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A Novel Bridgeless Single-Stage Step-Up Rectifier

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Abstract – This paper proposes a novel bridgeless single-stage step-up voltage rectifier. Rectification, voltage step-up, and power factor correction functions can all be achieved in a single-stage circuit. The proposed circuit could be used as a power supply for high-voltage battery chargers. The proposed circuit topology is based on a conventional voltage doubler. Two voltage doublers are connected in parallel for reducing the output voltage ripple. Two pairs of thyristors are implemented instead of the original diode for controlling the circuit. The analysis of the circuit operating process is demonstrated, and a prototype is built and tested. The experimental results verify that the proposed rectifier has good boost ratio, output voltage ripple, and power efficiency and an acceptable power factor function.

Keywords: Voltage doubler, Thyristor, Power factor correction, Bridgeless rectifier

1. Introduction

Nowadays, high-voltage dc power supplies are widely used for industrial, scientific, and military applications. In particular, they are used in test equipment such as accelerators, lasers, battery chargers, X-ray machines, dc-machine drivers, and electronic loads [1-3]. However, the conventional implementation usually contains a bridge rectifier and a DC-DC boost converter, as shown in Fig.1 [4]. The current flows through bridge diodes in addition to the switching component of the DC-DC converter, which results in higher conduction losses. In this paper, a novel bridgeless single-stage step-up rectifier is proposed and analyzed. Fig.2 shows the topology of the proposed circuit. The circuit has two voltage doublers connected in parallel, which guarantees that the output voltage ripple will be interleaved. Therefore, the ripple can be mitigated. The voltage stress over one output capacitor is also reduced to half of the output voltage, which reduces the capacitor size. Two pairs of thyristors are implemented instead of the original diodes in voltage doublers for regulating the output voltage [5-7]. By changing the firing angle of the thyristor, the output voltage can be controlled. The ac input side has an inductor for achieving a passive power factor function. A TCA785 phase control chip is used to control the proposed circuit [8]. It ensures that the gate signals of two pairs of thyristors are in a complementary mode, and it is also synchronized with the line frequency ac input voltage. The operating principles and theoretical analysis of the proposed circuit are given. The experimental results of a 1000 W prototype are presented to verify the performance of the proposed topology.

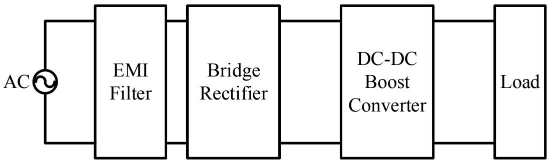

Fig. 1. Block diagram of conventional two-stage boost rectifier with PFC function

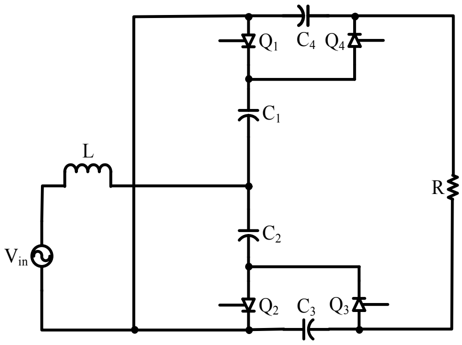

Fig. 2. Proposed circuit topology

2. Operating principle of proposed circuit

Fig. 3 shows the firing sequence of the thyristors in the proposed circuit.

Fig. 4 shows the operating principle of the proposed circuit. In phase 1, Q_2 and Q_4 are triggered. However, only Q_4 conducts, because Q_2 is still reversely biased. Energy from the ac source and C_1 flows into capacitor C_4. Energy from the ac source, C_1, and C_3 flows into the load. In phase 2, Q_2 conducts. Energy from the source also charges capacitor C_2. In phase 3, all thyristors are blocked, and energy circulates through C_3, C_4, and the load. In phase 4 to phase 6, the ac voltage is in the negative half cycle, and therefore, the operating principle is opposite to that in phase 1 to 3

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The typical waveforms of the circuit are shown in Fig. 5. This figure shows the ac input voltage, inductor current, switch current of Q_4, switch current of Q_1, capacitor voltage V_{C3}, capacitor voltage V_{C4}, and output voltage V_o from the top. In this figure, p1 to p6 denote phase 1 to phase 6, respectively.

