

High Power Factor Three Phase Rectifier for High Power Density AC/DC Conversion Applications

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Abstract

The conventional three-phase rectifier with bulky LC output filter has been widely used in the industry because of its distinctive advantages over the active power factor correction rectifier such as simple circuit, high reliability, and low cost. Over than 0.9 power factor can be achieved, which is acceptable in most of industry applications. This rectifier, however, is not easy to use for high power density applications since the LC filter is bulky and heavy. To solve this problem, a new simple rectifier is presented in this paper. By eliminating the bulky LC filter from the conventional diode rectifier without losing most of the advantages of the conventional rectifier, very high power density power conversion with high power factor can be achieved. Operation principle and design considerations are illustrated and verified by Pspice simulation and experimental results from a prototype of 3.3 kW rectifier followed by 100 kHz zero voltage switching full bridge PWM converter.

1. Introduction

The conventional three phase diode rectifier with bulky LC output filter shown in Fig. 1 has been widely used in the industry because of distinctive advantages over the active power factor correction rectifier including simple circuit, high reliability, and low cost. Above 0.9 power factor can be achieved and this is acceptable in most of industry applications. This rectifier, however, is bulky and heavy since the filter inductor should be big enough to be treated as a constant current source to achieve such a high power factor. The filter inductance is usually in the range of several mH to over than ten mH. The filter capacitor is also bulky. So, this kind of rectifier can not be easily used for the

applications which need high power density, such as telecommunication, computer, and aerospace power systems.

In recent years, three-phase six-switch PWM boost rectifier has been applied to the industry applications which need high power factor and/or power regeneration.[1-3]. By using digital signal processor (DSP) controller and a new generation IGBTs, 10-20kHz switching is possible and nearly unity power factor can be achieved without bulky filter inductors. This PWM rectifier, however, has drawbacks such as complicated power and control circuits, much increased cost, and reduced reliability. Furthermore, the weight and size of the rectifier are comparably large to the simple diode rectifier with LC filter. To obtain higher power density PWM rectifier, soft-switching technique is adopted, which allows 30-50kHz switching. [4-5] The overall efficiency is increased and the switching noise and EMI are considerably reduced. The weight and size, however, are not much reduced since the ferrite cores are required for input filter inductors instead of iron cores.

On the other hand, the single-switch boost rectifier has been studied. [6-8] Simple power circuit and simple control reduce the circuit complexity and cost. However, this single-switch rectifier also has drawbacks as follows; Maximum power is usually limited by several kW range since the rectifier is operated with discontinuous conduction mode (DCM); It is not easy to use 500V MOSFETs for the second stage DC/DC converter since the output voltage should be very high comparing to the line voltage peak for higher power factor, usually 1.5-2 times; The power density is not much higher than the six-switch PWM rectifier since the overall efficiency is less than the PWM rectifier and the additional input LC filter is necessary.

This paper presents a new high power density three phase diode rectifier is presented. By eliminating the bulky LC filter from the conventional diode rectifier without losing most of the advantages of the conventional rectifier, very

high power density power conversion with reasonably high power factor can be achieved. Operation principle and design considerations are illustrated and verified by Pspice simulation and experimental results from the 100 kHz, 3.3 kW prototype.

II. Basic Principle of the Proposed Rectifier

The conventional three phase rectifier followed by dc/dc converter with the basic operation waveforms is shown in Fig. 1. The bulky LC filter acts like a constant current source and then the line current is shaped as a square wave in phase with the input phase voltage. In this case, the power factor is usually higher than 0.9. The filter inductor usually has several mH to over than ten mH range inductance which operates at 360 Hz (three times of line frequency). This inductor and capacitor increase weight and size of the rectifier.

The proposed high power density rectifier with the basic operation waveforms are shown in Fig. 2. The low frequency bulky LC filter is eliminated from the dc-link and a high frequency three phase LC filter is added in the input side instead and then the dc-link voltage V_{dc} will follow the three phase rectified voltage waveform as shown in Fig. 2(b) since there is no low pass filter in the dc-link. The input current of the dc/dc converter which is like a square waveform at switching frequency flows directly through dc-link and input lines. The average of the dc-link current I_{dc-avg} is like the waveforms shown in Fig. 2(b) since the output voltage is regulated and constant power is delivered to the output. The line current will also be pulsating waveform as shown in Fig. 2(c) if the input filter is not added. If the input filter is added, however, the high frequency pulsating current is filtered out and the average dc-link current flows in the line as shown Fig. 2(d) which is very close to square wave in phase with the phase voltage. The power factor of the proposed rectifier is a little bit less than the conventional rectifier but it is very close. The input LC filter is operated at switching frequency of the dc/dc converter and thus, the weight and size of the filter is much smaller than the bulky LC filter of the conventional rectifier.

