
\begin{bmatrix}
v_{d,ref} \\
v_{q,ref}
\end{bmatrix} = \begin{bmatrix}
\sin\theta & -\cos\theta \\
\cos\theta & \sin\theta
\end{bmatrix} \begin{bmatrix}
v_{d,ref} \\
v_{q,ref}
\end{bmatrix}
\]

(5)

The transformation consists of Park’s transformations and Clarke’s transformation. Clarke’s transformation is used to convert the three-phase quantities (phases A, B, C) into the two-phase stationary quantities (\(\alpha\) and \(\beta\)). The Park’s transformation converts stationary two-phase (\(\alpha\) and \(\beta\)) into the rotating reference frame (\(d\) and \(q\)). Similarly, using the inverse park’s transformation technique, the rotating reference frame (\(d\) and \(q\)) has been converted into a stationary reference frame (\(\alpha\) and \(\beta\)). Furthermore, the stationary reference frame is converted into a three-phase AC system using inverse Clarke’s transformation technique.

IV. METHODOLOGY

The proposed Vienna rectifier with VOC controller (VOC-VR) is a three-phase three-level rectifier, which is controlled by the voltage-oriented controller algorithm.
The de-coupler controller is the key feature of the proposed VOC-VR system, which aims to provide unity power factor at the input side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Thus, the proposed controller for high-power applications that require a unity power factor at the input side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side.

The characteristics of two PI current controllers and PI voltage controllers are given in equation (6)-equation (8) [13]

\[ v_{d,\text{ref}} = \frac{v_d + 2\pi f L_d i_q}{K_p 1 K_i} \]  
\[ v_{q,\text{ref}} = \frac{v_q - 2\pi f L_d i_d}{K_p 2 K_i} \]  
\[ i_{d,\text{ref}} = \frac{K_p 3 (V_{dc,\text{ref}} - V_{dc})}{K_i} \]

where, \( K_p 1, K_p 2, K_i 2, K_i 3 = \text{gain values } \) PI current controller \( L_g = \text{source inductance} \).

The switching frequency for the current control loop will be larger than the bandwidth \( \alpha_l \) [33],

\[ \alpha_l < \frac{f_s}{10} \]  
\[ K_p 1 = K_p 2 = \alpha_l L_s \]  
\[ K_i 1 = K_i 2 = \alpha_l R_i \]

where, \( \alpha_l \) (rad/s) = current controller bandwidth.

For the voltage control loop, the PI controller is tuned by using a DC link capacitor as the following [34], [35]:

\[ K_p 3 \geq \frac{C_{dc,1} \xi \omega}{2} \]  
\[ K_i 3 \geq \frac{C_{dc,1} \xi \omega}{2} \]

where damping factor \( \xi \) is equal to 0.707 and \( \omega \) is angular frequency. Using initial values, tuning and modifications are made, which strengthens the proposed charging technique.

V. SIMULATION RESULTS

This section presents the simulation results of a VOC-based Vienna rectifier circuit. The performance of the proposed controller for high-power applications that require 600V/100A DC output is evaluated. The simulation parameters applied for the proposed system are summarized in Table 3.

Vienna rectifier with VOC controller has been simulated in MATLAB Simulink, and results are shown in Fig. 7 and Fig. 8. The input-current waveforms are shown in Fig. 7. The input-current harmonics for Vienna rectifier without a VOC controller and with a VOC controller are shown in Fig. 8 (a) and (b), respectively. From Fig. 7 and Fig. 8, it can be seen that the proposed control technique ensures THD of the input current is less than 3.27%, and the system maintains the unity power factor at the source side. Therefore, the proposed VOC-VR system has been proven to be applicable for...
TABLE 3. Specification of a VOC based vienna rectifier (VOC-VR).

| Parameter          | Symbol | Unit | Value |
|--------------------|--------|------|-------|
| Resistor Load      | $R_{load}$ | Ω   | 20    |
| Input inductance   | $L_f$  | mH  | 5     |
| Grid frequency     | $f$    | Hz  | 50    |
| Switching frequency| $f_s$  | kHz | 12    |
| Input resistance   | $R_f$  | Ω   | 5     |
| Source voltage     | $V_{in}$ | V  | 440   |
| Output voltage     | $V_{dc}$ | V  | 600   |
| Current controller | $K_{p1}$ and $K_{p2}$ | - | 67 |
| Voltage controller | $K_{p3}$ | - | $1.7 \times 10^4$ |
| Voltage controller | $K_{i1}$ and $K_{i2}$ | - | 0.00027 |
| Voltage controller | $K_{i3}$ | - | 0.017 |

FIGURE 7. Input current waveform of the proposed VOC-VR system with 440 V RMS IN and 650 V DC OUT.

