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2021

Molligoda, D., Ceballos, S., Pou, J., Satpathi, K., Sasongko, F., Gajanayake, C. & Gupta, A.
(2021). Hybrid modulation strategy for the Vienna rectifier. IEEE Transactions On Power
Electronics, 37(2), 1283-1295. <https://dx.doi.org/10.1109/TPEL.2021.3103766>

<https://hdl.handle.net/10356/152981>

<https://doi.org/10.1109/TPEL.2021.3103766>

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Hybrid Modulation Strategy for the Vienna Rectifier

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Abstract—The Vienna rectifier can produce three voltage levels, however only the connection to the neutral-point is fully controllable using the bidirectional switches. When the neutral-point voltage is not imposed in a phase-leg, the polarity of the pulses generated depends on the diode that is conducting in that phase-leg, which is defined by the current direction. As a result, the voltage pulses generated can go in the opposite direction to what is demanded by the controller, and the current becomes distorted. This can be mitigated by injecting a particular zero sequence so that the reference voltage is clamped to the neutral-point during the intervals where the current of a phase-leg has the opposite sign than its reference voltage. However, the converter is at risk of entering into overmodulation when operating with high modulation indices. In this paper, a hybrid modulation strategy is introduced where a calculated minimal amount of reactive current depending on the operating conditions is injected to avoid overmodulation. The reduction of reactive current required compared to the state-of-the-art solutions is up to 100% in certain operating conditions. With the proposed method, the Vienna rectifier can operate in a wide range of power factors without compromising the quality of the source currents. The concept is verified by simulation and in a 1-kW Vienna rectifier experimental setup.

Index Terms—Nonunity power factor, reactive power compensation, Vienna rectifier, zero crossing current distortion.

I. INTRODUCTION

Having the simplest circuit structure among the three-phase three-level converters, the Vienna rectifier, as depicted in Fig. 1, is increasingly popular in many unidirectional active front end applications. It has several advantages such as its ability to operate at unity power factor (UPF), which results in lower distortion in the source currents, high power density, high efficiency and high reliability [1]–[3]. In this topology, only half of the dc-link voltage appears across the bidirectional switches, hence low-voltage blocking capability is required in those switches. Such advantages make it an attractive topology for active front-end rectifier applications [1], [2]. The Vienna rectifier is similar to the T-type converter [4] and can achieve the same current waveform quality despite having fewer active switches. It can outperform a two-level six switch active rectifier by having higher efficiency, and it also demands smaller filter inductances for a given current ripple due to the three-level operation [5].

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Although the Vienna rectifier is a three-level converter, it has full control only of the neutral connection, which is achieved through bidirectional switches. Due to the diode connections to the positive and negative voltage rails, the current direction defines the top and bottom voltage levels. When the Vienna rectifier is operating other than unity power factor, there are instances where the voltage reference and the source current near the current zero crossings have opposite signs. This leads to erroneous voltage pulses near the current zero crossings that cause low-frequency distortion in the current waveform [5]–[11].

Significant reduction in current distortion can be achieved by clamping the leg that generates pulses with an opposite sign to the neutral-point [5], [12]. This method is ineffective at low power factors because the clamping duration has to be sustained for long duration. In [13], current oriented control is proposed where the angle information is extracted from the source current instead of the source voltage. It mitigates the zero crossing problem; however, the converter may not operate as desired when the inductance is low or operating with light loading [14], where the current waveforms are expected to have high current ripples.

A special zero sequence implemented in carrier-based PWM, which connects the ac terminals to the neutral-point during certain intervals, is proposed in [15] and [16]. A similar idea is implemented in [17] using a space-vector PWM approach, improving the input current waveform, and extending to both balanced and unbalanced dc-link voltages. However, in the above methods, large phase displacement angles at higher modulation indices would cause distortion in the source current waveform, unless the modulation index is restricted. This can be crucial in variable speed applications where the fundamental frequency and the modulation index could vary in a certain range. Generator-connected rectifier in more electric aircraft is an example. The converters used in aerospace applications should guarantee current waveform quality specified by DO-160 standard, throughout its operating range. If the above method is applied to the Vienna rectifier and proper action is not taken in certain operating points, overmodulation would occur deteriorating the current waveform quality. In [18], the method proposed in [16] is further improved with reactive power injection to extend the operating range. However, it involves excessive reactive power usage.

A third harmonic injection method to remove the current distortion in a Vienna rectifier with LCL filter is discussed in [19]. The reference voltage is shifted by adding the third harmonic such that the reference voltage would always have the same polarity of the current. The LCL filter is used because of its reduced volume and weight compared to the L filter. However, in applications where the reliability is a major

Fig. 1. Topology of the Vienna rectifier.

concern, the simpler, reliable L filter with less component count, might be preferred.

In this paper, the method proposed in [18] is further improved by using the special zero sequence and reactive power compensation (RPC), to create a hybrid modulation scheme that extends the operating range of the Vienna rectifier. The proposed method injects the minimum reactive current required just enough to avoid overmodulation caused by the notches generated by the special zero sequence. The reduction in reactive current achieved compared to [18] is spectacular. This means the hybrid modulation and control method would achieve good current waveform quality and efficiency at the same time. It also uses the min-max zero sequence, instead of the sinusoidal third harmonic injection used in [19]. The major advantages of the proposed hybrid modulation are,

- 1) Wide power factor range of operation without compromising the quality of source currents.
- 2) Operation with constraint-free modulation index.
- 3) Seamless transition between operating points.
- 4) Simple real-time reactive current calculation suitable to be implemented in a digital signal processor (DSP).