The proposed rectifier can be further simplified by adding a high frequency LC filter in the dc-link instead of the input three phase LC filter as shown in Fig. 3(a). In this case, the LC filter should be small enough to ensure that the dc-link voltage follows the three phase rectified voltage as shown in Fig. 3(b) and then, the filter inductor current will be just the average of the input current of the dc/dc converter. The same line current waveforms with that of the rectifier with ac side LC filter can be obtained with more reduced size and cost as shown in Fig. 3(c).

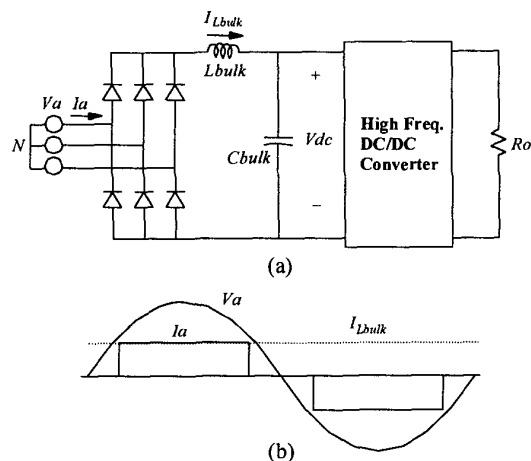


Fig. 1 Conventional three phase diode rectifier with dc/dc converter; (a) power circuit topology, (b) typical input phase voltage and current waveforms.

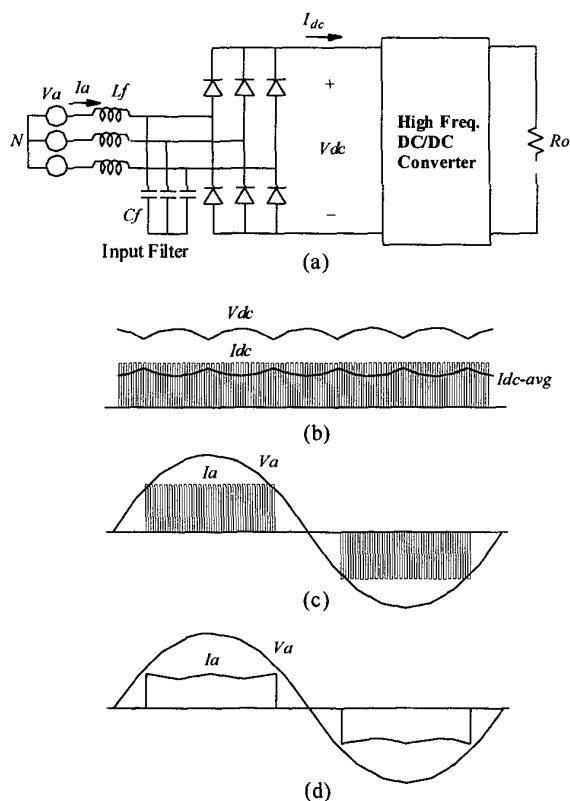


Fig. 2 Proposed high power density three phase rectifier; (a) power circuit topology, (b) dc-link voltage and current waveforms, (c) input phase voltage and current (without input LC filter), (d) input phase voltage and current (with input LC filter).

