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Invited Paper

Bridge-less Power Factor Correction Converter with Adaptive Switching Pulse Enabling Control

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Abstract. This paper describes an efficiency improvement method in the AC-DC converter that uses the power factor correction (PFC) circuit. Conventional PFC circuit uses diode rectifier that has a finite diode turn-on voltage, which causes some amounts of loss. We investigate here to replace the basic rectifier with a bridge-less circuit. However, because of the reverse current is generated in bridge-less circuit, the direct usage of the bridge-less in PFC circuit is difficult. We devise the switching circuit that limits the number of switching pulses to overcome the problem. Circuit simulations are used to verify the operation and effectiveness of the proposed method.

1. Introduction

The AC-DC converter is used to connect between commercial power circuit and consumer electronics appliances. The AC-DC converter is efficient when using capacitor input type power supply devices due to its simple circuit configuration. However, because the input current waveform distortion, high-order harmonics generation becomes a problem. To decrease high-order harmonics, power factor correction (PFC) circuit is used to control the input current waveform [1].

This paper focuses on the rectifier to increase efficiency. The diode used in basic PFC circuit requires a finite turn-on voltage. On the other hand, the bridge-less PFC circuit uses MOSFET instead of diode to reduce on-voltage. However, reverse current generation becomes a problem in bridge-less PFC circuit. The switching control circuit is devised to overcome the problem. The power circuit simulator SIMPLIS is used to verify the circuit operation. Also it is examined how much efficiency improvement is achieved, by comparing the basic PFC circuit, half-bridgeless rectifier circuit and full-bridgeless rectifier circuit performances.

2. Conventional PFC power supply

2.1 Basic PFC power supply

The basic PFC circuit is shown in Fig 1. Through the diode bridge the input waves are transformed to the rectifier waves. When the switches are off, the rectified voltage is propagated to the output resistor Ro and the capacitor C. The output voltage becomes almost constant because the electric charge is stored in the capacitor C. The ratio of the switching on-time and off-time determines the output voltage amplification ratio.

The feedback voltage (Vr) which is proportional to the output voltage (Vo) is compared with the reference voltage and its output is amplified. Then the amplified output is multiplied by the rectified sine wave and compared with the inductor current. Then further the output is compared with the sawtooth wave. It is for Electro-Magnetic Interference (EMI) noise reduction that uses frequency modulations in clock generator [2]. This generated signal is used as a switching signal for pulse width modulation (PWM).

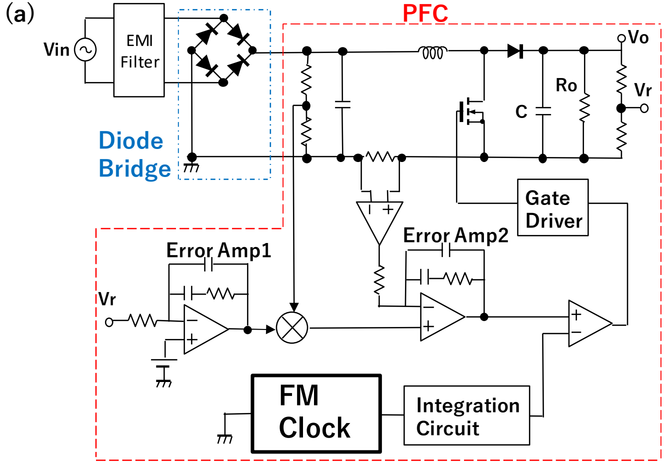

Fig. 1. Basic PFC power supply circuit diagram

2.2 Problems of conventional PFC power supply

(1) Recovery current of diodes

Fast transient response and small circuit size by using small inductors and capacitors are the benefits when high frequency clock is used. However, this also decreases the efficiency because the frequency of the recovery current generated in the diode increases. The recovery current occurs when the current switch of the diode is changed from on-state to off-state [3]. We observe that when the clock frequency is higher, the loss becomes larger.

(2) Turn-on voltage in diode rectifier

The diode in rectifier has a finite turn-on voltage. Therefore, the AC-DC power supply using a diode rectifier would be set to drive the turn-on voltage. The turn-on voltage relatively occupies a large proportion of the input voltage in the case of the small input voltage operation, which degrades the efficiency.

