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Current Distortion Mitigation in Grid-Connected Vienna Rectifier During Nonunity Power Factor Operation

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Abstract—The Vienna rectifier is an attractive converter solution due to the three-level voltage generation and its simple structure. When the Vienna rectifier operates with nonunity power factor, the reference voltage and the input current have different signs during some intervals around the current zero crossings. This creates low-frequency distortion in the current waveforms. One of the preferable methods to reduce this distortion is the zero sequence injection which, however, risks the converter entering into overmodulation. This paper analyses the above distortion and introduces the operation of the Vienna rectifier in two modes, which includes injecting a proper zero sequence and reactive power compensation. This allows the converter to operate in a wide range of power factors without constraining the modulation index. The required reactive current is obtained analytically from the instantaneous values of the converter at any operating point.

Index Terms—Active front end rectifier, current distortion at zero crossing, nonunity power factor, reactive power compensation, Vienna rectifier.

I. INTRODUCTION

The Vienna rectifier, shown in Fig. 1, is a three-phase converter that can generate three voltage levels at each ac terminal. It offers numerous benefits such as simple circuit topology, unity power factor operation and low distortion in the grid currents. Besides, the bidirectional switches only need to block half of the dc-link voltage. This results in low conduction losses and low cost [1], which makes it attractive for active front-end rectifier applications. Despite being a three-level converter, only the midpoint connection is fully controlled through the bidirectional switches in the Vienna rectifier. When an ac terminal is not clamped to the neutral point, the current direction will define the polarity of the voltage pulse. If the reference voltage and the input current are in phase, the desired voltage will be produced at the converter input terminals. However, if there is a phase displacement angle, there are intervals where the reference voltage and the input current have different signs. If no appropriate action is taken, the voltage pulses generated by the converter during this interval will have reverse polarity. This produces low-

Fig. 1. The Vienna rectifier topology.

frequency voltage distortion, which degrades the quality of the grid currents [2]–[8].

Among the various solutions to the above current distortion problem, clamping the leg that generates pulses with an opposite sign to the midpoint was introduced in [2], [9], resulting in significant current distortion reduction. However, if the clamping interval is too long (i.e., when operating with low power factors), significant low-frequency distortion is still produced. In [9] and [10] few other clamping techniques are discussed including third harmonic injection.

This paper analyzes a grid-connected Vienna rectifier system and adapts the carrier-based modulation and control strategies described in [11], [12]. As a further improvement, it adds reactive power compensation, to avoid overmodulation in situations where the method in [11], [12] cannot be used. The Vienna rectifier discussed in this paper has two operating modes. In Mode-1, a zero sequence is injected into the three-phase reference signals to clamp the bidirectional switches to the neutral point when there exists a sign difference between the grid current and the reference voltage. In Mode-2, some reactive power is injected to achieve unity power factor (UPF) at the converter side instead of at the grid side. Mode-2 enables the converter to operate with full modulation index,

Fig. 2. Control applying same gate pulses to both switches.

which could not be achieved with Mode-1 for certain phase displacement angles. Furthermore, a hysteresis band is used when switching between the modes to ensure a smooth and stable mode transition.

II. VIENNA RECTIFIER OPERATION

The Vienna rectifier has six switches, each pair connecting a phase-leg to the neutral point of the dc bus. First, let's assume both neutral-point-clamp switches, S_{1x} and S_{2x} , are given the same gate pulses based on the following logic:

$$S_{1x} = S_{2x} = 1, \text{ if } v_{carr1} < v_{refx} \leq v_{carr2} \quad (1)$$

where x refers to the three phases of the converter, i.e. $x = \{a, b, c\}$. v_{carr1} and v_{carr2} are the lower and upper carrier signals, respectively, while v_{refx} is the reference signal fed to the modulator. Fig. 2 shows the generated gate pulses for the two switches in a particular phase by comparing the reference signal with the carriers, based on (1).

Focusing on a phase-leg of the Vienna rectifier (phase-leg x), when the reference voltage of the converter is in the positive half-cycle and the current flows in the positive direction (towards the converter), if the switches are off, the top diode D_{2x} conducts forming a positive voltage pulse v_{xn} (Fig. 3(a)). If the switches are on, then the current flows through the switches to the neutral point (Fig. 3(b)). On the other hand, if there is a phase shift between the reference voltage and the current there would be an interval in the positive half-cycle where the current is negative. In this interval, when the switches are off, the bottom diode D_{1x} conducts creating a negative voltage pulse in v_{xn} as shown in Fig. 3(c), which is undesired as it creates distortion.

Likewise in the negative half-cycle, if the switches are on, then the phase-leg x will be clamped to the neutral point (Fig. 3(e)). When both switches are off, the polarity of the voltage pulse is defined by the current direction. When the current is negative, a negative voltage pulse is created (Fig. 3(d)), but if the current is positive, a positive voltage pulse is created, which produces distortion (Fig. 3(f)). Therefore, the only voltage level that is fully controlled in the Vienna rectifier is the neutral point level. The top and bottom levels are decided by the current direction.