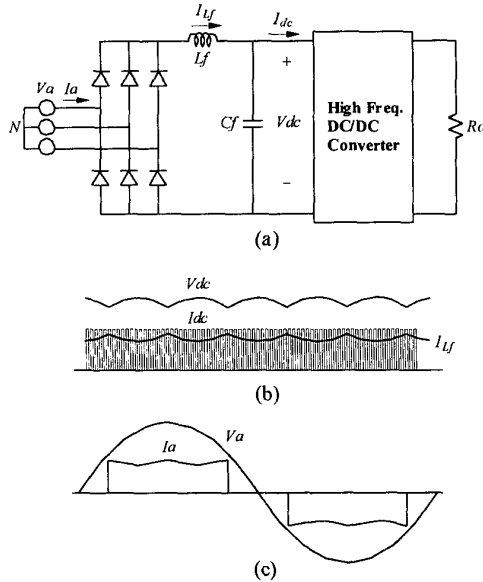


Fig. 3 Proposed high power density rectifier with dc-link side high frequency LC filter: (a) power circuit, (b) dc-link voltage and current waveforms, (c) input phase voltage and current waveforms.

III. Problems and Solutions

The proposed rectifier, however, has two problems due to the small dc-link capacitor: it is not easy to protect the switching devices in the dc/dc converter under the surge from the line and the hold-up time is too short under line voltage sag. To solve these problems, a bulky capacitor with an active switch can be added in the dc-link as shown in Fig. 4(a). The bulky capacitor is initially charged up to the peak of the rectifier voltage and Sdc is normally off. So, the bulky capacitor is disconnected from the power flow path, which ensures the basic operation of the proposed rectifier. When the surge comes from the line, the anti-parallel diode Ddc is turned on and then, the dc-link voltage is clamped by the bulky capacitor voltage, which protects the over voltage of the switching devices. The dc-link voltage (bulky capacitor voltage) is increased a little bit during the short surge period and decreased very slowly after the surge by discharging through the discharging resistor Rcb. The Rcb is added to protect unexpected charging up of the bulky capacitor. When there is a line voltage sag, the Sdc is turned on and then the dc-link voltage is held by the bulky capacitor voltage and decreased slowly allowing the regulation of the output voltage. When the line voltage comes back, the bulky capacitor is charged up through the anti-parallel diode Ddc and the anti-parallel diode blocks when the capacitor voltage reaches the peak of the rectified voltage. The switch Sdc is

turned off and then the bulky capacitor disconnected from the power flow path ensuring high power factor rectification.

IV. Design Considerations

A. Design of LC filter

The dc-link filter should be properly designed. If the cut-off frequency of the LC filter is too high, the pulsating current will not be properly filtered out. If the cut-off frequency is too low, the power density and input power factor will be decreased. If the cut-off frequency is further lowered (close to 360 Hz), the LC components will be oscillated. The design, however, is not so critical since the switching frequency of the second stage dc/dc converter is usually very high comparing to 360 Hz. The cut-off frequency of 20-30 times lower than the switching frequency is enough to filter out the pulsating current. In the circuit tested in this paper, the switching frequency is 200 kHz, and the cut-off frequency is chosen with 8 kHz, about 25 times lower frequency.

B. Design of Clamp and Holder

The bulky capacitor with an active switch and a resistor can be added to the proposed rectifier to protect the devices and to provide required hold-up time. If a surge comes from the line, the anti-parallel diode is turned on and the dc-link voltage is clamped by the bulky dc-capacitor voltage and the capacitor voltage is increased. The capacitor voltage is discharged through the Rcb. Rcb should be high enough not to discharge during the valley period of the

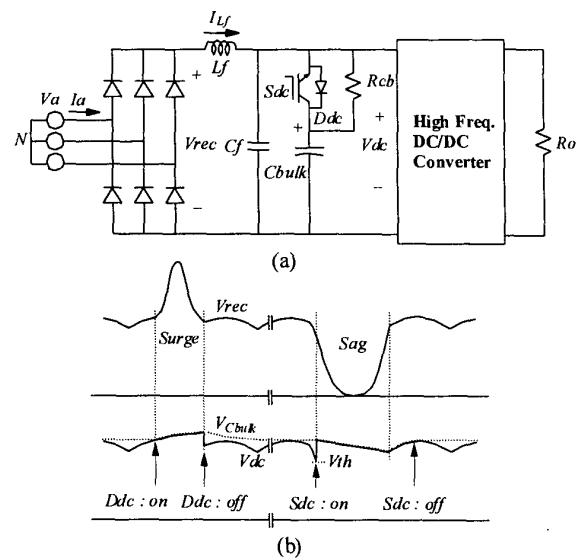


Fig.4 Proposed rectifier with dc-link voltage protection circuit; (a) power circuit, (b) operation waveforms.