As shown in the figure, the output voltage consists of two interleaved capacitor voltages, as a result of which the output voltage ripple can be reduced considerably.

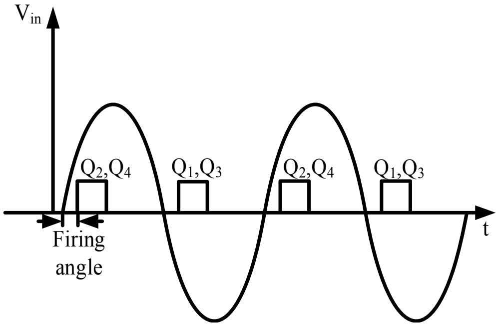


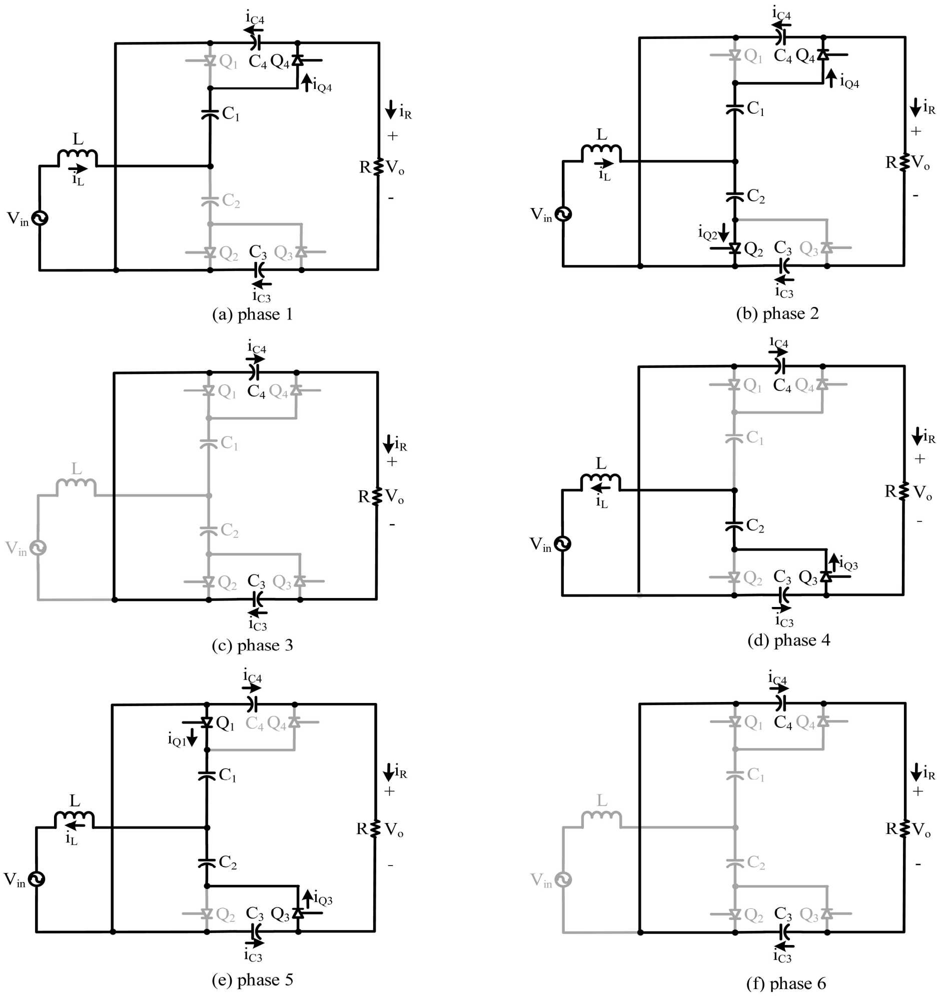
Fig. 3. Firing sequence of thyristors

3. Theoretical analysis

Theoretically, a conventional voltage doubler provides dc voltage with two times the magnitude of the ac voltage source under no load condition [9-12]. In our circuit, we connect two voltage doublers in parallel, and therefore, the output voltage ripple of two capacitors can be interleaved. The maximum output voltage of our circuit should be four times the magnitude of the ac voltage source under no load condition. Considering that the firing angle of the thyristors can be changed to control the output voltage, the output voltage can be expressed as follows:

$$V_o = 4 \times V_m \tag{1}$$

where V_m is the maximum voltage in the time duration between the firing point and the zero-crossing point. A detailed explanation for V_m is shown in Fig. 6. As an example, two different maximum voltages for angles of 30° and 135° are shown. For an input voltage of V_{in} = 110 V rms, under no load condition, output voltage of V_o = 622 V and 439 V can be obtained for a firing angle of 30° and



(a) phase 1 (b) phase 2 (c) phase 3 (d) phase 4 (e) phase 5 (f) phase 6

Fig. 4. Circuit operation principle in each period

135°, respectively.

The output voltage of the proposed circuit never reaches $4V_m$ under load condition owing to the poor voltage regulation of the voltage doubler [13]. According to [13], V_{drop} can be expressed as follows:

$$V_{drop} = 2 \times [I_{load} / (6fC)] \times (4n^3 + 3n^2 - n) \tag{2}$$

where I_{load} is the load current; C, the output capacitance; f, the input AC frequency; and n, the number of stages (for proposed circuit, n = 1). The output voltage under load condition is given as follows:

$$V_o = 4 \times V_m - V_{drop} \tag{3}$$

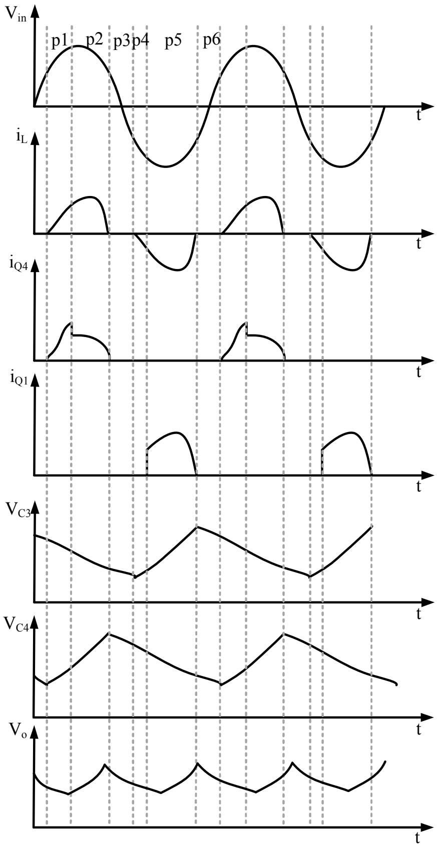


Fig. 5. Typical waveforms of the proposed circuit

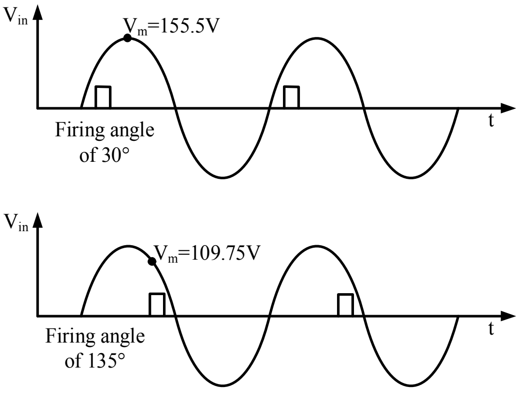


Fig. 6. V_m under different firing angles

4. Design procedures

The TCA785 phase control IC is used as the control chip for triggering the thyristor in the proposed circuit. Fig. 7 shows the full schematic of the driver circuit. Pin V_{sync} is the input for the synchronous voltage. Usually, this voltage is sensed from the input AC voltage. The switching signal of the thyristors is controlled by the chip to be synchronized with this AC voltage, which means that the firing angle should be constant. The supply voltage of TCA785 and two transistors is 10 V dc. These two transistors are operated as switches. The transistor and the connected isolation transformer are called a forward-converter-type isolated driver because this driver is operated in a manner similar to a forward converter [14]. The design of the isolated transformer requires one to consider the voltage-second. This parameter also