FIGURE 8. Total harmonic distortion of the proposed VOC-VR system with 440 V RMS IN and 650 V DC OUT.

FIGURE 9. DC output voltage and output current of the Vienna rectifier with VOC controller with 350 V AC RMS input and 650 V DC output voltage.

FIGURE 10. DC output voltage and output current of the Vienna rectifier with VOC controller with 350 V AC RMS input and 220 V DC output voltage for slow charging stations.

VI. EXPERIMENT SETUP

A scaled-down demonstrator, the Vienna rectifier board with a resistive load, has been set up to verify the proposed voltage-oriented controller for the Vienna rectifier. The digital controller is preferred due to the limitations of design complexity, slow dynamic response, and high component costs by conventional analog controllers. The digital controller in the proposed system has been developed using a TMS320F28337xD microcontroller. The experimental setup of the proposed system is shown in Fig 12 and 13. It consists from this system also show that DC current has been maintained approximately at 90A, which can be used for EV fast charging and welding applications [13]. By scaling down the proposed system and optimizing PI parameters in the VOC controller, the rectifier can be used for slow charging scenarios (250 V/40 A output) as shown in Fig. 10 whereas, the Vienna rectifier with PFC controller can maintain the DC voltage up to 200 V with 16.5 A [36]. As a consequence, the Vienna rectifier with a PFC controller can only be used for slow charging applications (Level 1 charging). The transient analysis has been performed by studying the system performance in the case of an instantaneous increase in the load by a factor of 2. The DC output voltage during the transient condition is shown in Fig. 11.
of input filters, a Vienna rectifier board, output filters, and a digital controller board. The input voltage and current were measured using a power analyzer. The PCB board of Vienna rectifier with TMS320F28337xD microcontroller is shown in Fig. 14. The MOSFET model used in the rectifier was 65C7190, and the diode model was C4D08120A. The primary filter inductor was 3 mH in each phase, the total output capacitance was 180 µF, and the switching frequency of the rectifier was 50 kHz.

A. INDUCTOR DESIGN

The harmonics in the switching frequency will be reduced by using the input inductor \((L_i)\). Among other considerations, the design of the inductor depends on current ripple and the selection of the core material that can withstand the current ripple. \(V = L_i (di/dt)\), gives the voltage across the inductor. The voltage equation for Vienna rectifier is,

\[
\left( \frac{V_{bus}}{2} - V_{rms} \right) = L_i \frac{\Delta i_{pp}}{D \cdot T_s} \quad (12)
\]

where the time \(T_s = 1/F_{sw}\) is switching period, and \(D\) is duty cycle. The current ripple \(\Delta i_{pp}\) is,

\[
\Delta i_{pp} = D \cdot T_s \cdot \left( \frac{V_{bus}}{2} - V_{rms} \right) \quad (13)
\]

The duty cycle \(D = m_a \cdot \sin(\omega t)\), where \(m_a\) is the modulation index and input voltage \(V_{rms} = D \cdot (V_{bus}/2)\), then current ripple can be derived as,

\[
\Delta i_{pp} = \frac{V_{bus} \cdot T_s \cdot m_a \cdot \sin(\omega t) \cdot (1 - m_a \sin(\omega t))}{L_i} \quad (14)
\]

It is clear from equation 14, the peak ripple changes in a sinusoidal manner. Equation 15 gives the maximum value by differentiating equation 14.

\[
\frac{d(\Delta i_{pp})}{dt} = K \{\cos(\omega t) (1 - m_a \sin(\omega t)) \}
- m_a \sin(\omega t) \cos(\omega t)\} = 0 \quad (15)
\]

At \(\sin(\omega t) = 1/ (2 \cdot m_a)\), the maximum current ripple has been attained, and it is derived in Equation 16.

\[
\Delta i_{pp} = \frac{V_{bus} \cdot T_s \cdot m_a}{L_i} \quad (16)
\]

\[
L_i = \frac{V_{bus}}{4 \cdot F_{sw} \cdot \Delta i_{pp_{max}}} \quad (17)
\]

Using equation (17), required inductance can be calculated, and suitable core material can be selected for inductor design.
B. OUTPUT CAPACITOR SELECTION

The ripple in the DC output voltage will be minimized by placing a capacitor at the output side. Output capacitor value can be calculated using equation (18) based on the output voltage ripple specification.

\[
C = \left( \frac{1}{3} \right) \frac{P_{ac}}{4 \times f \times (V^2 - (V - \Delta V)^2)}
\]  

where,

- \( f \) = Grid frequency
- \( P_{ac} \) = AC power (input power) and
- \( \Delta V \) = change in input voltage