3. Efficiency Improvement Method in PFC Circuit

3.1 Basic PFC Circuit with Silicon Carbide Schottky Barrier Diode (SiC-SBD)

Recovery current is generated at the diode located between the inductance and the output capacitance as shown in Fig 1. First, we have replaced this diode with the Silicon Carbide Schottky Barrier Diode which has small recovery current and high breakdown voltage.

3.2 Half-Bridgeless PFC Switching Control Operation

Usually the power loss of MOSFET is less than the diode. Fig 2 shows that two diodes are replaced with the MOSFETs which operate to switch the input current; this is called half-bridgeless PFC circuit. In this circuit, when the high-side voltage of the input source Vin is high, the input current flows through diode D2 into PFC circuit and returns to the source through sw1. When the polarity of Vin is changed, the input current flows through diode D1 into PFC circuit and returns to the source through sw2. Switching pulse that controls the MOSFETS is shown in Fig 3. We see that when input voltage Vin > 0, the switch sw1 is an on-state and the switch sw2 is in a switching state. On the other hand, when input voltage Vin < 0, the switch sw2 is an on-state and the switch sw1 is in a switching state.

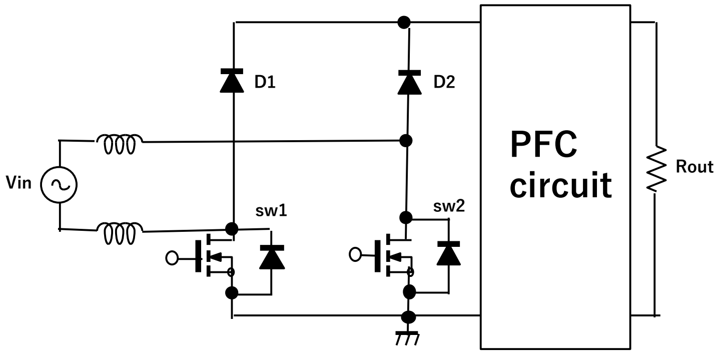

Fig. 2. Half-bridgeless circuit

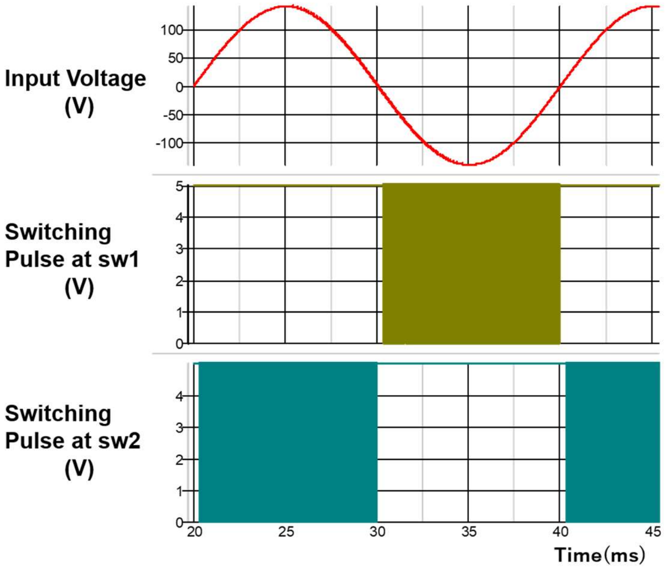

Fig. 3. Switching pulse generation of the half-bridgeless circuit.

3.3 Full-Bridgeless PFC Switching Control Operation

Fig 4 shows a full-bridgeless circuit. In this circuit, all diodes in the diode bridge are replaced with MOSFETs to improve the efficiency much more. When the high-side voltage of the input source Vin is high, the input current flows through sw3 into PFC circuit and returns to the source through sw2. When the polarity of Vin is changed, the input current flows through sw1 into PFC circuit and returns to the source through sw4.

However, there is a problem when Vin is lower than the certain voltage VLim, the electric charge in the output capacitance flows in the reverse direction to the input source. To solve this problem, the operation of the MOSFETs sw1 and sw3 should be limited according to the absolute voltage of Vin. The switching pulse that controls the MOSFETs is shown in Fig 5. We see that when the input voltage Vin > 0, switch sw4 become switching state first and then the switch sw3 is switching, while the switch sw1 is an off-state and the switch sw2 is an on-state. On the other hand, when the input voltage Vin < 0, switch sw2 become switching state first and then the switch sw1 is switching, while the switch sw3 is an off-state and the switch sw4 is an on-state. We have investigated to set the voltage VLim to prevent the reverse current for various input voltages and output currents.

