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# A High Power Density Three-Phase PFC Converter Based on VIENNA Topology

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***Abstract*- This paper presents a front end grid connected power converter which is based on a non-regenerative three-level bidirectional-switch VIENNA rectifier. The whole system is controlled by a digital method. The controller is implemented in carrier based PWM strategy. The control method and the simulation are presented. An experimental prototype is built to verify the theoretical analysis and the simulation. The experimental results are given. The switching frequency of the converter is 100 kHz; the efficiency reaches 96.5% at the rated condition. During the wide input range, the THDi value is controlled to be less than 5%.**

***Index terms*- *Power Electronics, Power Factor Correction, High Efficiency, High Switching Frequency, VIENNA***

## I. Introduction

The development of a high power density three-phase AC/DC converter has been a hot topic in power electronics due to the increasing requirement in applications like electric vehicles (EV), aircraft and aerospace, where light weight or a small volume is usually requested. With the emerging high frequency device technology, the operating frequency of the converter can be potentially pushed to tens of kHz to hundreds of kHz at high voltages and high power conditions. The extended switching frequency range brings opportunities to further improve the power density of the converter.

The family of non-regenerative three-level rectifiers is characterized by reduced number of active switching devices, high power factor, and low voltage stress, which make it a suitable topology for medium- and high-power applications with high power density. The Vienna rectifier originally evolved from these topologies, where together with the latter new ones forms a family of functionally equivalent circuit topologies [1][2]. The dedicated application of VIENNA topologies is to maximize the power density of three-phase power supplies for telecommunication applications [3]-[6].

Due to the developments on semiconductors devices, magnetic materials, capacitor and cooling technologies, the VIENNA rectifiers remain as one of the preferred candidates when power density is a design objective [3][4][6]. Nowadays, electrical or hybrid vehicles, which have strict power density and minimum weight requirements, have become a potential user for this kind of rectifiers. Due to their notable performance, VIENNA rectifiers have also been recently considered for industrial motor drives and UPS systems. The term "VIENNA type rectifiers" is usually used to represent the whole non-regenerative three-level boost rectifier family.

Several methods have been proposed for the control design of the VIENNA-type rectifier [5]. Hysteresis current control is simple to implement, as the switch-gating signals are generated by comparing the reference and measured currents. Hysteresis current control has the drawback of a varying switching frequency. This method can be simply implemented by simple analog circuitry and logic-gate arrays. Backman and Rojas proposed a simple carrier-based control approach and discussed the inherent relationship between the space-vector modulation (SVM) and the carrier-based pulse width modulation (PWM), without a clear presentation on the zero-sequence component generation for the carrier-based implementation [7][8][9]. Constant-frequency integration control and unity power factor control feature both simplicity and constant switching frequency, but they do not provide closed-loop regulation for the dc-link neutral-point voltage. Consequently, in order to limit the voltage unbalance of the dc link, larger dc-link capacitors are needed [10]. The three-level space-vector based control scheme provides a clear insight into system control and operation, however, a large calculation effort is required for the implementation, which

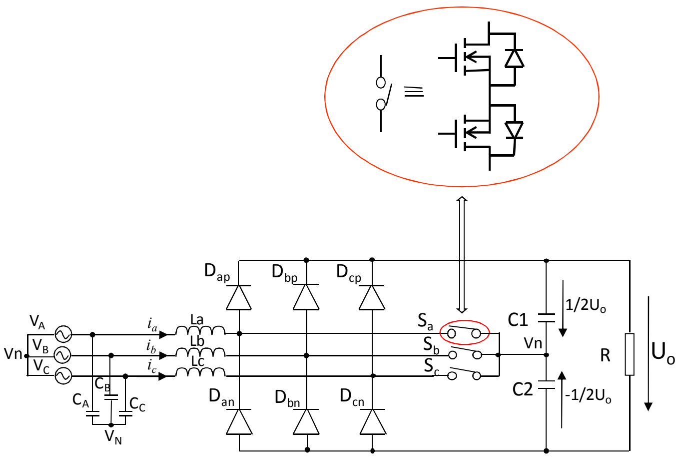


Fig. 1. Non-regenerative three-level bidirectional-switch VIENNA rectifier.



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has limited its application for high–switching frequency applications.