The paper is organized as follows. In Section II, two selected distortion mitigation techniques are discussed in detail. Section III introduces the proposed hybrid modulation technique with the derivation of reactive current required, and an analysis on current waveform quality and efficiency. Section IV focuses on the benefits of the proposed method supported with experimental validation. Finally, Section V summarizes the main conclusions of the paper.

II. DISTORTION MITIGATION METHODS

Two main control methods to operate the Vienna rectifier that avoid low-frequency distortion in the input currents are discussed in this section, i.e. the zero sequence injection method and the reactive power injection method.

A. Zero Sequence Injection Method

The injection of zero sequence allows the Vienna rectifier to operate at nonunity power factor at its ac-terminals (method-1). It is based on the idea of using a special zero sequence voltage [15], [16] for the time duration when the voltage reference and the input current of a given phase leg have

TABLE I
PARAMETERS OF THE VIENNA RECTIFIER UNDER STUDY

Parameter	Value
Output power, P_{out}	416 W
DC-link voltage, V_{dc}	100 V
RMS line-to-line voltage, V_{l-l}	60.6 V
Filter inductor, L	3 mH
DC-link capacitors, C	220 μ F
Switching frequency, f_{sw}	50 kHz
Fundamental frequency, f	60 Hz

opposite signs, in such a way that the reference voltage for this leg is clamped to zero.

Let us define a normalized three-phase set of voltages as:

$$v_x = m \sin(\omega t + \delta_x) \quad (1)$$

with $x \in [a, b, c]$, where v_x is the normalized voltage of phase x , $\delta_{a,b,c} = \{0, 4\pi/3, 2\pi/3\}$ and m is the modulation index defined by

$$m \triangleq \frac{\hat{E}}{v_{dc}/2} \quad (2)$$

where $\hat{E}$ is the phase voltage amplitude and v_{dc} is the dc-link voltage.

Analogously, a three-phase set of currents with the polarity given in Fig. 1 is defined:

$$i_x = I \sin(\omega t + \delta_x + \phi) \quad (3)$$

with $x \in [a, b, c]$, where I is the amplitude of the current and ϕ is the phase displacement angle between the voltage reference and the current.

Following the idea commented above, the special zero sequence that clamps to zero the phase leg with different

Fig. 2. Main waveforms when the special zero sequence is injected to the Vienna rectifier.

Fig. 3. Consequences of the zero sequence injection: (a) Reference voltage after adding the zero sequence; v_{source} source voltage waveform, i_a input current and v_{refa} reference voltage signal of phase a , (b) modulation index restriction based on the phase displacement angle, and (c) maximum reference voltage when the zero sequence is injected without modulation index constrain.

voltage and current polarity can be expressed as a common mode voltage (v_{cm1}),

$$v_{cm1} = \begin{cases} -m \sin(\omega t), & k\pi \leq \omega t < k\pi + \phi \\ -m \sin(\omega t - \frac{2\pi}{3}), & \frac{(3k+2)\pi}{3} \leq \omega t < \frac{(3k+2)\pi}{3} + \phi \\ -m \sin(\omega t + \frac{2\pi}{3}), & \frac{(3k+1)\pi}{3} \leq \omega t < \frac{(3k+1)\pi}{3} + \phi \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where $k \in \mathbb{Z}$. This common mode voltage can be combined with the well-known min-max zero sequence used to maximize the range of modulation index within the linear region, in such a way that the total common mode voltage used adopts the expression:

$$v_{cm} = \begin{cases} v_{min-max}, & \text{if } v_x i_x > 0 \\ v_{cm1}, & \text{otherwise} \end{cases} \quad (5)$$

with,

$$v_{min-max} = -\frac{\max(v_{an}, v_{bn}, v_{cn}) + \min(v_{an}, v_{bn}, v_{cn})}{2} \quad (6)$$

where v_{an} , v_{bn} and v_{cn} are the original reference voltage signals for phases a , b and c , respectively.

According to (5), when the voltage reference and the current of a given phase-leg have the same polarity, the common mode voltage is calculated according to the min-max approach to maximize the modulation index range. If the voltage reference and the current of a particular phase have opposite polarity, the min-max common mode voltage is substituted by the special zero sequence given by (4) so that the phase leg is clamped to zero.

In this way, regardless of the current polarity, the voltage reference matches the voltage generated by the Vienna rectifier, thus eliminating the low-frequency distortion in the current waveform. Fig. 2 illustrates the main waveforms when (5) is used in the Vienna rectifier with the system parameters listed in Table I. With the selected operating point, the special zero sequence generates notches in the reference signals as shown in Fig. 3(a), which may produce overmodulation, especially when operating with high modulation indices. As a result, the modulation index has to be limited.