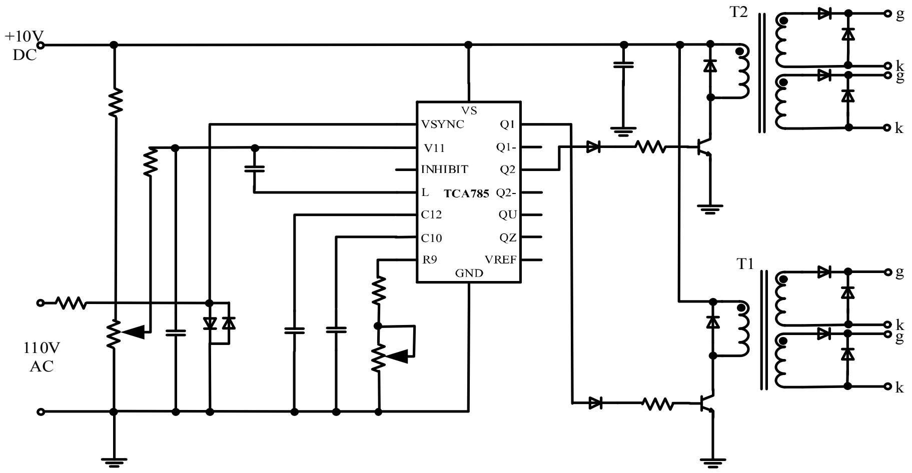


Fig. 7. Thyristor driver circuit for the proposed topology

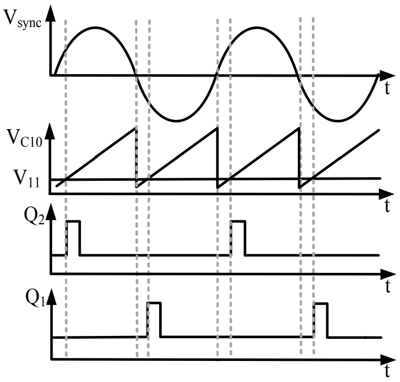


Fig. 8. Tuning principle of the firing angle

determines the core size of the transformer. For our circuit, a 30° duration of the trigger signal is required, which means that the time is around 1.6 ms. The thyristor has a minimum triggering voltage to turn on. With these two parameters, we can calculate the voltage-second to design the isolated transformer. TCA 785 has a function to change a thyristor's firing angle. The principle is shown in Fig. 8. V_{sync} is the synchronization voltage. V_{C10} is the ramp voltage. Q_1 and Q_2 are trigger signals. By tuning the variable resistor between V_{11} pin and ground in Fig. 7, the value of the control voltage V_{11} can be changed, and therefore, the firing angle can be changed.

5. Simulation Verification

PSIM is used to simulate our proposed circuit. Fig. 9 is the simulation result of the circuit under 110V input voltage, 250 Ω load and firing angle of 30°. It shows input voltage V_{in}, input current I_{in}, output voltage Vo and output capacitor voltage V_{c3}, V_{c4}. From the figure we can find the output capacitor voltages are interleaved. Fig. 10 is the simulation result of the circuit under 110V input voltage, no load and firing angle of 30°. After calculation, it can be found the simulation results matches theoretical analysis very well.

