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A Single-stage LED Driver for The Street Lighting System

Abstract. *A single-stage LED driver for the street lighting is proposed. The system consists of a constant current circuit and a constant voltage circuit, and the constant voltage circuit is gotten by integrating a buck-boost circuit and a flyback circuit.The peak current control mode is adopted in the constant current circuit which is a boost circuit and works in PWM mode. The theoretical analysis and design procedures of the proposed lighting system are proposed and discussed in detail in the paper.*

Streszczenie. *Opisano system świateł LED stosowanych do oświetlenia ulic. System składa się z przetwornicy buck-boost pracującej w trybie PWM. (**Sterownik do świateł LED stosowanych do oświetlenia ulicy**)*

Keywords: LED, single-stage；buck-boost；flyback
Słowa kluczowe: LED, oświetlenie, przekształtnik buck-boost..

Introduction

Since the encapsulation technology of LEDs has become mature in the recent years, the LEDs are applied to the lighting areas such as the LCD backlight, the street lighting and the car head lighting [1-3]. Generally, the use of LEDs is the development direction of the future lighting system.

If neglecting the affection of the junction temperature, the illumination of the LEDs is in proportion to its average current, so the LEDs need constant current control. The luminance of a single LED is very low, so the LEDs are usually used in series. While if all LEDs are connected in series, the whole system will stop working if one of the LEDs is broken, so the LED arrays are always with parallel connection. Traditional LED driver is consists of three parts, which is the power factor correction (PFC) circuit, the DC/DC voltage regulate circuit and the constant current circuit [4]. The boost converter working in the DCM state is usually adopted for the PFC circuit, while a flyback converter or a forward converter is usually adopted for the voltage regulate circuit. If the PWM dimming control method is adopted, the system will have wider scope of dimming, so the PWM dimming control method is usually adopted for the constant current circuit [5], and the DC/DC converter such as the buck circuit, the boost circuit, the buck-boost circuit and the sepic circuit become a reasonable choice[6-9]. Though the three-stage LED driver circuit can reach a high power factor and have a fast output voltage response, the cost is high and the multi-stage in series reduces its efficiency,so as to reduce the cost and increase the efficiency of the system, integrating the PFC circuit and the DC/DC regulate circuit into one single-stage circuit become a feasible choice.

In paper [3], the buck circuit and flyback converter are integrated to drive white light LEDs. Due to the buck circuit has a dead zone, the power factor is not high enough. The boost circuit and flyback are integrated in paper [10], however the bus voltage is too high, which increases the voltage stress and the costs of the system. Paper [11] proposes a single-stage topology based on the active clamp technology, but the control methods are very complex and the cost is still high. In this paper, the buck-boost circuit and the flyback circuit are integrated by using the same switch. Both buck-boost circuit and flyback circuit are working in the DCM state. The buck-boost circuit can realize the PFC function while the output bus voltage is controlled to a relative low condition, and the flyback circuit can realize the regulation of the output voltage very well. The constant current circuit is a boost circuit based on the peak current control.

Configuration of the system

The single-stage constant voltage circuit proposed in this paper is shown in Fig. 1. L_b, Q_1, D_b, C_b form a buck-boost circuit, while the flyback converter is consist of Q_1, T, D_r, C_{bb} and the load. We can see that the two circuits are integrated together by using the same switch Q_1. The constant current circuit adopted here is the boost circuit with the parallel form in the practical application.

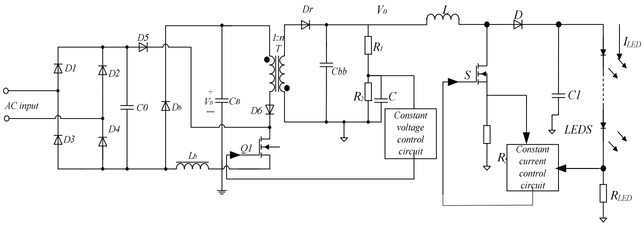


Fig.1 The LED lighting system proposed

Single-stage DC-DC converter

Fig. 2 shows the proposed AC/DC converter used in the street lighting system. The converter has five working modes, and they are described in detail as follows.

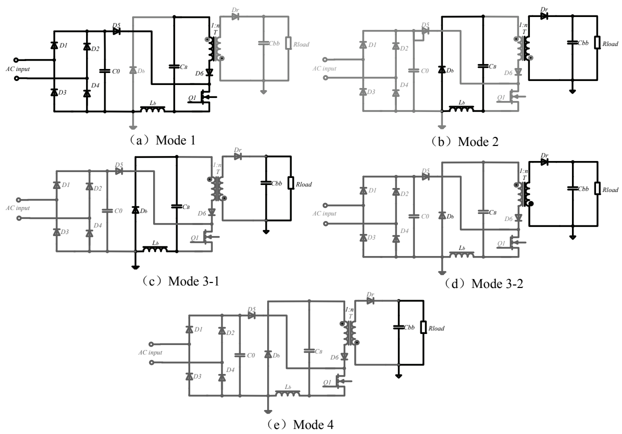


Fig.2 The equivalent circuit for each working mode

Mode 1: this mode starts at t_0 when the drive signal of Q_1 comes. As Q_1 is on, the input voltage passes through D_5, Q_1 and the main inductor L_b is charged, meanwhile the primary inductor of the transformer is charged by the output capacitor of the buck-boost circuit. This mode ends when Q_1 is turned off.