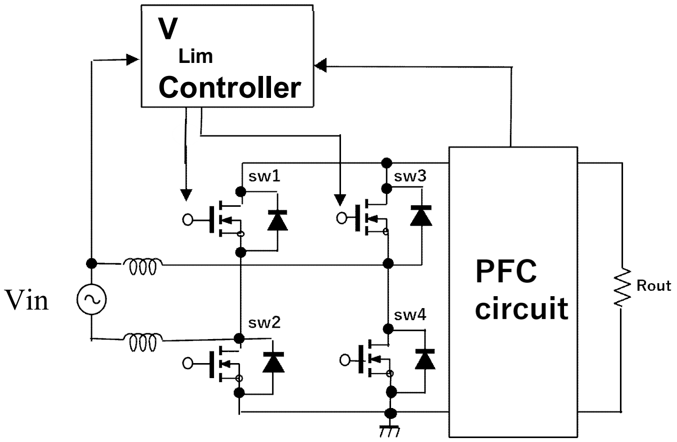

Fig. 4. Full-bridgeless circuit

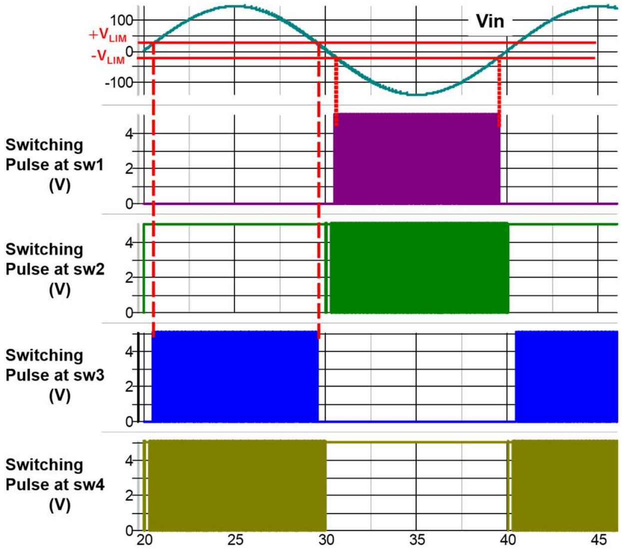

Fig. 5. Switching pulse generation of the full-bridgeless circuit.

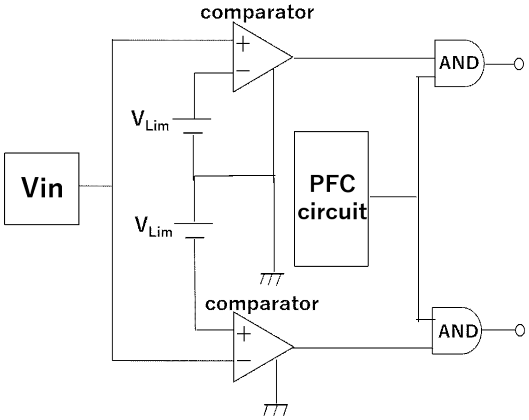

Fig. 6. V_{Lim} controller circuit

4. Simulation result

4.1 Efficiency comparison of basic PFC and bridgeless rectifier circuit

The waveforms of basic PFC circuit with SiC-SBD are shown in Fig 7. Continuous conduction mode (CCM) controls the current waveform to change continuously, so the input current (Iin) and the input voltage (Vin) have the same waveform shape. This is well-known in the case of the resistive loading. On the other hand, in motor drive and capacitor input type circuits, the shapes of input current (Iin) and input voltage (Vin) are different, which causes some amounts of energy loss.

The waveforms of half-bridgeless rectifier circuit and full-bridgeless rectifier circuit are shown in Fig 8 and Fig 9, respectively. We see that the shapes of the half-bridgeless and the full-bridgeless waveforms are very similar to those of the basic PFC in Fig 7.

The simulation condition is shown in Table 1. The efficiency comparison of basic PFC and bridgeless rectifier circuit conversion is shown in Table 2. The clock generator uses a fundamental frequency of 200kHz and a modulation frequency of ±40kHz for EMI reduction. We see that the basic PFC circuit with SiC-SBD has the lowest efficiency. The parameters in full-bridgeless circuit are shown in Table 3, and the full-bridgeless circuit has the highest efficiency. Therefore, when the number of diodes decreases due to reduction of finite diode turn-on voltage, the efficiency improves.