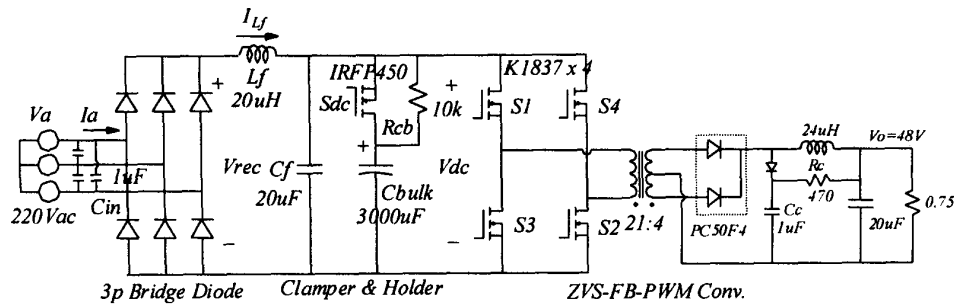


Fig. 5 Circuit diagram of the proposed rectifier with ZVS full bridge PWM converter used for simulation and experiment.

rectifier voltage and low enough to discharge during the average period between surges. The capacitance of the bulky capacitor depends on the required hold-up time.

V. Simulation and Experimental Results

To verify the operational principle of the proposed rectifier, a 3.3 kW rectifier followed by a 100kHz ZVS full bridge PWM converter is simulated using Pspice.

A prototype is built and tested. The circuit diagram used for simulation and experiment is shown in Fig. 5. A 20 uH inductor and a 20 uF capacitor are used for the dc-link LC filter and a 3000uF capacitor and IRFP450 MOSFET are added for clamping surge voltages and providing the required hold-up time. A 10 kohm is used for the discharging resistor, which is high enough not to affect the overall efficiency. A low cost three phase bridge diode pack is used for the rectifier and 1uF filter capacitors are added in the line side to reduce the diode reverse recovery. K1837 MOSFETs from Hitachi are used for the primary switches. The output voltage of the dc/dc converter is tightly regulated.

Fig. 6 shows the simulated waveforms of the conventional rectifier where a 10 mH inductor and 3000 uF capacitor are used for the dc-link filter. The input current shows clean and almost square wave except a small ripple as expected. The dc-link voltage is like a dc waveform.

Fig. 7 shows the simulated waveforms of the proposed rectifier with high frequency filter in the dc-link side. It can be seen that the dc-link voltage has 360 Hz ripple as expected and the duty cycle is inversely varied with the rectifier voltage since the output voltage of the dc/dc converter is tightly regulated. The input current has proportional ripple to the duty cycle. The power factor of the proposed rectifier is a little bit reduced but it is very close to that of the conventional diode rectifier.

Fig. 8 shows the primary voltage and current waveforms of the full bridge dc/dc converter, which are typical waveforms of ZVS full bridge converter using phase shift PWM method. The waveforms are very clean thanks to complete ZVS.

Fig. 9 shows the experimental waveforms of the conventional rectifier with the same bulky LC filter used in simulation. The dc-link voltage is almost rippleless and the output voltage is tightly regulated. The input current shows almost square wave except a small ripple which is also almost same as that of the simulated waveforms. The measured power factor is about 0.91.

Fig. 10 shows the experimental waveforms of the proposed rectifier with dc-link side high frequency LC filter and open loop control of dc/dc converter. The dc-link voltage

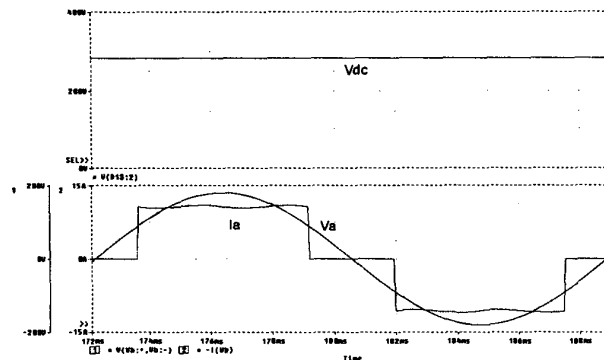


Fig. 6 Simulated waveforms of the conventional three phase rectifier with bulky LC filter.