VII. EXPERIMENTAL RESULTS

The proposed VOC-based Vienna Rectifier has been experimentally tested to provide constant DC voltage at low input current THD. It is observed from Fig. 15 and 16 that input voltage and current show sinusoidal waveforms when the rectifier was tested with varying load (\( V_{AC} = 280 \) V RMS). The power measured during these experiments was 612W and 1364 W. The total harmonic distortion for input current was recorded at 2.5% for 612 W operation. The total harmonic distortion for input current was observed 0.96% for 1364 W operation, as shown in Fig.16. The experiments were done for an input voltage of 350 V AC and output voltage of 700V DC. In these tests, the recorded total harmonics distortion of input current was 7% for the output power of 960W and 3.5% for the output power of 1865W, as shown in Fig. 17 and Fig. 18, respectively. As input current THD is less than 5% in most cases, the IEEE-519 standard is satisfied, and the system provides a good power factor at the input side. The DC voltage at the output side is constant, and it is maintained at 600 V or 700 V – similar to the reference voltage. Table 4 demonstrates the experimental results of the Vienna rectifier with a VOC controller for the input voltage of 208 V AC RMS and output voltage of 600 V DC. The tests were carried out for different load conditions. The DC output voltage is shown in Fig. 19.

Table 5 demonstrates the experimental results of the Vienna rectifier with a VOC controller for the input voltage of 350 V AC RMS with 700 V DC output voltage.
FIGURE 18. Input voltage and current waveforms for 350 V AC, 700 V DC, 1865 W and THD = 3.5%.

FIGURE 19. DC output voltage of 600 V DC with 612 W load.

FIGURE 20. Input current THD in % for 350 V AC RMS in and 700 V DC out with 1865 W.

Experimental power output vs. efficiency is shown in Fig. 21. The efficiency is maintained above 95% for the different power ratings.

Experimental power output vs. input current THD is shown in Fig. 22. The input current THD is less than 5% for most of the cases. Hence, the input current THD satisfies the IEEE-519.

Experimental power output vs. power factor is shown in Fig. 23. Power factor is maintained between 0.8 and 1 for different loading conditions. The power factor for the proposed system achieves unity for the majority of loading conditions, 200 W – 1500 W.

VIII. BENCHMARKING

The proposed VOC-based Vienna rectifier (VOC-VR) system improves the rectifier designs from the past works. Table 6 provides a comparison between the proposed system and the published rectifier systems for similar applications. The SEPIC converters and 3 phase-controlled converters are used for medium power applications, for example, wind power applications [38], [39]. The Vienna rectifier with the PFC controller has been used in low-power applications, including slow charging stations for electric vehicles. The voltage produced by the conventional PFC controller-based Vienna rectifier was approximately 200 V DC, which is less than the proposed system [36]. This is mainly because the
optimization of PI parameters in a conventional PFC controller is challenging for higher output voltage. The optimized PI parameters in the VOC controller give much better results compared to the PFC controller. Hence, the PFC controller-based Vienna rectifier system cannot be used in high-power applications like welding power sources or fast-charging DC stations.

Moreover, the results show that design process of the proposed system is much simpler and use of VOC with the PWM modulator is ideal for specified applications such as EV charging stations and welding power. Using same input filter proposed in the VOC-VR system, the conventional Vienna rectifier designed for high-power applications could increase the input current distortion. Therefore, in order to minimize the total harmonic distortion in input current, the VOC-based PWM control is proposed for the Vienna rectifier.

The simulation and experiment results show that the average input currents THD is less than 5% for most of the cases in the VOC-VR system. In other words, when the proposed system is used in EV fast-charging stations or welding power applications, it will not cause much distortions in the input current, and input power factor would be close to unity.

IX. CONCLUSION

In this research work, a three-level Vienna rectifier based on a voltage-oriented controller (VOC-VR) has been designed and experimentally tested. The proposed system has been simulated using MATLAB Simulink software targeting high-power applications such as DC-fast chargers for electric vehicles. The proposed controller for Vienna rectifier focused on combining voltage-oriented controllers with the PWM method. In proposed design, the reactive and unstable active currents are counteracted by the input and output filters and Voltage Oriented Controller (VOC) with Vienna rectifier. The proposed design also guarantees a sinusoidal current at the input side with minimum ripples and distortions. The system’s power factor is maintained at unity, and total harmonic distortion of the input current is kept less than 5 %, which meets the IEEE-519 standard. The benefit of the proposed controller over conventional PFC controller has been demonstrated by simulations and experimental results. Low THD, good power factor, and smaller filtering requirements make the voltage-oriented controller-based Vienna rectifier an ideal candidate in electric vehicle charging stations.

CONFLICT OF INTEREST STATEMENT

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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