Fig. 3. Various operating states of a phase-leg in the Vienna rectifier. Positive half-cycle with: (a) Current in the positive direction, (b) clamping to the neutral point, and (c) current in the negative direction. Negative half-cycle with: (d) Current in the negative direction, (e) clamping to the neutral point, and (f) current in the positive direction.

Fig. 4. Bidirectional switch pair controlled with a single gate pulse.

The main waveforms simulated with both switches controlled together are depicted in Fig. 4, for the system parameters listed in Table I. Even though the converter operates with UPF at the source side, a phase shift exists at the converter terminals due to the filter inductor. The phase shift between the reference voltage and the current at this operating point is 6.9 degrees. This results in distortion in the generated voltages at the converter input terminals, which happens around the zero crossings of the input current, as shown in Fig. 4. Low-frequency current harmonics can be observed in Fig. 5(a). In this operation mode, the total harmonic distortion (THD) is 8.17%. These low-frequency harmonics could be attenuated

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Filter inductor, L	5 mH
DC-link capacitors, C	1500 μ F
RMS line-to-line voltage, V_{l-l}	400 V
DC-link voltage, V_{dc}	700 V
Output power, P_{out}	12.25 kW
Fundamental frequency, f	50 Hz
Switching frequency, f_{sw}	50 kHz

Fig. 5. Frequency spectrum of the input current (a) when both switches are controlled with the same pulses, (b) when the proper zero sequence is added (Mode-1), and (c) with reactive power compensation and the min-max zero sequence (Mode-2).

Fig. 6. Voltage oriented control for the Vienna rectifier with the zero sequence addition.

by additional filtering, but this would increase the size, weight and cost of the system, besides reducing its power density.

III. DISTORTION MITIGATION METHODS

A. Zero Sequence Injection (Mode-1)

In this section the bidirectional switch pair is driven independently using the control strategy mentioned in [12]. When the switches are operated independently, they will be clamped to the neutral point during the time period where the input current and the reference voltage have opposite signs. This reduces the low-frequency distortion in the line-to-line voltages, although it is not completely eliminated. Consequently, the current waveforms still contain certain low-frequency distortion. To improve the power quality, [11] and [12] propose the use of a zero sequence voltage. The zero sequence voltage is calculated in such a way that during the time intervals when the voltage and the current of a given phase have different polarity, the corresponding reference voltage for this phase is clamped to zero. The zero sequence voltage calculated in this way is fed into the voltage oriented control (VOC), as shown in Fig. 6. In this manner, the voltage generated by the Vienna rectifier is able to match the reference voltage regardless the current polarity, and the low-frequency distortion is completely eliminated. The main waveforms are depicted in Fig. 7 and the improvement in the current low-frequency harmonics when this method is used are shown in Fig. 5(b).

Fig. 7. Main waveforms of zero sequence injection.

Fig. 8. Phasor diagram of UPF operation at the source (black) and at the converter terminal (in blue).

B. Reactive Power Compensation (Mode-2)

In practice, when the Vienna rectifier operates with UPF at the grid side, the phase displacement angle between the current and the voltage at the converter side will not be zero due to the voltage drop in the filter inductor. The phase displacement angle will depend on the inductor value, fundamental frequency and loading conditions (grid current). For working conditions implying large modulation indices and large displacement angles, the zero sequence injection method described above may produce overmodulation [12].

Fig. 9. Mode-2 with reactive current injection.

Fig. 10. The proposed reactive power assisted hybrid modulation scheme for the Vienna rectifier.

To overcome this drawback, a calculated amount of reactive power can be injected such that the phase displacement angle is reduced and overmodulation is avoided. Since the voltages are measured at the grid side, a certain amount of reactive power reference is needed to achieve UPF at the converter side. As a result, because the voltage references and the grid currents are in phase, no distortion is produced and hence there is no need to inject any zero sequence to the voltage reference signals. The two scenarios (UPF at the grid side and UPF at the converter side) are illustrated in Fig. 8 using phasor diagrams. The triangle defined by the grid voltage, parasitic resistive voltage drop in inductor, converter terminal voltage, inductor voltage drop denoted by vectors $\mathbf{E}_d$, $\mathbf{RI}$, $\mathbf{V}$ and $\mathbf{V}_L$, respectively, represent UPF operation at the source. On the other hand, vectors $\mathbf{E}_d$, $\mathbf{V}_L$, $\mathbf{RI}_1$ and $\mathbf{V}_{IL}$ represent UPF operation at the converter terminals. The grid currents in the two scenarios are $\mathbf{I}$ and $\mathbf{I}_1$, respectively. The main waveforms of this mode are captured in Fig. 9.

The amount of reactive current required to achieve UPF at the converter terminals can be calculated by solving the triangles in Fig. 8 as follows:

$$I_q = -\frac{E_d}{2\omega L} \left[1 - \sqrt{1 - \left(\frac{2\omega L I_d}{E_d} \right)^2} \right] \quad (2)$$

where E_d and I_d are d-axis component of the grid voltage and d-axis current, respectively. These parameters are readily available in the controller as instantaneous values and therefore knowledge of the load is unnecessary.