The highest modulation index that the converter can operate without producing overmodulation is determined by examining

the maximum value of the reference signal once the zero sequence is added, which according to (5), leads to the following constraint:

$$m \leq \frac{1}{\sqrt{3} \sin(\frac{\pi}{6} + \phi)} \quad (7)$$

Equation (7) provides the maximum modulation index that the Vienna rectifier can operate without producing overmodulation and current distortion, as a function of the phase displacement angle between the voltage reference and the current. This condition is graphically illustrated in Fig. 3(b). If the condition is violated and the modulation index is unconstrained, as shown in Fig. 3(c), then the maximum reference voltage will exceed $v_{dc}/2$ and the converter will not be able to generate these voltages. If no action is taken, this will result in low-frequency distortion in the source currents.

B. Reactive Power Injection Method

While the Vienna rectifier is operating with UPF at the source side, the phase displacement between the voltage reference and the current will be nonzero due to the voltage drop across the boost inductor. This phase displacement depends on the value of the boost inductor, source current and also the fundamental frequency. For operating conditions with large phase displacements and large modulation indices, the modulation index may have to be restricted to avoid overmodulation (according to Fig. 3(b)) if the zero sequence injection method described in Section II-A is used [16]. An alternative method

Fig. 4. Phasor diagram for the Vienna rectifier when it is operating in different configurations: Black-A- UPF at the source, blue-B- UPF at the converter and green-C- UPF at the boundary of overmodulation.

to eliminate the zero crossing distortion without compromising the modulation index is by operating at UPF at the converter ac terminals. This can be achieved by RPC, which reduces the phase displacement between the reference voltage and the source current [15], [18], [20], [21]. With the correct amount of reactive current injected, the modulation index does not need to be restricted and the converter can operate with high modulation indices.

Fig. 4 illustrates different operating configurations illustrated by phasor diagrams. UPF operation at the source side is represented by the polygon enclosed by the source voltage, voltage drop due to the series resistance in the inductor, converter reference voltage, voltage drop across inductor denoted by vectors $\mathbf{E}_d$, $\mathbf{R}\mathbf{I}_1$, $\mathbf{V}_{\text{ref}1}$ and $\mathbf{V}_{L1}$, respectively. Similarly, UPF operation at the converter terminals is represented by the vectors $\mathbf{E}_d$, $\mathbf{V}_{\text{ref}2}$, $\mathbf{R}\mathbf{I}_2$ and $\mathbf{V}_{L2}$. The source currents in the two operating conditions are $\mathbf{I}_1$ and $\mathbf{I}_2$, respectively. When the reactive current component is added, the current vector follows the trajectory shown in red dotted line. By solving the polygons in Fig. 4, the amount of reactive current needed to achieve UPF at the converter ac terminals can be calculated as follows:

$$\sin \alpha = \frac{V_{L2}}{E_d} = \frac{\omega L I_2}{E_d} = \frac{I_{q2}}{I_2} \quad (8)$$

where α is the angle between the input current vector and the

Fig. 5. Main waveforms for UPF operation at the converter terminals using RPC in the Vienna rectifier.

Fig. 6. Reactive current injected to achieve UPF at converter.

source voltage vector, when the rectifier is operating with UPF at its terminals. Expanding I_2 in (8),

$$\omega L (I_1^2 + I_{q2}^2) = I_{q2} E_d \quad (9)$$

Solving (9) for I_{q2} with some mathematical operations, the calculated reactive current for achieving UPF at the converter terminals is:

$$I_{q2} = -\frac{E_d}{2\omega L} \left[1 - \sqrt{1 - \left(\frac{2\omega L I_1}{E_d} \right)^2} \right] \quad (10)$$

where E_d and I_1 are d-axis components of the source voltage and current, respectively. These are instantaneous values available in the controller, and information of the load is not required. Although this solution solves the current distortion issue, since it involves reactive current injection, the converter power rating would increase.

Fig. 5 depicts simulated main waveforms of the Vienna rectifier when the RPC is performed such that UPF is at the converter terminals. By having UPF at the converter terminals, the distortion created by the notches is removed, at the cost of increased power rating.

Fig. 6 shows the reactive current demand analysis with respect to the modulation index of the converter and the phase displacement angle. The simulation uses a fixed source voltage and constant power. Therefore, the active current component would be constant, and the phase displacement angle is varied by changing the fundamental frequency of the source.

The main limiting factors in the methods discussed thus far are as follows. The zero sequence injection method, with UPF at the source side, offers the benefit of reduced low-frequency current distortion, but restricts the modulation index range. Having the UPF at the converter side (method-2) resolves this issue, but increases the component ratings as it involves significant reactive power injection.

III. HYBRID MODULATION STRATEGY FOR THE VIENNA RECTIFIER

This Section introduces a hybrid modulation method that uses only a fraction of the reactive current compared to the reactive power injection method, while avoiding overmodulation.

If the converter is about to enter overmodulation due to the notches created by the special zero sequence, then a calculated amount of reactive current depending on operating conditions will be injected just enough to avoid overmodulation.

By considering the equality condition of (7), the angle just before overmodulation can be expressed as:

$$\sin\left(\frac{\pi}{6} + \phi_{lim}\right) = \frac{1}{\sqrt{3}m} \quad (11)$$

where ϕ_{lim} is defined as the critical phase displacement angle and can be obtained as follows.