This paper presents front end grid connected power converter which is based on non-regenerative three-level bidirectional-switch VIENNA rectifier. The whole system is controlled by digital method. The controller is implemented in carrier based PWM strategy. In Section II, both the control method and the simulation will be briefly introduced. In Section III, the experimental results will be given. The switching frequency of the converter is 100 kHz, the efficiency is 96.5% at the rated condition. Finally, the conclusion of this work is given.

## II. System Control Strategy and Simulation Results

As shown in Fig. 1, the non-regenerative three-level bidirectional-switch VIENNA rectifier considered in this paper is presented. $V_A$,$V_B$, and $V_C$ are the three-phase voltages of the grid. $S_a$, $S_b$, and $S_c$ are the bidirectional switches, which consist of two MOSFETS which are connected in series. $L_a$, $L_b$ and $L_c$ are the input inductors, and $U_o$ is the output voltage. As shown in the figure, the neutral point $V_n$ of three-phase line voltage is connected with the output capacitors $C_1$ and $C_2$.

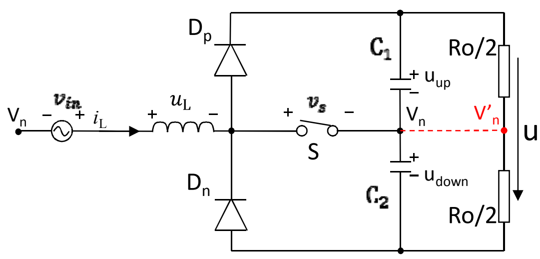



Fig. 2. Topology of physical decoupled single-phase three-level rectifier.

The output capacitor is supposed to be large enough so that the output voltage can be regarded as a constant. When the neutral point is introduced, this converter can be decoupled into three single phase three-level power factor correction (PFC) converters, phase A, phase B, and phase C can each be controlled as an individual PFC converter. In order to simplify the analysis, the parameters of each phase are supposed to be the same. Considering the load sharing for each phase, the output resistor of the decoupled single-phase rectifier is triple that of the VIENNA rectifier, i.e. $R_o$=3$R$ (wherein $R$ is shown in Fig. 1). The physical decoupled single-phase topology is shown in Fig. 2. It should be noted that $R_o$ has not been connected to the neutral point $V_n$. As shown in Fig. 2, when the circuit is operating at steady state, the output voltage of $C_1$ and $C_2$ are equal; therefore the neutral point of $R_o$, $V_n$', can be regarded as the equipotential point of $V_n$.

In order to simplify the analysis, the following assumptions should be made:

1) The circuit is already in steady state, i.e. the input voltage $v_{in}$, the output voltage, and the input current are in steady state.
2) Due to the large output capacitor, the output voltage of $C_1$ and $C_2$ are constant during each switching period, i.e. $u_{up} = u_{down} = u_o/2$. $v_{in}$ also can be regarded as constant in each switching period.
3) All of the devices and lines are regarded as ideal components.

If the input voltage of $v_{in}$ is in the positive half waveform, $D_p$ and S are turned on and turned off alternatively, thus the inductor $L_i$ is discharged and charged, respectively. During this stage, the upper capacitor $C_1$ is charged. If $v_{in}$ is in the negative half waveform, $D_n$ and S are turned on and turned off alternatively, meanwhile the inductor $L_{a,b,c}$ is discharged and charged, respectively. During this stage, the down capacitor $C_2$ is charged. Therefore, during every line period of every phase, $C_1$ and $C_2$ are charged alternatively. Thus the line input current $i_a$, $i_b$ and $i_c$ can be controlled independently.

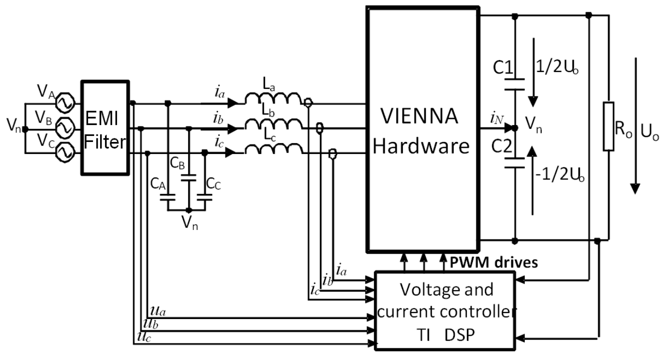



Fig. 3. Digital implementation of three-phase VIENNA rectifier.

