Command Generation for Wide Range Operation of Hysteresis Controlled Vienna Rectifiers

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Abstract*— Hysteresis current controllers inherently present wide bandwidth and have been proposed for application in Vienna rectifiers switching at high frequencies. In these applications, near zero ac input currents are required at no load. Since the hysteresis band is limited by switching losses and delays, controlling low current amplitudes becomes an issue in Vienna rectifiers. In this paper it is described a suitable alternative to overcome such limitation, satisfying both the control of the power flow at no load and the minimum current amplitude requirements. Test results on a 400A / 380V Vienna rectifier are present to support the theoretical analysis.

I. INTRODUCTION

Designed originally to maximizing the power density, Vienna topology is a unidirectional three-phase three-level PWM rectifier [1]-[4], which incorporates a bridge rectifier and bidirectional switches as shown in the fig. 1. The bridge rectifier, made by fast recovery diodes, has two functions: work as a freewheel to the energy when the corresponding IGBT is off and doing the rectification action. The IGBT switching can be controlled by the hysteresis current control to get the sinusoidal ac currents waveform [5],[6]. The hysteresis current controller in a block diagram representation is presented in fig. 2. A classical cascaded control scheme is used. The inner current control loop and modulation are implemented using the hysteresis control. The outer loop consists in a dc bus voltage regulation loop. The dc bus voltage is inherently split in Vd1 and Vd2 due to the three-level nature of the Vienna rectifier. In order to guarantee the dc voltages balancing, an extra feedback loop is included to force Vd1 ≈ Vd2.

Research papers in this area in general shows rectifiers system near nominal operating conditions [4]-[6]. Also, in classical applications of hysteresis current control such as in induction motor drives, the minimum current demanded at no load from the inverter is the magnetizing current, which is comparable to the rated current [7],[8]. In these situations, the problems arising from near zero reference currents were not apparent and, consequently, were not addressed.

In rectifier applications, for example in welding machines, the demanded power is near zero at no load

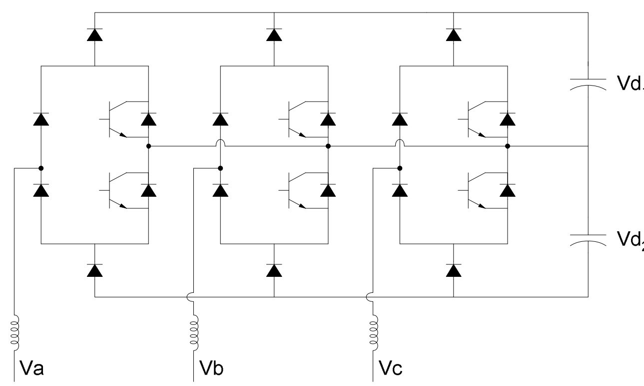


Figure 1 – Vienna Rectifier

conditions. Therefore, the hysteresis controller should command very low fundamental current amplitude However, under these conditions, the nature of the hysteresis controller requires certain conditions for proper current control, such as high switching frequency (implying high losses) and/or larger input inductors. Further difficulties arise from switching delays and DSP restrictions, such as the resolution of the D/A conversion, and tolerances of real components. All these restrictions bring important consequences under low load conditions: poor ac current control; poor dc bus voltage regulation, risking overvoltage and damage to dc bus capacitors and power semiconductors. There are some possible solutions to solve this issue, such as changing the gate driver and related circuits to reduce delays and increase the switching frequency with low losses and using a high performance DSP controller. All those solutions are considered costly, mainly when the rectifier hardware is already available.

This paper proposes an alternative control methodology, using a quasi-sinusoidal current reference and pulse-width current control in the low power operation conditions. An important feature in the proposed method is the continuity of the power flow throughout the operating range, ensuring