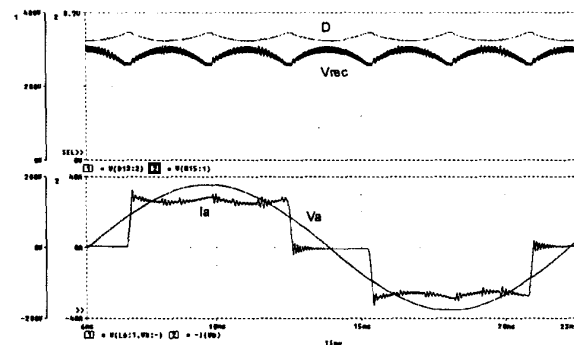


Fig. 7 Simulated waveforms of the proposed three phase rectifier with line side high frequency LC filter.

waveform is not a dc but rectified voltage of three phase voltage as expected. The output voltage has the same 360 Hz ripple since the output voltage is not regulated. The input current waveform has the same ripple with the dc-link voltage.

Fig. 11 shows the experimental waveforms of the proposed rectifier with the closed loop control of dc/dc converter. The output voltage, however, is well regulated with 48V. The duty cycle of the dc/dc converter is inversely varied according to the dc-link voltage and thus, the average input current of dc/dc converter is also inversely proportional to the dc-link voltage. The pulsating input current of dc/dc converter is filtered out by the high frequency LC filter. So, the average current flows in the ac-line and almost same waveforms are achieved as those of the simulated. The measured power factor is about 0.9, a little smaller than that of the conventional rectifier.

Fig. 12 shows the waveforms of the proposed rectifier when there is a voltage sag in the line. To give a voltage sag, a chopper circuit including a switch and a diode is added right after three phase rectifier. The switch is normally turned on and turned off for 8 ms to make the situation of a half period voltage sag. When the switch is turned off, the rectifier output voltage is abruptly decreased to zero and the dc-link voltage follows quickly since the filter capacitor is very small. When the dc-link voltage reaches the threshold, the switch S_{dc} is turned on and then, the dc-link voltage becomes the bulky capacitor voltage. The dc-link voltage is now much slowly decreased during the period of voltage sag maintaining the output voltage regulation. In this case, the hold-up capacitor should be big enough to hold dc-link voltage for the required time. When the line voltage is recovered, the bulky capacitor charged up to the peak of the rectifier voltage and then stops. The output voltage is regulated during the voltage sag. The input surge protection is obviously done by the anti-parallel diode of S_{dc}. The experimental test for this purpose is omitted here since it is not easy to make surge in the ac-line.

Fig. 13 shows the measured efficiency of the prototype. The efficiency of dc/dc converter only is about 94% and the overall efficiency is about 93%.

VI. Conclusion

The new simple high power factor high power density three phase rectifier is presented. Operation is illustrated and well verified by Pspice simulation and experimental results.

The proposed rectifier has most of advantages of the conventional rectifier with bulky LC filter such as simple circuit, high reliability, low cost and high power factor (about 90%). By eliminating bulky dc inductor, very high

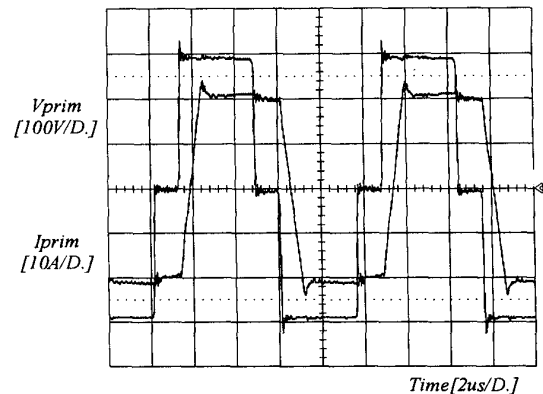


Fig. 8 Experimental waveforms of the ZVS full bridge PWM converter (primary voltage and current).