By simplifying (11):

$$k \sec \phi_{lim} = 1 + \sqrt{3} \tan \phi_{lim} \quad (12)$$

where $k = \frac{2}{\sqrt{3}m}$, which leads to,

$$0 = 1 - k^2 + 2\sqrt{3} \tan \phi_{lim} + (3 - k^2) \tan^2 \phi_{lim} \quad (13)$$

By solving the quadratic equation and using the known $\phi_{lim} = 5.26$ degrees at $m = 1$:

$$\tan \phi_{lim} = \frac{-3\sqrt{3}m^2 + 2\sqrt{12m^2 - 4}}{9m^2 - 4} \quad (14)$$

Equation (14) provides the critical displacement angle as a function of the modulation index. The phase shift between the voltage at the converter terminals and the current should always be equal or smaller than this critical displacement angle. Otherwise, the use of the special zero sequence voltage leads to overmodulation. The proposed hybrid modulation strategy injects the required fraction of reactive current so that the phase shift between voltage and current remains always below ϕ_{lim} . This operating condition is illustrated in Fig. 4. The hybrid current corresponds to I_h , and it has an angle ϕ_{lim} with the voltage at the converter terminals and δ with the source voltage. The steady state operation of this mode is represented by the polygon enclosed by the source voltage, voltage drop due to the series resistance in the inductor, converter reference voltage, voltage drop across inductor denoted by vectors $\mathbf{E}_d$, $\mathbf{R}\mathbf{I}_h$, $\mathbf{V}_{ref-h}$ and $\mathbf{V}_{L-h}$, respectively. By making use of the properties of the vector addition, the following equalities in the d and q axis are obtained:

$$E_d = v_{refh} \cos(\phi_{lim} + \delta) + RI_1 + \omega LI_{qh} \quad (15)$$

$$0 = v_{refh} \sin(\phi_{lim} + \delta) + RI_{qh} - \omega LI_1 \quad (16)$$

From (15)

$$v_{refh} = \frac{E_d - RI_1 - \omega LI_{qh}}{\cos(\phi_{lim} + \delta)} \quad (17)$$

and substituting v_{refh} in (16)

$$0 = \tan(\phi_{lim} + \delta)[E_d - RI_1 - \omega LI_{qh}] + RI_{qh} - \omega LI_1 \quad (18)$$

By using the sum identity for the tangent

$$\tan(\phi_{lim} + \delta) = \frac{\tan(\phi_{lim}) + \tan(\delta)}{1 - \tan(\phi_{lim}) \tan(\delta)} \quad (19)$$

Fig. 7. Flowchart of the reactive current reference (i_{q-ref}) calculator.

Fig. 8. Comparison of reactive current injection with UPF at the converter side and the proposed hybrid modulation strategy.

Considering

$$\tan(\delta) = \frac{I_{qh}}{I_1} \quad (20)$$

equation (19) can be simplified as

$$\tan(\phi_{lim} + \delta) = \frac{I_1 \tan(\phi_{lim}) + I_{qh}}{I_1 - I_{qh} \tan(\phi_{lim})}. \quad (21)$$

By substituting (21) in (18)

$$0 = [E_d - RI_1 - \omega LI_{qh}][I_1 \tan(\phi_{lim}) + I_{qh}] + [I_1 - I_{qh} \tan(\phi_{lim})][RI_{qh} - \omega LI_1] \quad (22)$$

which can be further simplified as

$$0 = (E_d - RI_1)I_1 \tan(\phi_{lim}) - \omega LI_1^2 + E_d I_{qh} - (R \tan(\phi_{lim}) + \omega L)I_{qh}^2 \quad (23)$$

Solving the resulting quadratic equation and neglecting the series resistance, the critical reactive current just enough to avoid overmodulation can be calculated as

$$I_{qh} = \frac{E_d}{2\omega L} \left[1 - \sqrt{1 - \left(\frac{2\omega LI_1}{E_d} \right)^2 + v_\beta} \right] \quad (24)$$

where $v_\beta = 4\omega LI_1 \tan(\phi_{lim})/E_d$.

For lower phase displacement angles and for lower modulation indexes, the required reactive current is zero, as the zero sequence alone can handle the distortion compensation, since there is no risk of overmodulation. The flow chart in Fig. 7 details the algorithm used for deciding when to

Fig. 9. Reduction in the reactive current requirement to avoid overmodulation with the proposed hybrid modulation instead of operating with UPF at the converter side.

Fig. 10. VOC with the zero sequence injection for the Vienna rectifier with the hybrid modulation.

Fig. 11. Main waveforms when hybrid modulation is used in the Vienna rectifier.

Fig. 12. Overcoming the modulation index restriction with the proposed modulation and control strategy.