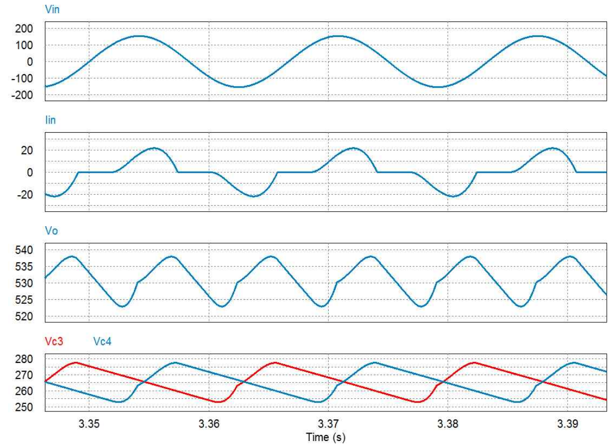


Fig. 9. Simulation results under 250 Ω load and firing angle of 30°

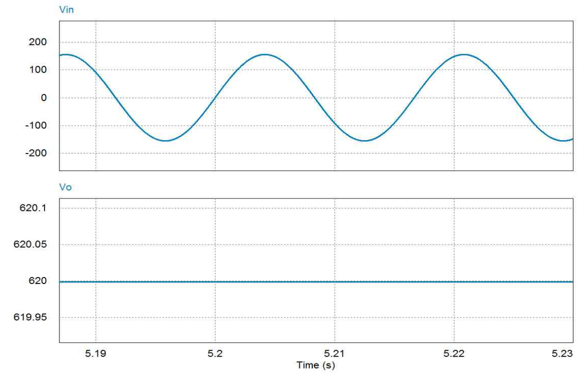


Fig.10. Simulation results under no load and firing angle of 30°

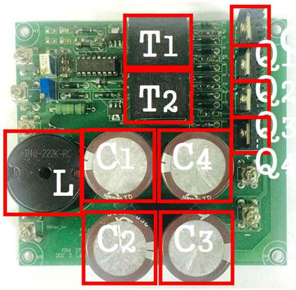


Fig. 11. Photograph of the proposed prototype circuit

6. Experimental Verification

An experiment is conducted to verify the proposed circuit. A prototype, which has 110 V AC input voltage and 1000 W output power, is built for the experiment. Fig. 11 shows a photograph of the proposed prototype circuit. The circuit parameters are $C_1 = C_2 = C_3 = C_4 = 1000$ μF and L = 2 mH. The experiment was carried out for firing angles of 30° and 135°, respectively.

The experimental results with no load and with 250 Ω load are shown in Figs. 12-15. The experiment result of the output voltage well coincides with our theoretical results as obtained in section 3. It can be seen that the output voltage can be regulated by changing the firing angle. Fig. 16 shows the interleaving of the output capacitor voltages. By this approach, the output voltage ripple of the circuit can be reduced sharply. The voltage ripple of one output capacitor is around 15%, and it is reduced sharply to 6.6% by interleaving. The voltage stress over one output capacitor is also half of the output voltage, which reduces the output capacitor size. Fig. 17 shows the measured results of the efficiency and power factor of our circuit for 1000 W output power. The efficiency is more than 87%, and the power factor is 0.8. This power factor is relatively good for passive power factor correction [15-17].