TABLE I. Switching mode of the system and the neutral point current $i_N$

| $S_a$ | $S_b$ | $S_c$ | $i_N$ |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | $i_c$ |
| 0 | 1 | 0 | $i_b$ |
| 0 | 1 | 1 | $- i_a$ |
| 1 | 0 | 0 | $i_a$ |
| 1 | 0 | 1 | $-i_b$ |
| 1 | 1 | 0 | $- i_c$ |
| 1 | 1 | 1 | 0 |

The whole system can be controlled by a single DSP. The digital implementation for the system is given in Fig. 2. The input voltage $V_A$, $V_B$, $V_C$ and the input current $i_a$, $i_b$, $i_c$ are sampled, meanwhile the output voltage of $U_o$ is sampled. The neutral point current $i_N$ is related with the state of $S_a$, $S_b$ and $S_c$. The correspondence between the state of $S_a$, $S_b$, $S_c$ and $i_N$ are given in detail in Table I.

The overall system circuit schematic is shown in Fig. 3, and the controller is shown in Fig. 4. $F_1(s)$ and $F_2(s)$ are PI modulators. $F_1(s)$ is used to regulate the output voltage, $U_o$;

$F_2(s)$ is used to regulate the input current of every phase. The sampled input voltage is normalized and the absolute value is

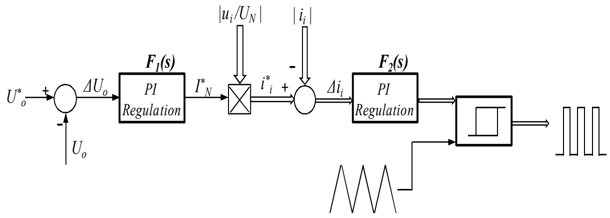



Fig.4. Control diagram for the system: *i=a,b,c*

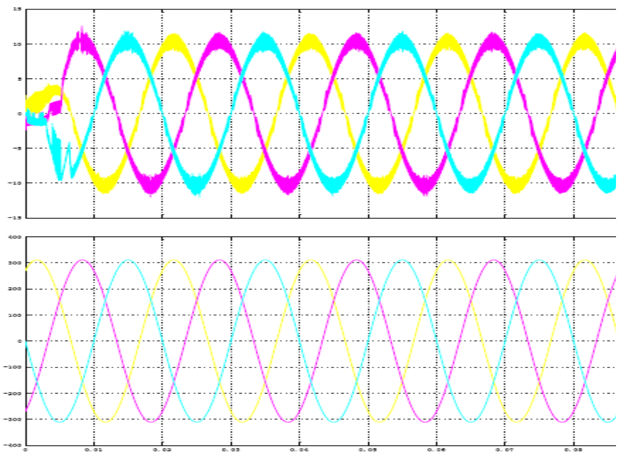


Fig. 5. Simulation results of the three-level bidirectional-switch VIENNA rectifier

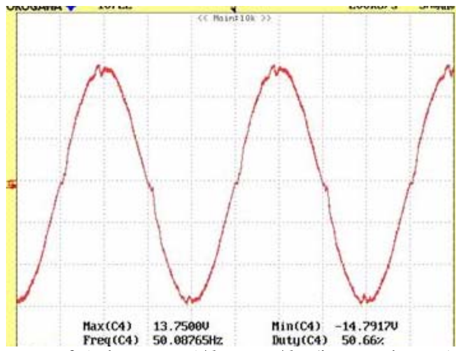
taken at the same time, whereas the absolute value of the sampled input current is taken. The output of each phase current loop is compared with the carrier, which then produces the gate drive signal for each phase. This implementation is simple and effective. The control method is simulated in MATLAB, and Fig. 5 gives the simulation results. The rated power is 5 kW. The upper horizontal axis shows the input current of each phase, the lower one shows the input voltage of each phase.