Fig. 13. Current THD variation when different modulation and control methods are used in the Vienna rectifier.

use the reactive current. From the available measurements in the controller, the phase displacement angle is calculated and the corresponding maximum allowable modulation index (m_{max}) is calculated, as represented in Fig. 3(b). If m_{max} is greater than the modulation index, then there is no need for reactive power compensation as no distortion is caused by the zero sequence. However, if the modulation index of the converter is greater than m_{max} then i_{qh} should be injected by solving (24) as the required reactive current. Fig. 8 depicts the reactive current requirement for the hybrid operation for different modulation indices and phase displacement angles. As expected, the converter needs more reactive current when the phase displacement angle and modulation index increase and follows the boundary line shown in Fig. 3(b). As Fig. 8 shows, the required reactive current is much less compared to operating at UPF at the converter side, as depicted in Fig. 6. The reduction in reactive current is shown in Fig. 9.

Fig. 10 illustrates the implementation of the proposed control for the Vienna rectifier. The reference voltage that comes out of the voltage oriented control (VOC) is injected with the zero sequence voltage provided by (5). The source synchronization is done by a phase-locked loop (PLL), in such a way that the direct axis is aligned with the source voltage vector and the quadrature axis is leading 90 degrees. Consequently, i_d is responsible for the active power transfer, and i_q defines the reactive power component. The i_{q-ref}

calculator block solves (24) and runs the algorithm in Fig. 7 giving the controller the magnitude of the reactive current reference and when to inject the reactive current.

Fig. 11 shows the main waveforms of the hybrid modulation method. It achieves similar current waveform quality as that of the UPF at the converter terminal with RPC method, but with only injecting a fraction of the reactive current. For the operating point given in Table I, the reactive current requirement is reduced from 1.04A to 0.27A.

Fig. 12 illustrates the modulation index restriction removed by the proposed hybrid modulation and control scheme. Now the converter can operate with high phase displacement angles without current distortion, even at higher modulation indices. In the RPC region, the i_{q-ref} calculator determines the correct amount of reactive current just enough to avoid overmodulation. Fig. 13 illustrates the current THD variations when these three modulation and control methods are used. As it shows, the first method (special zero sequence injection with UPF at source side) produces more distortion in the current waveform when the phase displacement increases.

The efficiencies are obtained using PLECS thermal models throughout the operating range in the Vienna rectifier when the hybrid modulation method is used as opposed to operating with method-2, defined by;

$$\eta = \frac{v_{dc}i_{dc}}{v_{dc}i_{dc} + losses} \quad (25)$$

where the losses are the conduction and switching losses of the rectifier. 70° C ambient temperature and 0.1° C/W case to ambient thermal resistance are assumed for the analysis.

The conduction power loss normalized by the output power when the hybrid modulation method and method-2 are used, is illustrated in Fig. 14(a). As the modulation index reduces because the dc-side voltage increases, conduction loss reduces for both methods. However, in method-2, the reduction in loss is less, compared to hybrid modulation as more reactive current is involved. As the phase displacement increases, the conduction loss increases in both cases, but more in method-2 for the aforementioned reason.

Fig. 14(b) depicts the switching loss representation. When the modulation index reduces as the dc-side voltage increases, in both cases the switching loss increases, but it is more significant in method-2 (as the current amplitude is more in method-2). At higher phase displacement angles the current amplitude difference will be more in the two methods and it is reflected in the switching loss. Furthermore, as the neutral point clamping time increases, the number of switching transitions will be lower in the hybrid modulation compared to method-2, thus showing lower switching losses for larger phase displacement angles, more noticeably in low modulation indices.

As Fig. 14(c) illustrates the proposed hybrid method has better efficiency throughout the operating region. When the modulation index is the maximum ($m = 1.15$), operating at UPF at the converter side and the hybrid method become identical, as both methods inject the same amount of reactive current at $m = 1.15$. Interestingly, the hybrid method has better efficiency compared to method-2, particularly when the

TABLE II
OPERATING POINTS IN THE EXPERIMENT

Operating Point	A	A ₁	B	B ₁	C
Load Resistor (Ω)	44	44	21	44	21
Fundamental frequency (Hz)	60	30	60	60	120
Phase displacement (degrees)	2.9	2.9	6.2	6.2	12.25
modulation index	0.99	0.79	0.99	0.79	1.14

TABLE III
COMPLEXITY COMPARISON BETWEEN MODULATION TECHNIQUES

Modulation	UPF at Source	UPF at Converter	Hybrid
ISR execution time (μs)	8	8.85	9.26

modulation index is lower. This is because the reactive current requirement is much lower in the hybrid method compared to method-2, as shown in Fig. 9.