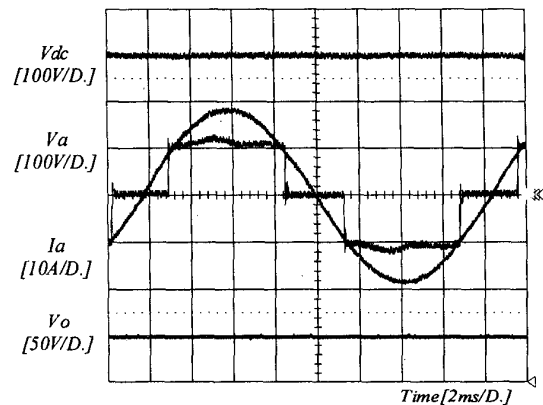


Fig. 9 Experimental waveforms of the three phase rectifier with bulky LC filter. (upper: dc-link voltage, middle: phase voltage and current, lower: output voltage)

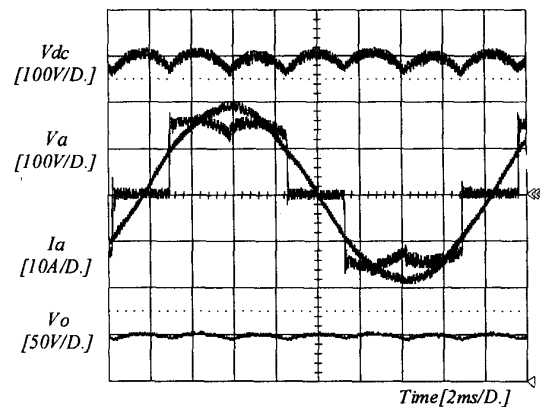


Fig. 10 Experimental waveforms of the proposed three phase rectifier with open loop output voltage control.

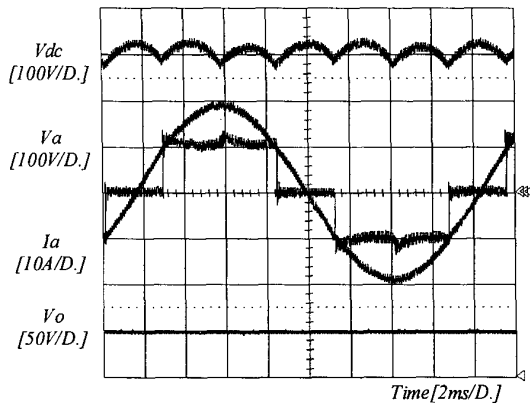


Fig. 11 Experimental waveforms of the proposed three phase rectifier with closed loop output voltage control.

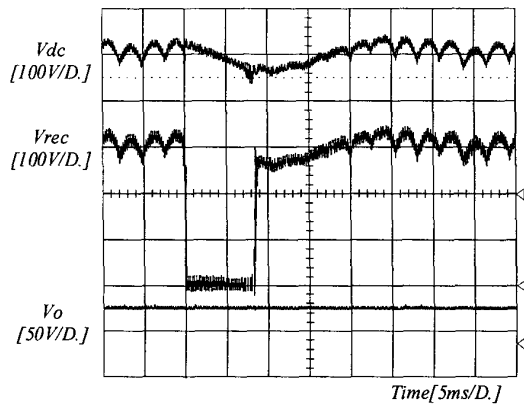


Fig. 12 Experimental waveforms of the proposed three phase rectifier when the voltage sag exists in the line.

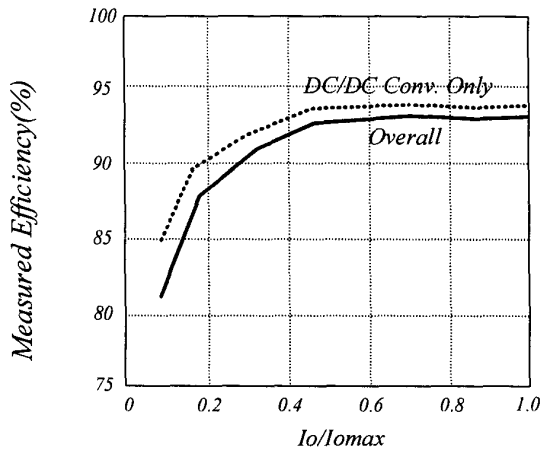


Fig. 13. Measured Efficiency of the proposed three phase rectifier.

power density can be achieved and the surge or sag in the line can be completely protected by including a bulky capacitor with a switch in the dc-link. The proposed rectifier can be effectively used for the applications where high power density is required, such as aerospace applications.

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