## III. Experimental Results

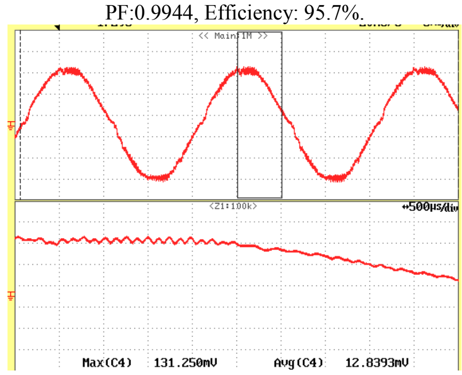
Based on the topology shown in Fig. 1 and the implementation system shown in Fig. 3, an experimental prototype is built to verify the analysis and the simulation. The operating frequency of the converter is 100 kHz. The input inductance of $L_a$, $L_b$ and $L_c$ is 130 *uH.* Discrete Cool-MOSFETs are chosen for the bidirectional switches. Fast-recovery diodes are chosen for the rectifier diodes. The rated output power is 5 kW. The controller was implemented with a TMS320F2808 DSP.

As shown in Fig. 6, the input current of phase A, $i_a$, is illustrated. When the input phase voltage is 170 VRMS, the input current of $i_a$ is given in Fig. 6(a). The PF value is 0.9944 and the efficiency is 95.8%. When the input phase voltage is 220 VRMS, the input current is shown in Fig.6(b). The PF value is 0.993, the efficiency reaches 96.5%. The measured PF values and THDi values for several different input voltages are shown in Table II. During the wide input range, the THDi value is limited to be less than 5%.

Finally, Fig. 7 gives the soft start waveforms during the startup process. The input current of $i_a$ and the output voltage of $U_o$ are shown respectively. It can be seen that the input current is regulated within 5 line periods after startup.

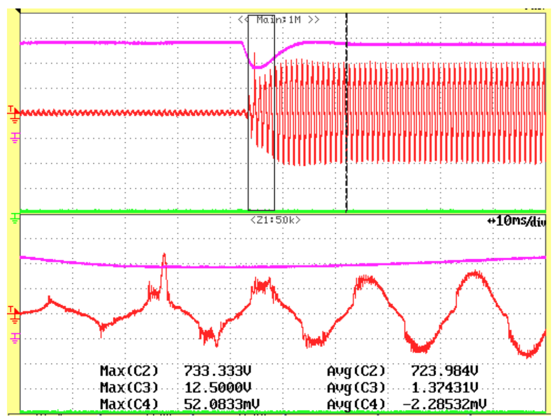



(a)Input current of *A* phase $i_a$: *5A/div*, *5ms/div* (input voltage, 170 VRMS) PF:0.9944, Efficiency: 95.7%.




(b) Input current of *A* phase $i_a$: *5A/div*, *5ms/div* (input voltage, 220 V) (PF:0.993, efficiency: 96.5%).

Fig. 6. Experimental current waveforms.




Input current of *A* phase $i_a$ *and output voltage* $U_o$
$i_a$: *5A/div*, *5ms/div* (input voltage, 220 VRMS)
$U_o$:*200V/div*, *5ms/div*

Fig. 7. Experimental results of soft start.

TABLE II. Experimental Results for the THDi and PF (Power level: 5kW)

| PF | THDi (the same control parameters)(%) | | | Input Voltage (VRMS) |
|---|---|---|---|---|
| | A | B | C | |
| 0.9951 | 4.8 | 4.7 | 4.9 | 220 |
| 0.9958 | 3.9 | 3.6 | 3.7 | 210 |
| 0.9956 | 3.1 | 3.4 | 3.3 | 202 |
| PF | THDi (adjusting the control parameters when the input voltage was adjusted)(%) | | | Input Voltage (VRMS) |
| 0.9925 | 4.0 | 4.2 | 4.5 | 180 |
| 0.9948 | 3.1 | 3.4 | 3.2 | 170 |

## IV. CONCLUSION

This paper presents a front end grid connected power converter which is based on non-regenerative three-level bidirectional-switch VIENNA rectifier. The whole system is controlled by digital method. The controller is implemented in carrier based PWM strategy. In Section II, both the control method and the simulation are introduced. In Section III, the experimental results are given. The switching frequency of the converter is 100 kHz; the efficiency is 96.5% at the rated condition.

The implemented controller is simple and effective; therefore, it can be realized by a single low cost DSP.

## ACKNOWLEDGMENT

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