IV. EXPERIMENTAL RESULTS

This Section discusses the benefits of using the proposed modulation and control technique for the Vienna rectifier with experimental validation. Several experiments were performed using the C2000 Texas Instruments (TI) Vienna rectifier. The bidirectional switch is constructed by integrating two IPP65R190C7 MOSFETs connected in common source configuration. The diodes used are SiC C4D08120A. The control methods are implemented on a 32-bit DSP TMS320F28379D. A programmable ac power source is used to generate the source voltages and a resistive load bank is connected at the dc side of the converter. The experimental setup is shown in Fig. 15. Steady state and transient waveforms from the converter are obtained and discussed below. Five operating points designed as A, A₁, B, B₁ and C, as listed in Table II with their locations as marked in Fig. 12, have been considered for the experiment. The fundamental frequency of the voltage source had to be adjusted according to Table II in order to reach the different operating points. The corresponding waveforms when the Vienna rectifier is operating in these points are illustrated in Fig. 16 with the current spectrum in each case depicted in Fig. 17. The operating points are selected such that B, and C will be above the boundary of overmodulation (orange zone in Fig. 12) where reactive current injection is needed to operate the converter without overmodulation. As Points A, A₁ and B₁ lie beneath the boundary of overmodulation (green zone in Fig. 12), the converter does not require any reactive power compensation because the notch created by the special zero sequence is less than half the dc-link voltage. The zero sequence calculation from the measurements and the reactive current calculation using the real-time values should be executed within the 20 μs time interval in the DSP. With the DSP running at 200MHz clock frequency, the PWM interrupt service routine (ISR) that executes the proposed hybrid modulation only needs an execution time of 9.26 μs , which is a marginal increase compared to the other two methods discussed. A summary of the ISR execution times is listed in Table III.

Fig. 14. Efficiency analysis for the Vienna rectifier with different modulation and control methods: (a) Conduction loss, (b) switching loss and (c) efficiency at different operating conditions.

Fig. 15. Experimental setup of the Vienna rectifier.

A. Wider Range of Operation with Less Reactive Current

When the Vienna rectifier is operating with method-1, the current harmonic distortion is generally more compared to the other two methods. This is illustrated in Figs. 16(a), (d), (g), (j) and (m) corresponding to points A, A₁, B, B₁ and C, respectively. When the rectifier is operating in the orange zone, as the phase displacement angle between the current and the reference voltage increases, the current distortion is more in this method due to the increase of overmodulation period. This is reflected in V_{an} in Fig. 16(m), corresponding to the Point C, which has the highest phase displacement with maximum modulation index and it has the worst current quality in the study. When the Vienna rectifier operates with UPF at its terminals with the help of calculated reactive current, the current waveform quality improves, but at the cost of higher current rating. This is due to the additional reactive current component. This operating mode is illustrated in Figs. 16(b), (e), (h), (k) and (n) corresponding to points A, A₁, B, B₁ and C, respectively.

The main waveforms from the proposed hybrid modulation method are depicted in Figs. 16(c), (f), (i), (l) and (o) corresponding to Points A, A₁, B, B₁ and C, respectively. The hybrid method shows similar performance to the UPF at the source with zero sequence method for operating points which are under the boundary of overmodulation (Points A, A₁ and B₁). This is because there is no overmodulation at these points, hence no reactive current is required. However, for the operating points above the boundary of overmodulation (B and C), the proposed hybrid modulation has superior current waveform quality (Fig. 17) when compared with UPF at the source with the special zero sequence and the results are con-

TABLE IV
REDUCTION IN REACTIVE CURRENT WHEN THE PROPOSED HYBRID MODULATION IS USED REPLACING METHOD-2.

Operating Point	i_{q2} (A)	i_{qh} (A)	% reduction in i_q
A	0.26	0	100
A ₁	0.26	0	100
B	0.95	0.22	77
B ₁	1.42	0	100
C	1.42	1.24	13

sistent throughout the operating points. This can be achieved by a fraction of the reactive current required in the second method where the UPF is kept at the converter terminals. The reduction in reactive current for the five operating points in the experiment are summarized in Table IV.

Fig. 18(a) illustrates a comparison of harmonics against the DO-160 standard limits when the Vienna rectifier is operating in Point-C, with the UPF at the source side injecting the zero sequence to clamp the switches. The aerospace standard DO-160 is used as the regulation since an aerospace generator-connected rectifier is a potential application of the Vienna rectifier. As the figure shows, there is a clear violation of the standard for the 5th and 7th harmonic when method-1 is used. On the other hand, when the proposed hybrid modulation method is applied for the same operating point, as illustrated in Fig. 18(b), the converter operates with good current waveform quality and within the regulation limits.

Therefore, these results demonstrate that the hybrid modulation scheme produces low current THD values and exhibits the best current waveform quality among the methods discussed, using the minimum reactive current.

B. Efficiency Analysis

Fig. 19 illustrates an efficiency analysis performed in the Vienna rectifier with the three methods discussed, using experimental setup for the operating points listed in Fig. 12.

In the experiment, the points A, A₁, B₁ will have similar losses for the hybrid method and operating with UPF at the source side, i.e. method-1. In these points, the hybrid method does not use any reactive power as the points are below the boundary of overmodulation.

Fig. 16. Experimental results with different modulation and control techniques. Operating Point A (60Hz): (a) Injecting the special zero sequence, (b) UPF at converter with RPC and (c) hybrid modulation. Operating Point A₁ (30Hz): (d) Injecting the special zero sequence, (e) UPF at converter with RPC and (f) hybrid modulation. Operating Point B (60Hz): (g) Injecting the special zero sequence, (h) UPF at converter with RPC and (i) hybrid modulation. Operating Point B₁ (60Hz): (j) Injecting the special zero sequence, (k) UPF at converter with RPC and (l) hybrid modulation. Operating Point C (120Hz): (m) Injecting the special zero sequence, (n) UPF at converter with RPC and (o) hybrid modulation.