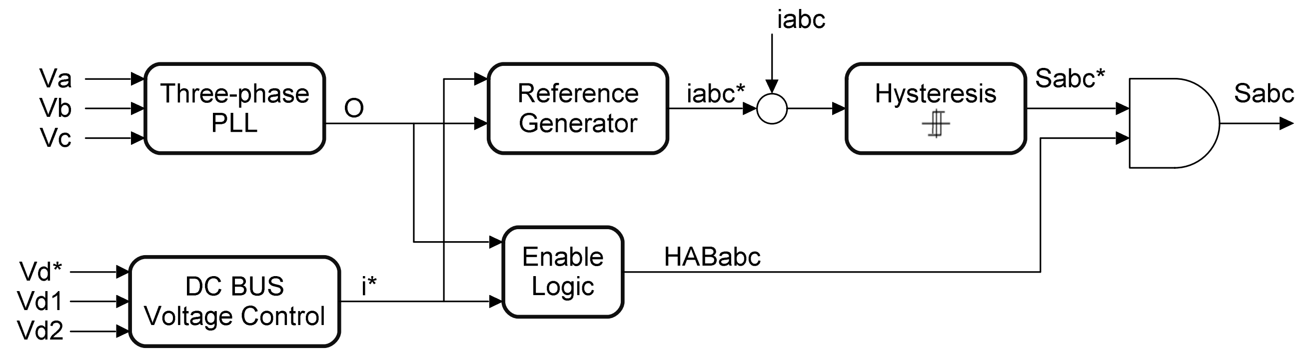


Figure 2 – Controller Block Diagram

a proper control of the dc bus voltage and avoiding abrupt power transitions, undesirable due to problems, such as dc voltage unbalance.

II. HYSTERESIS CONTROL

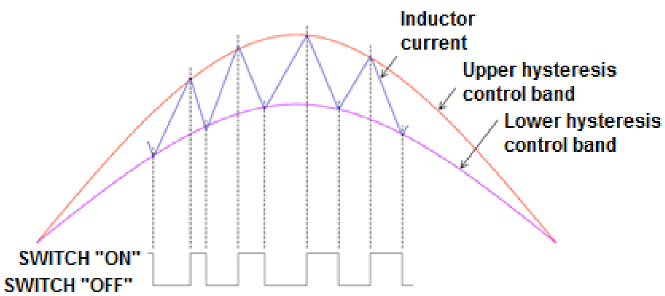


Figure 3 -Hysteresis control of three-phase active rectifiers

Fig.3 shows the basic control concept of the hysteresis type control [9]. Two current bands, a lower and an upper band, are set-up. The current is controlled by means of on-off switching of the switch, to be within the boundaries set-up by the control bands. The range of the switching frequency can be controlled by increasing/decreasing the current control bands. This type requires a second control loop for balancing the two output capacitors, although the center point voltage is naturally stable [6]. The major advantage of hysteresis control, compared to a constant switching control, is that the power harmonics are distributed over a wide frequency range due to the time-varying frequency [3]. Constant frequency control might require a small EMI filter at the input to comply with conducted EMI standards [6].

III. VIENNA RECTIFIER OPERATION

As described above, currents are controlled through the diagram presented at fig. 2. In standard hysteresis control, there are no restrictions on the minimum amplitude of commanded currents and the current reference can reach very low amplitudes, certainly lower than the Vienna rectifier can control properly, as discussed. The proposed method of reference synthesis consists on using different reference waveforms depending on the required power level: sinusoidal for high power demand and quasi-sinusoidal for low power demands, where the standard realization of the hysteresis current control has limited performance. The quasi-square wave amplitude is maintained constant and the control is performed by the each phase enable signal, which is a function of demanded currents. In other words, the power injected into the dc bus is controlled by the pulse width of the reference current, as presented at fig. 4.

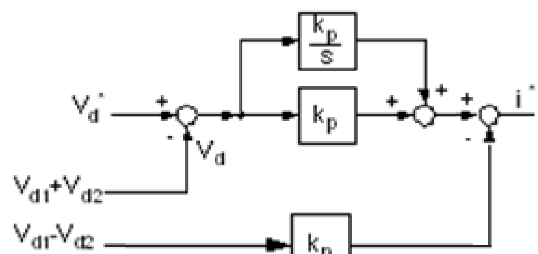


Figure 4 – DC Bus Voltage Control Block

A. *Command Generation*

Such described problems into Vienna rectifier control can be solved using a different from the commanded current generation and enable signal. First of all, it is important to understand that the High Power, or normal, operation control is performed to the block diagram presented at fig. 2 and 4. Through DC Bus regulation, the control is based on the sum and the difference of each capacitor voltages to generate the current command, naturally synchronized with input voltages (once it is a characteristic of Vienna topology). In High Power operation, the commanded currents are synthesized as sinusoidal waves with variable amplitude and all phases are enabled to conduce current.
Some operational conditions, as no-load, demand less current than the rectifier can synthesize due to already described issues. And, above this limit, a different command generation is used, as well as phase enable signals are

controlled. This operation, denoted in this paper as Low Power Operation, is divided on three states, called operation modes which will be detailed.