Table.1 Parameters of simulation conditions

Parameters	Simulation Value
Input voltage	100[Vrms]@50Hz
Inductor	1[mH]
Capacitor	500[uF]
Clock frequency	200[kHz]
Switch R_{ON}	5[mΩ]

Table.2 Each circuit conversion efficiency

Kind of circuit	Efficiency (%)
PFC with SiC-SBD	82.6
Half-Bridgeless rectifier circuit	94.3
Full-Bridgeless rectifier circuit	99.6

Table.3 Parameters in Full-Bridgeless rectifier circuit

Parameters	Simulation Value
Input voltage	100[Vrms]@50Hz
Input current	5.25[A]
Output voltage	396[V]
Output current	1.32[A]
V_{Lim}	40[V]

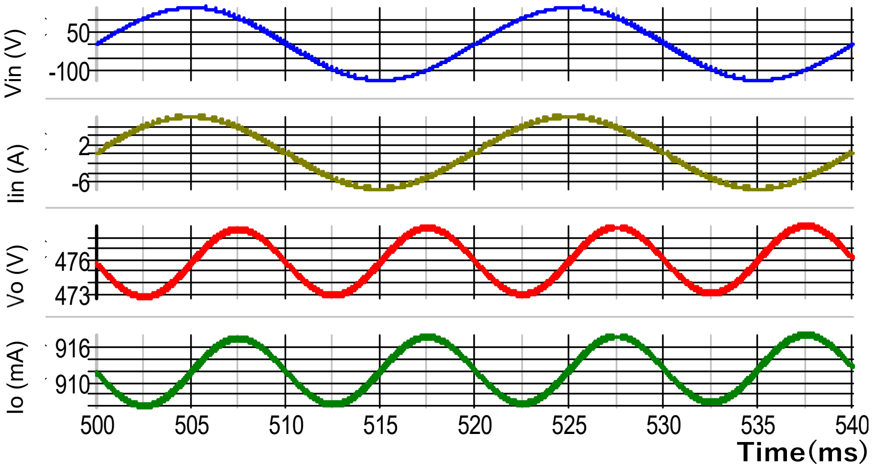

Fig. 7. Waveforms in basic PFC circuit with SiC-SBD

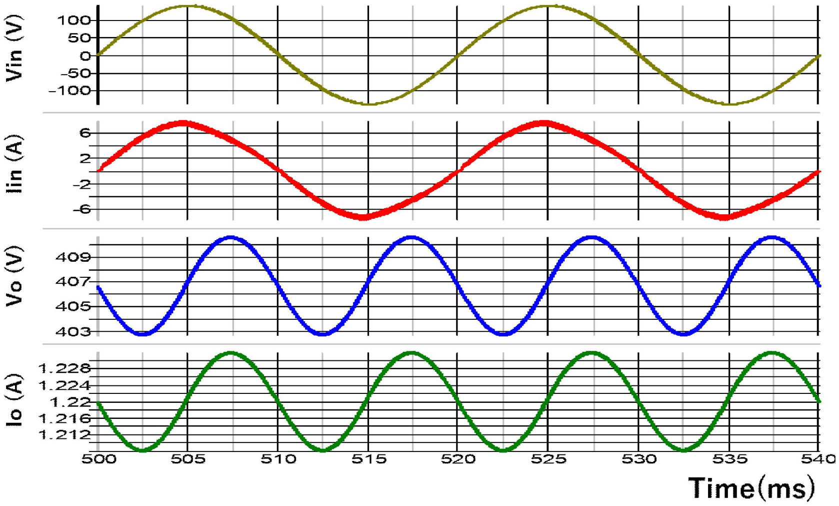

Fig. 8. Waveforms in half-bridgeless rectifier circuit

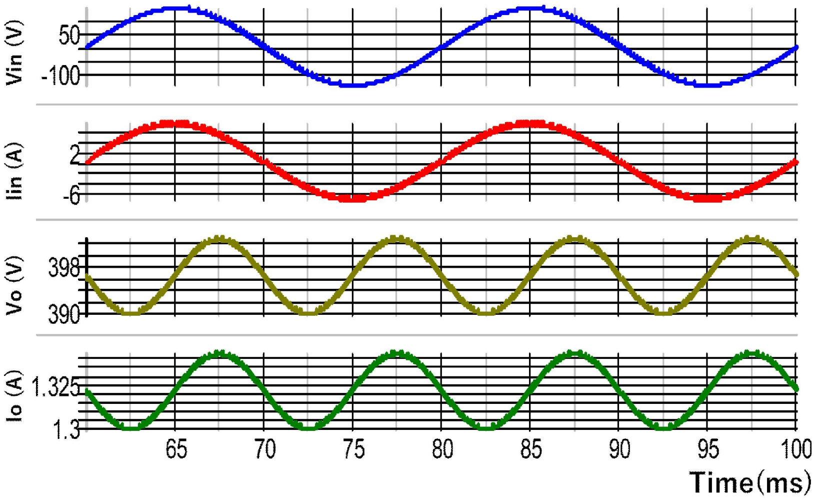

Fig. 9. Waveforms in full-bridgeless rectifier circuit

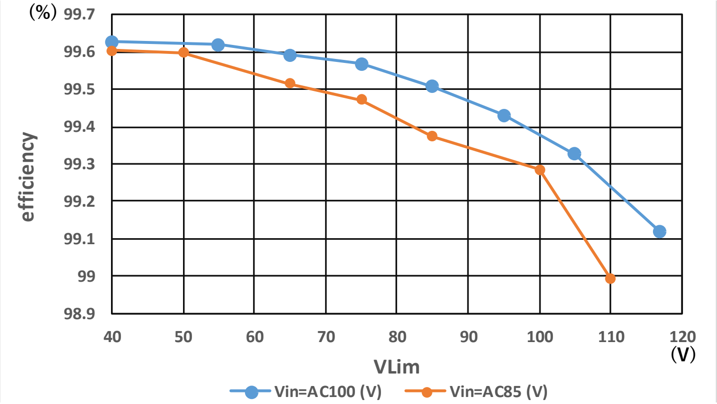

Fig. 10. Relationship between VLim and efficiency

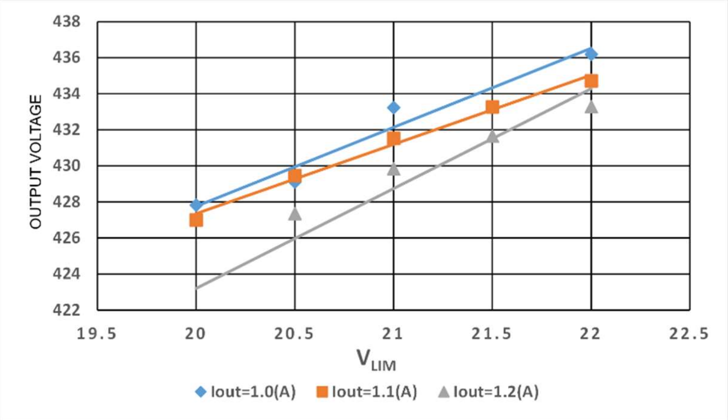

Fig. 11. Relationship between minimum VLim and output voltage

4.2 Full-Bridgeless PFC operation

The relationship between VLim and efficiency for different input voltage Vin is shown in Fig 10. The efficiency is almost constant when VLim < 50. Meanwhile, when VLim > 50 the efficiency decreases rapidly.

When input voltage Vin=100[Vrms], the relationship between minimum VLim and the output voltage for several output currents Iout is shown in Fig 11. We see that as VLim increases, the output voltage increases. VLim needs to be large for reverse current prevention. So considering their tradeoff is required. The relation between minimum VLim and the output voltage is linear at Iout= 1.0A as shown in Eq. (1):

$$V_{out} = 4\times V_{Lim} + 347\ [V] \qquad (1)$$

5. Conclusion

We have proposed a high efficiency PFC circuit by decreasing the number of used diodes and clarified their design tradeoffs. However, because of the recovery current in full-bridgeless PFC circuit, it is necessary to adjust the switching control. Proposed full-bridgeless PFC circuit using the reference voltage VLim controller solved the problem that prevents reverse current. We have to select minimum VLim when the circuit operates for good efficiency. We have shown that the basic PFC circuit with SiC-SBD has the lowest efficiency at 82.6%, next is Half-Bridgeless rectifier circuit with efficiency 94.3%, and the highest efficiency is Full-Bridgeless rectifier circuit at 99.6%.

References

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