On the other hand, Point B is above the boundary of overmodulation, which means if the Vienna rectifier is controlled by method-1, it would create overmodulation. This is reflected in the increased current THD, as shown in Fig. 17(f). In this case, when the converter operates in method-1 the phase displacement between the current and the reference voltage would be 6.2 degrees. When the hybrid modulation is used, the angle will be reduced to 5.26 degrees, which is the

critical angle for Point B (calculated by solving (14)). This is done by injecting 0.22A of reactive current. The experimental results show that the hybrid modulation has better performance compared to method-1 even though it injects the above reactive current. This is because when method-1 is used, the converter operates in overmodulation and the higher harmonic content produces extra losses. However, when method-2 is used, this phase displacement angle is made zero by injecting 0.95A

Fig. 17. Experimental current spectrum from different operating points: (a) Point A, (b) Point A₁, (c) Point B, (d) Point B₁, (e) Point C and (f) summary of current THD.

Fig. 18. Vienna rectifier tested to comply with DO160 Aerospace Standard at Point-C: (a) With method-1 and (b) with hybrid modulation.

Fig. 19. Efficiency of the Vienna rectifier setup at different operating points.

of reactive current, and hence it has the lowest efficiency for Point B.

Since Point C operates with a modulation index $m = 1.14$, when the converter operates with the hybrid modulation, the reactive current injected is 1.24A, which is lower than the reactive current used in method-2 (1.42A). Therefore, when the converter is operating at Point C, the proposed hybrid modulation shows higher efficiency, compared to method-2. However, in this operating point, method-1 would perform better even with overmodulation as the reactive currents in the other two methods are significant. Overall, the hybrid modulation has better efficiency than method-2, and equal

Fig. 20. Effect of the voltage loop bandwidth on the current waveform quality under different modulation and control techniques: (a) Injecting the special zero sequence [16], (b) UPF at converter with RPC and (c) hybrid modulation scheme.

Fig. 21. Seamless transition between operating points: (a) The special zero sequence is injected, (b) operating with UPF at the converter side with RPC and (c) with the hybrid modulation.

or less efficiency compared to method-1, depending on the operating point.

C. Transient Response

Selection of the voltage loop bandwidth in the VOC is important in this application and it would be a trade-off between the current THD and the transient response. For the experiments illustrated in Fig. 16, a 10Hz voltage control loop bandwidth was selected. The experiment was repeated with different voltage loop bandwidths in the VOC under the three different modulation and control methods discussed in this paper, which are summarized in Fig. 20. In all the three methods, slower voltage loop yields better line current quality. The improvement in current waveform quality is better when the converter operates with UPF at the converter terminals with RPC, however at the cost of increased component rating. The proposed hybrid method generates good current waveform quality, with less reactive current requirement.

D. Seamless Transition

The proposed hybrid modulation does not inject any reactive current unless there is overmodulation, caused by the special zero sequence. If reactive current is required, (24) provides the exact reactive current value and the transition between operating points would be seamless, unlike the solution that forces the converter to operate with UPF at the converter terminals.

Fig. 21 depicts the main waveforms when the operating point is shifted from Point A to B. According to Fig. 21(a), when the converter operates in Point A, injecting the special zero sequence does not create any overmodulation. However, when the operating point is shifted to Point B, if no special action is taken, the current waveform will be distorted due to

overmodulation. This is evident when the current THD values (operating Point B) in Fig. 21(a) are compared with those in Fig. 21(b), the latter being corrected with RPC operating UPF at the converter terminals. In Fig. 21(c), the step change in the reactive current is less when hybrid modulation is used, compared to UPF at the converter terminals with RPC (Fig. 21(b)) and the transition happens smoothly.

V. CONCLUSION

In this paper, the current distortion produced in the Vienna rectifier around zero current crossings has been analyzed and a hybrid modulation method has been presented to reduce such distortion. The method consists of adding a special zero sequence to the reference signal while maintaining UPF at the source-side. However, overmodulation may be produced when operating with high modulation indices and large phase displacement angles. This problem can be avoided by injecting a calculated amount of reactive current in real-time just to avoid overmodulation created by the notches introduced by the special zero sequence. By using the proposed method, low-frequency distortion due to the current zero crossings can be avoided without restricting the modulation index, and with a minimal amount of reactive current. The study on efficiency shows clear improvements agreeing with the reactive current savings achieved by the hybrid modulation and control. Furthermore, the effect of the voltage control loop bandwidth that regulates the dc-link on the current waveform quality is demonstrated. When the operating point is shifted the transients are smooth as the reactive current step is small.

When the proposed hybrid modulation is used, full control of the converter can be achieved, as if it was a T-type converter (with top and bottom switches instead of only diodes). The proposed method can also be used for variable source voltages

such as those generated from a variable-speed permanent magnet synchronous generator. Effectiveness of the proposed methods has been demonstrated and verified by a hardware prototype.