Low Power Operation is based on the described principle for High Power operation: DC Bus voltage regulation and synchronism with input voltages, but the commanded current reference and the phase enable signals are special. Current references are quasi-square waves synchronized with input voltages and fixed amplitude, which is the minimum synthesizable though the wide range rectifier. Then the current control is performed by phases enable signals. The current reference controls the pulse width of the phase enable signal, making it narrower or wider according to the current demand. Each Low Power Operating mode has its own forms to enable the phases:

- Mode 1: When a very low current is demanded, just one phase supplies the circuit and the others are disabled, as presented at fig. 5. The enable pulse growths in the direction of the arrow with the growth of demanded current. Since synchronized operation, the input current is supplied only thought two phases, as will be proved by experimental results. The maximum current is reached when the pulse width doesn't allow two phases conduction anymore, as presented in fig. 5(b).

- Mode 2: To reach higher currents is necessary that another phase conduces current too. This is performed enlarging the enable signal of the same phase as show at fig. 5(c). In this case, the enabled phase conduces as mode 1 complete and during the enable range with the other phase, as show in test results section. This mode, as the previous, has a limit, show at fig. 5(d).

- Mode 3: To reach the highest currents of Low Power Operation is necessary enable other phase. Fig. 5(e) shows that the one phase was completely enabled, though 1 and 2 modes, and a second phase is enabled. The enable pulse growths in the direction of the arrow with the growth of demanded current, on fig. 5(e), until reach the maximum, in fig. 5(f).

- Mode 4 or High Power Operation: When the demanded current is higher than Low Power limit, all enable signals are active, that means, all phases are enable to conduce currents and the current reference turns again into sinusoidal one to perform high power operation.

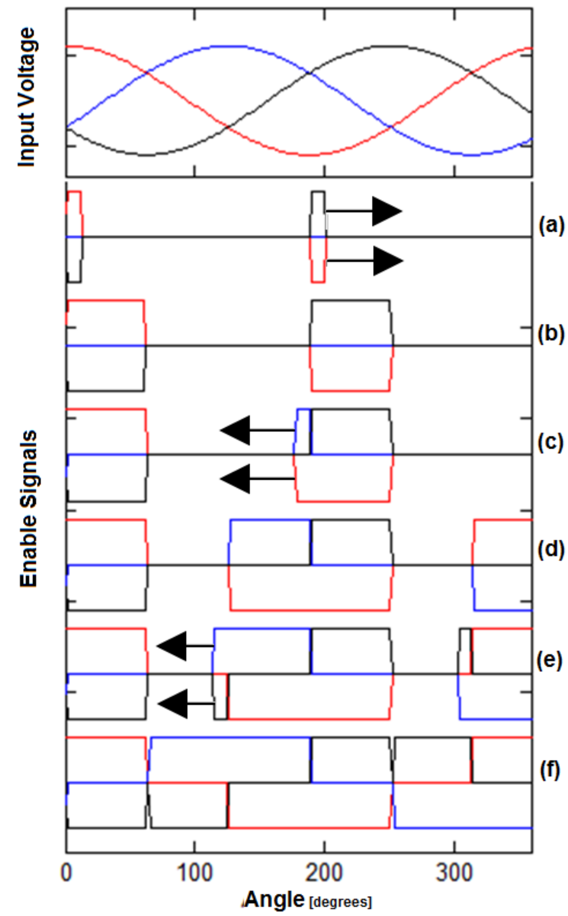


Figure 5 – Input Voltages and Enable Signals for Low Op. Mode: 1(a) and (b), 2(c) and (d) and 3(e) and (f)

B. *Continuous Power Flow*

Operation with different modes and conceptual changes on control during the operation and cause disrupt points where the current, and then the power doesn't change between modes smoothly.

The transition between different operating modes in the low power region, according to the proposed method, guarantees continuous power flow as seen in fig. 6. Such characteristic yields better control of the dc bus voltage, with smooth transition between operating modes.

C. *Commands for Single-phase operation*

If it is demanded from the Vienna rectifier, it can also operate in single-phase mode, once one of Vienna topology advantages is the multi-voltage operation. The hardware presented on test results section also can be feed by other three phase voltage levels, as 380 and 440V. Low power operation has the same issues already pointed out. A new operating mode was created. The current reference is again a pulse width modulated quasi-square waveform with fixed amplitude and a pulse width varies the power injected into the dc bus. The transition between different operating modes in the single-phase case is also smooth with continuous power flow, ensuring a better control of the dc bus voltage and avoiding abrupt transitions between modes.