Using the parameters given in Table I in (2), the reference reactive current required by the controller is obtained as $I_q = 3.9A$. To extend the range of the modulation index by 15%, the zero sequence $-(V_{max} + V_{min})/2$ is inserted in this operation mode. Now, the current waveform is in-phase with the converter terminal voltage, as shown in Fig. 9. The input current frequency spectrum is illustrated in Fig. 5(c). When the Vienna rectifier operates with UPF at the grid side, the reactive power for the filter inductor is provided by the converter. On the other hand, if the converter is operated such that UPF is achieved at the terminals of the converter, the grid needs to provide that reactive power, meaning that UPF is no longer achieved at the grid side. Nevertheless, the benefit is that the reference voltages and the grid currents of the Vienna rectifier are in phase, hence current distortion at the zero crossing is eliminated without the need of using a zero sequence injection, thus avoiding overmodulation. The improvements in the current THD, discussed above are summarized in Table II.

IV. COMBINED OPERATION

Previous section shows that both modes of operation have their own limitations. Zero sequence injection mode (Mode-1) is more suitable for low modulation index operation, while reactive power compensation (Mode-2) is preferred for situations where the modulation index is high. This section introduces a reactive power assisted hybrid modulation scheme, that selects between the two modes depending on the specific working conditions. In this way, the advantages of both methods are combined and the cons are compensated. The proposed scheme for the reactive power assisted hybrid modulation is illustrated in Fig. 10. It comprises a mode selector block, a detector and a reactive current calculator. The mode selector chooses between the two modes, based on the maximum reference voltage v_{refmax} it receives from the detector, as shown in Fig. 10.

TABLE II
COMPARISON BETWEEN MODULATION TECHNIQUES

Modulation	Together	Mode-1	Mode-2
Current THD %	8.17	0.20	0.18

TABLE III
OPERATING POINTS WHEN SWITCHING BETWEEN MODES

Parameter	Mode-1	Mode-2
Load Resistor (Ω)	50	40
Modulation index	0.8	1

Fig. 11. Mode transitions: (a) Transition from Mode-1 to Mode-2 and (b) transition from Mode-2 to Mode-1.

The detector calculates v_{refmax} using the estimated steady-state values of the system d - q voltage components in Mode-1 using (3) and (4) with $E_q = 0$. Assuming that i_q is zero:

$$V_d = RI_d + E_d \quad (3)$$

$$V_q = \omega LI_d + E_q \quad (4)$$

where V_d, V_q, E_d and E_q are steady-state voltages in d and q axes. The phase displacement angle ϕ is given by:

$$\phi = \tan^{-1} \left(\frac{\omega LI}{E} \right) \quad (5)$$

which changes with the input current I , fundamental frequency and grid voltage. If the detected v_{refmax} makes the converter enter into overmodulation, the operation mode is changed from Mode-1 to Mode-2. Otherwise, it remains in Mode-1. If Mode-2 is selected, the reactive current calculator block will solve (2) using instantaneous values and provides the suitable reactive current reference to the VOC to operate the Vienna rectifier. When the two modes are combined, the Vienna rectifier has no constraints in the modulation index within the normal operation mode, provided the phase displacement angle at the converter terminals is in the interval $[-\pi/6, \pi/6]$.

In the simulations in Fig. 11, the mode transition is triggered by a shift in the operating point, as mentioned in Table III. In Fig. 11(a), the dc side load resistor is reduced from 50Ω to 40Ω and the modulation index is increased from 0.8 to 1 at time $t = 0.025s$, hence forcing the converter to switch from Mode-1 to Mode-2. In the next experiment, depicted in Fig. 11(b), the operating point is switched back to the initial conditions at time $t = 0.02s$, such that the converter should change from Mode-2 to Mode-1. To avoid multiple unintended transitions between modes, this change is not instantaneous and a hysteresis band is required. If the v_{refmax} from the

detector is below the hysteresis band limit (0.98) during half-a-fundamental period, the converter will change back to Mode-1. This is what happens in Fig. 11(b) at $t = 0.03s$. At this point, v_{refmax} is below 0.98 for half-a-period and the converter changes from Mode 2 to Mode 1 accordingly. These results show the correct operation of the proposed hybrid modulation scheme. The transition points between modes are easily detected based on the instantaneous measurements of the current and voltage. Consequently, the transitions from Mode-1 to Mode-2 and vice versa are properly performed depending on the specific working conditions. These results prove that the proposed hybrid strategy is able to extend the operation of the Vienna rectifier without low-frequency distortion under a wide range of modulation indexes and phase displacement angles.

V. CONCLUSION

In this paper, a carrier-based modulation and control technique to overcome the distortion around the current zero crossing in a grid-connected Vienna rectifier has been proposed. The solution consists of injecting a proper zero sequence (Mode-1) and reactive power compensation (Mode-2) with UPF at the converter terminals. A detector runs in parallel to check the peak of the reference signals to determine the operation mode that needs to be applied to the converter at any time. When the two modes are combined, the Vienna Rectifier can operate in a wide range of power factors without constraining the modulation index, and with low current distortion.

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