REFERENCES

- [1] J. W. Kolar and F. C. Zach, "A novel three-phase utility interface minimizing line current harmonics of high-power telecommunications rectifier modules," *IEEE Trans. Ind. Electron.*, vol. 44, no. 4, pp. 456–467, Aug. 1997.
- [2] J. W. Kolar and T. Friedli, "The essence of three-phase PFC rectifier systems—part i," *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 176–198, Jan. 2013.
- [3] T. Friedli, M. Hartmann, and J. W. Kolar, "The essence of three-phase PFC rectifier systems—part ii," *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 543–560, Feb. 2014.
- [4] M. Schweizer and J. W. Kolar, "Design and implementation of a highly efficient three-level T-Type converter for low-voltage applications," *IEEE Trans. Power Electron.*, vol. 28, no. 2, pp. 899–907, Feb. 2013.
- [5] T. Viitanen and H. Tuusa, "Space vector modulation and control of a unidirectional three-phase/level/switch Vienna I rectifier with LCL-type AC filter," in *Proc. 34th Annu. Conf. on Power Electron. Specialist, (PESC)*, vol. 3, Jun. 2003, pp. 1063–1068.
- [6] H. Xu, W. Yao, and S. Shao, "Improved SVPWM schemes for Vienna rectifiers without current distortion," in *Proc. IEEE Energy Convers. Congr. and Expo. (ECCE)*, Oct. 2017, pp. 3410–3414.
- [7] F. Wang, Y. Teng, Z. Yuan, and J. Xu, "A maximum power factor of control algorithms of three-level Vienna rectifier without current distortion at current zero-crossing point," in *Proc. IEEE 8th Int. Power Electron. and Motion Control Conf. (IPEMC-ECCE Asia)*, May 2016, pp. 2325–2331.
- [8] A. R. Izadinia and H. R. Karshenas, "Current shaping in a hybrid 12-pulse rectifier using a Vienna rectifier," *IEEE Trans. Power Electron.*, vol. 33, no. 2, pp. 1135–1142, Feb. 2018.
- [9] A. Rajaei, M. Mohamadian, and A. Yazdian Varjani, "Vienna-rectifier-based direct torque control of PMSG for wind energy application," *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2919–2929, Jul. 2013.
- [10] L. Dalessandro, S. D. Round, U. Drogenik, and J. W. Kolar, "Discontinuous space-vector modulation for three-level PWM rectifiers," *IEEE Trans. Power Electron.*, vol. 23, no. 2, pp. 530–542, Mar. 2008.
- [11] D. Mukherjee and D. Kastha, "Voltage sensorless control of the three-level three-switch Vienna rectifier with programmable input power factor," *IET Power Electron.*, vol. 8, no. 8, pp. 1349–1357, Aug. 2015.
- [12] J. Alahuhtala, J. Virtakoivu, T. Viitanen, M. Routimo, and H. Tuusa, "Space vector modulated and vector controlled Vienna I rectifier with active filter function," in *Proc. 2007 Power Convers. Conf. - Nagoya*, Apr. 2007, pp. 62–68.
- [13] D. Mukherjee and D. Kastha, "Voltage sensorless control of Vienna rectifier in the input current oriented reference frame," *IEEE Trans. Power Electron.*, vol. 34, pp. 8079–8091, Aug. 2019.
- [14] M. Leibl, J. W. Kolar, and J. Deuringer, "Sinusoidal input current discontinuous conduction mode control of the Vienna rectifier," *IEEE Trans. Power Electron.*, vol. 32, no. 11, pp. 8800–8812, Nov. 2017.
- [15] J. Lee and K. Lee, "A novel carrier-based PWM method for Vienna rectifier with a variable power factor," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 3–12, Jan. 2016.
- [16] D. A. Molligoda, J. Pou, C. J. Gajanayake, and A. K. Gupta, "Analysis of the Vienna rectifier under nonunity power factor operation," in *Proc. Asian Conf. on Energy, Power and Transport. Electrification (ACEPT)*, Oct. 2018, pp. 1–7.
- [17] W. Ding, C. Zhang, F. Gao, B. Duan, and H. Qiu, "A zero-sequence component injection modulation method with compensation for current harmonic mitigation of a Vienna rectifier," *IEEE Trans. Power Electron.*, vol. 34, no. 1, pp. 801–814, 2019.
- [18] D. A. Molligoda, J. Pou, S. Ceballos, K. Satpathi, F. Sasongko, C. J. Gajanayake, and A. K. Gupta, "Current distortion mitigation in grid-connected Vienna rectifier during nonunity power factor operation," in *Proc. IEEE Ind. Electron. Soc. (IECON)*, 2020, pp. 4085–4090.
- [19] J. Park, J. Lee, and K. Lee, "Sinusoidal harmonic voltage injection PWM method for Vienna rectifier with an LCL-filter," *IEEE Trans. Power Electron.*, vol. 36, no. 3, pp. 2875–2888, Mar. 2021.
- [20] X. Li, Y. Sun, H. Wang, M. Su, and S. Huang, "A hybrid control scheme for three-phase Vienna rectifiers," *IEEE Trans. Power Electron.*, vol. 33, no. 1, pp. 629–640, Jan. 2018.
- [21] Y. Fu, N. Cui, J. Song, Z. Chen, C. Fu, and C. Zhang, "A hybrid control strategy based on lagging reactive power compensation for Vienna-type rectifier," *IEEE Trans. Transport. Electrification*, vol. 7, no. 2, pp. 825–837, Jun. 2021.

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