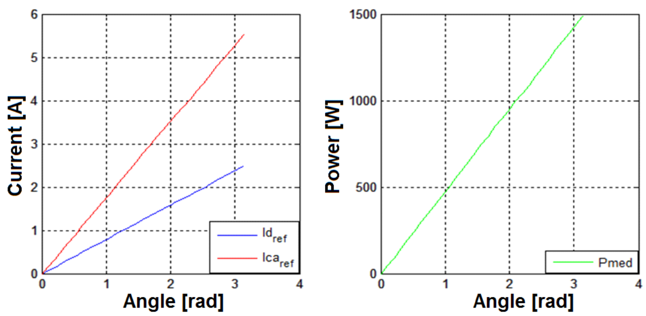


Figure 6 – Current components and input power as a function of the quasi-square wave reference current pulse width.

IV. TEST RESULTS ON PROPOSED COMMAND GENERATION

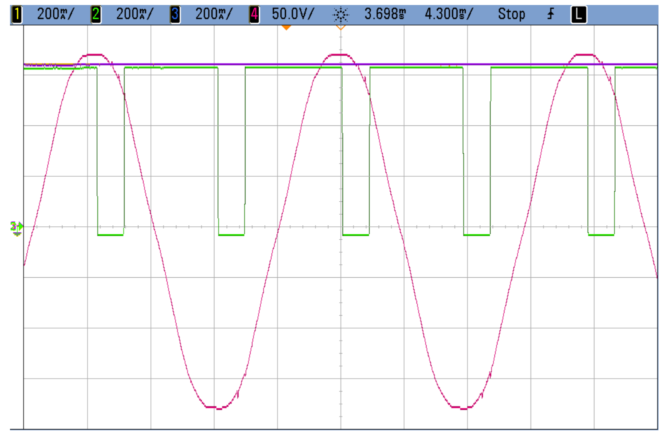
In order to support the theoretical analysis, this section presents the test results on a 400A / 220V Vienna rectifier. This test was performed in a hardware containing the rectifier, dc bus and variable resistive load, as presented at fig 7.

Figure 7 – Vienna prototype

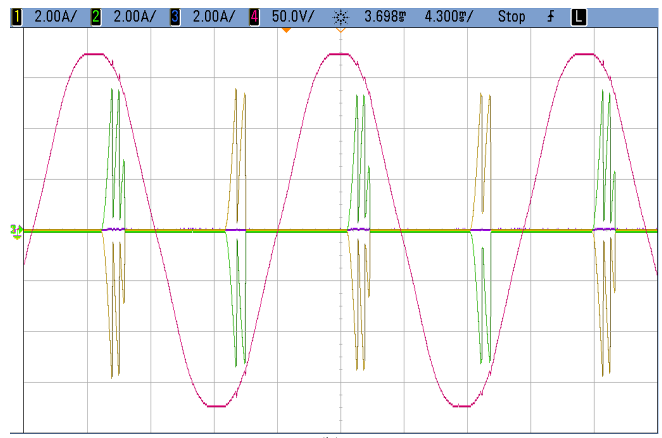
A. *Control Operation Modes*

The wide range operation was divided, in order to avoid some issues in near no-load conditions. To illustrate the operation of high power and low power operation modes and its subdivisions, a variable resistive load has used to active each mode of operation. The tests results are presented at figs. 8, 9, 10 and 11, showing: each enable signals (except for high power operation mode because all phases are constantly enabled) and the input currents in each of them with the input phase voltage.

Near zero power flows in mode “1”, that means, only control circuitry drains power from the dc bus. Fig. 6 shows the operation for a load of 114 W. As described, just one enable signal (active low) is active for narrow angle.