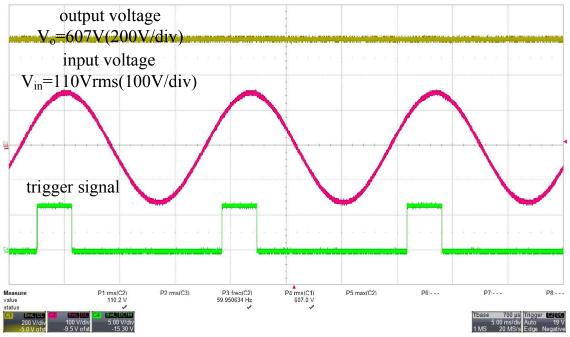


Fig. 12. Experimental results under no load condition and firing angle of 30°

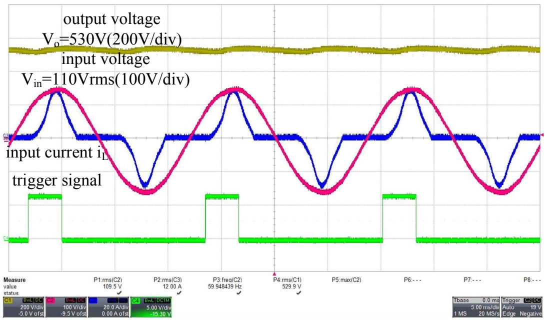


Fig. 13. Experimental results under 250 Ω load and firing angle of 30°

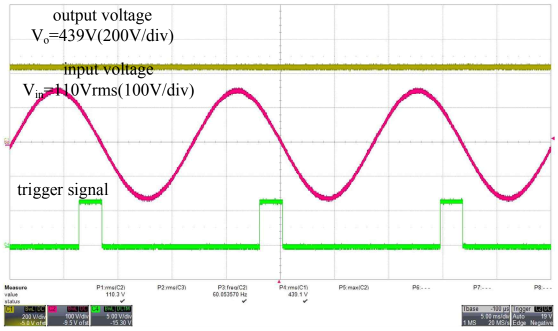


Fig. 14. Experimental results under no load condition and firing angle of 135°

7. Conclusion

In this paper, a single-stage bridgeless voltage rectifier based on a voltage doubler is proposed. This topology can achieve rectification, voltage step-up, and power factor correction functions in one stage. The circuit was analyzed theoretically, and its operational principle and experimental results were demonstrated. The experimental result agreed with the theoretical ones. However, the power factor is below 0.9 because of the use of passive power factor correction. This is a drawback that should be resolved in the future.

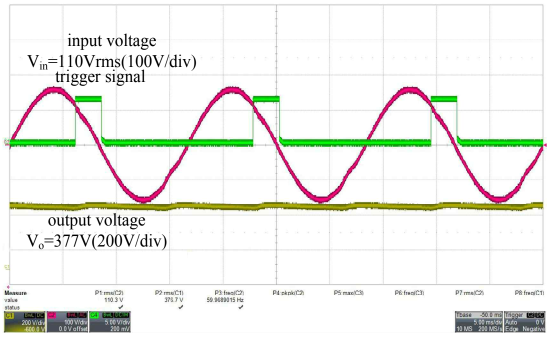


Fig. 15. Experimental results under 250 Ω load and firing angle of 135°

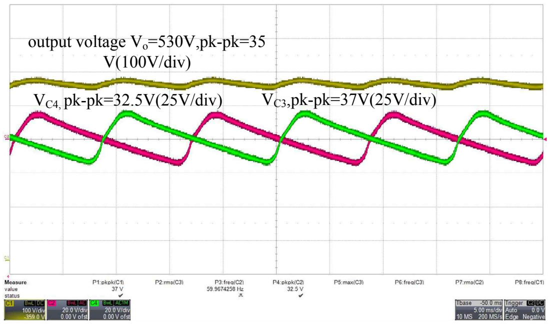
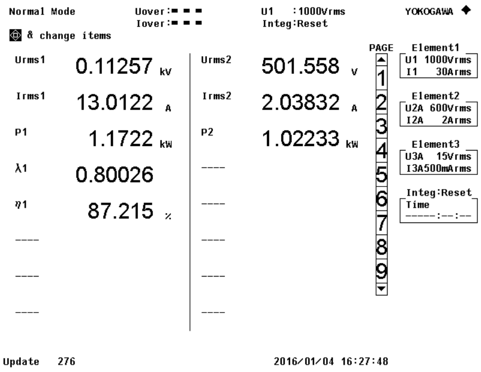


Fig. 16. Interleaving of two output capacitor voltages



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Normal Mode          Uover:■ ■ ■      U1   :1000Vrms        YOKOGAWA ◆
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◈ & change items
                                                   PAGE   Element1
Urms1    0.11257 kV  | Urms2   501.558 V           ▲    U1 1000Vrms
                     |                             1    I1    30Arms
Irms1    13.0122  A  | Irms2   2.03832 A           2      Element2
                     |                             3    U2A 600Vrms
P1        1.1722 kW  | P2      1.02233 kW          4    I2A    2Arms
                     |                             5      Element3
λ1       0.80026     | ----                        6    U3A  15Vrms
                     |                             7    I3A500mArms
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Fig. 17. Measured results of power efficiency and power factor under 250 Ω load and 1000 W output power

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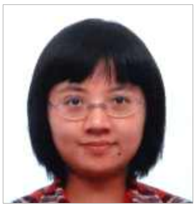

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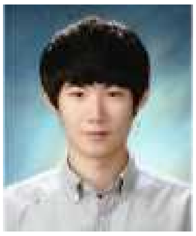

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