(a) * Enable signal active low

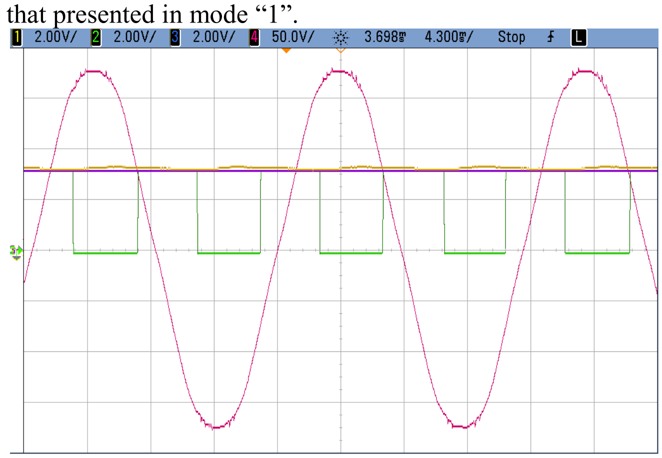


(b)

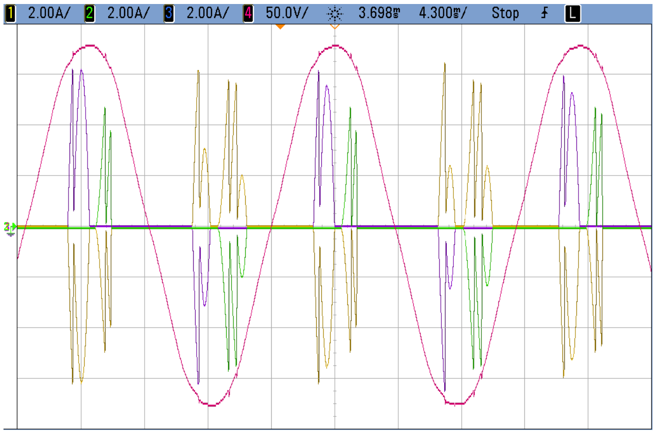
Figure 8 – Operating mode 1

In this mode, the current is only enabled to flow between phases A and C, as show at fig.5(b).

As the demand current growths, more power flows in mode “2”. Fig. 7 shows the operation for a load of 297 W. As described, just one enable signal is active for wider angle that presented in mode “1”.



(a) Enable signal active low
Figure 9 - Operating mode 2

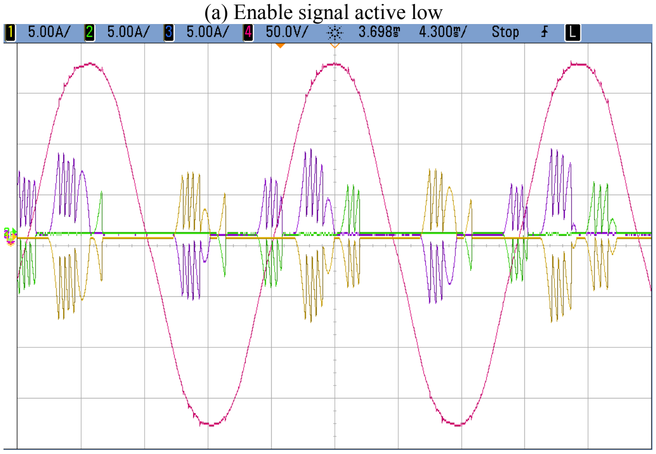


(b)
Figure 9 - Operating mode 2

In this mode, the current is only enabled to flow between phases A and C and phases A and B, as show at fig.9(b).

As the demand current continues to growth, more power flows in mode "3"and a new enable signal is created, similar to the previous signal used in operating modes 1 and 2. Fig. 8 shows the operation for a load of 423 W. As described, the enable signal is active for widest angle for one phase and other phase is now active.

(a) Enable signal active low



(b)
Figure 10 – Operating Mode 3

In this mode, the current is only enabled to flow between phases A-C, A- B and B-C, as show at fig.10(b)

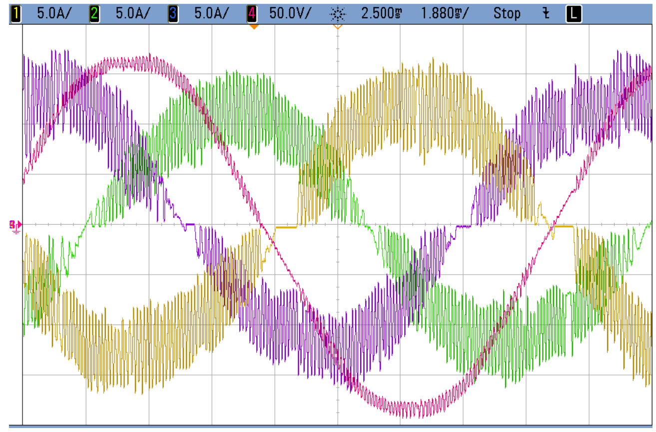


Figure 11 – Operating mode 4: line current and voltage

On the Operating mode 4, the enable signals are all active and the control of the bus voltage is performed normally. The Fig. 9 shows the currents on this operating mode for a 3426W resistive load.

B. *Total Harmonic Distorcion (THD)*

Some tests have been taken in order to verify the input current harmonic content at different power levels. Table 1 present the results of input current, fundamental current and THD (related with fundamental value), by changing the resistive load value. The current spectrum is showed in Fig. 12. The input voltage is 220 volts and all modes input current has only the odd harmonics, evaluated until 27th presented at fig.12.

Although the analysis of harmonic currents is critical on most of applications, even with high THD value, the demanded currents on evaluated low power modes (1, 2 and 3) drain less than 1% of maximum capability of this equipment. Also low power modes are active just on normal operation intervals, that is with no load.

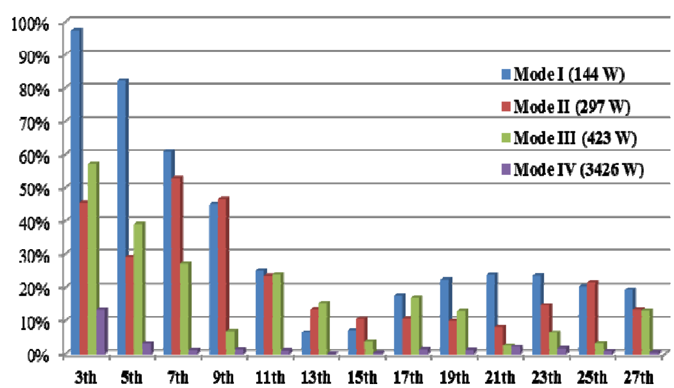


Figure 12 – Current Harmonics pro mode

TABLE 1 – THD Test Results

Mode/Power	I_{rms}	I_{60hz}	$THD_i(\%)$
I (114 W)	1,32 A	0,70 A	159,6 %
II (297 W)	1,88 A	1,30 A	105,0%
III (423 W)	2,40 A	1,74 A	95,03%
IV (3426 W)	9,25 A	9,12 A	17,06%

C. DC Bus Voltage Control

The system controls the dc bus voltage control independently that mode, so there is no voltage unbalance in wide range operation. Fig 13 presents the turn-on condition with no load, controlled by mode '1'. After pre-charge process, each capacitors are charged until 310V equally.

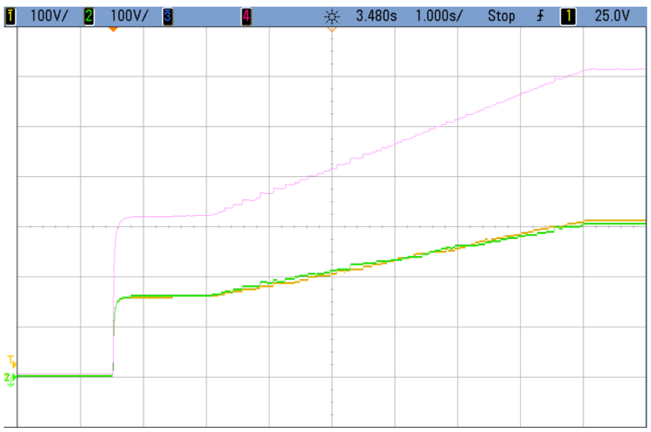


Figure 13 – DC Bus voltages and sum signal

V. CONCLUSION

In rectifier applications, for example in welding machines, the demanded power is near zero at no load conditions, which demands very low fundamental current amplitude from the hysteresis controller. Under these conditions, the hysteresis controller requires certain conditions for proper current control, which brings many difficulties, restrictions and consequences under low load conditions.

This paper proposed an alternative control methodology, using a quasi-sinusoidal current reference and pulse-width current control in the low power operation conditions. An important feature in the proposed method is the continuity of the power flow throughout the operating range, ensuring a proper control of the dc bus voltage and avoiding abrupt power transitions. Also, the harmonic issues was discussed and presented high THD into low power mode, but the effect is minor, once the current levels are very low. Voltage unbalance was totally avoided in all modes.

Future work involves evaluate the operation with different loads, such as RL and an inverter. Also the energy conversion efficiency will be evaluated and compared with the normal operation and the fixed frequency operation.

ACKNOLEGMENT

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