Mode 2: Q_1 is turned off at t_1, when L_b starts to discharge through the diode D_b and the capacitor C_b. Meanwhile D_r is on, that is to say the secondary side of the transformer starts to provide energy to the load. Just define that the time when the main inductor of the buck-boost circuit stops discharging is t' and the time when D_r is turned off is t''. If t'>t'', this mode ends at t_2=t'', else this mode ends at t_2=t'.

Mode 3-1: If t'>t'', the inductor L_b will continue to discharge. This mode ends at t_3 when L_b stops discharging.

Mode 3-2: If t''>t', the secondary side of the transformer will continue providing energy for loads until the D_r is turned off. This mode ends at t'_3.

Mode 4: The energy transferred to the load is supplied by the output capacitor C_{bb} in the secondary side of the transformer. This mode ends at t_4 when the turn-on signal of Q_1 comes again.

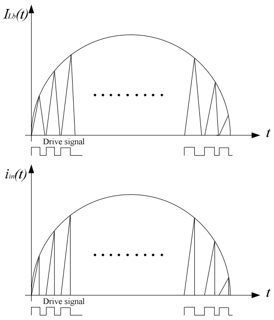


Fig.3 Waveforms of inductor current and input current

Fig.3 shows the waveforms of inductor current and input current for the buck-boost circuit working in the DCM state. For the buck-boost circuit, the main inductor current reaches its peak value when the switch is turned off, as seen in (1).

(1)
$$I_{peak}=\frac{V_{in}\sin(2\pi f_l t)}{L_b}DT_s$$

Where $V_{in}\sin(2\pi f_l t)$ is the input voltage, *D* is the duty ratio, T_s is the switching period.

The average current of the inductor is calculated as follows.

(2)
$$I_{avg}=\frac{V_{in}\left|\sin(2\pi f_l t)\right|}{2L_b}D^2T_s$$

As a result, the buck-boost circuit in DCM state can be seen as an equivalent resistance R_e, as shown in (3).

(3)
$$R_e=\frac{2L_b}{D^2T_s}$$

Then the average input power can be obtained as follows:

(4)
$$P_{in}=\frac{1}{\pi}\int_0^{\pi}I_{avg}V_{in}\sin(2\pi f_l t)d\theta=\frac{D^2V_{in}^2T_s}{4L_b}$$

As for the flyback circuit, the analysis is the same as mentioned above. Similarly, the input peak current, average input current and the equivalent resistance of the flyback circuit can be achieved in the equations as follows.

(5)
$$I_{peak\_fly}=\frac{V_B}{L_{b\_p}}DT_s$$

(6)
$$I_{avg\_fly}=\frac{V_B^2}{2L_{b\_p}}D^2T_s$$

(7)
$$R_{e\_fly}=\frac{2L_{b\_p}}{D^2T_s}$$

where L_{b_p} is the incuctor of the the transformer in the primary side.

Therefore the peak current and the average current in the secondary side can be obtained in (8) and (9).

(8)
$$I_{peak\_fly\_s}=\frac{V_B}{nL_{b\_p}}DT_s$$

(9)
$$I_{avg\_fly\_s}=\frac{V_B{}^2}{2V_0L_{b\_p}}D^2T_s$$

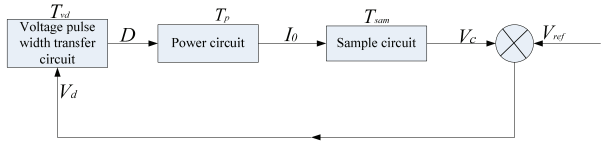


Fig.4 The control chart for constant voltage control

Fig. 4 shows the small signal block diagram for the single-stage AC/DC converter. From Fig.4, it can be seen that by sampling the power stage and comparing it with the reference value, the error signal can be easily obtained, and the error signal can be transformed into the pulse width modulation signal through adjustment.

The low frequency equivalent circuit of the proposed AC/DC converter is showed in Fig. 5.

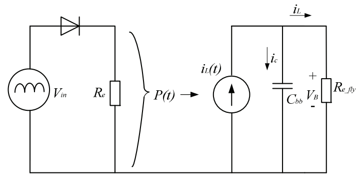


Fig.5 Low frequency equivalent circuit of proposed the converter

Here the equation can be obtained as follows:

(10)
$$C_{bb}\frac{dv_B}{dt}+i_L=\frac{V_{in}^2d^2}{2L_{b\_p}f_Sv_B}$$

Adding the small signal interference into the system, then the equation can be gotten as follows:

(11)
$$G(s)=T_p=i_L(s)/d(s)=\frac{\dfrac{2I_L}{C_{bb}DR_{e\_fly}}}{s+\dfrac{V_B+I_LR_{e\_fly}}{V_LR_{e\_fly}C_{bb}}}$$

The low-pass filter is used to sample the output signal V_0, then (12) can be gotten.

(12)
$$T_{sam}(s)=\frac{1}{R_1C}\times\frac{1}{s+\dfrac{R_1+R_2}{R_1R_2C}}$$

The drive circuit adopted here is UC3842, from which the voltage pulse width transition function of the system T_{vd} can be gotten as follows.

(13)
$$G_c(s)=G(s)T_{sam}(s)T_{Vd(s)}$$

Analysis of the constant current circuit

The constant current control is adopted here to drive the LEDs. Because that the LED arrays are connected in series, the constant current drive unit adopts boost circuit under peak current control so as to drive more LEDs in each branch. The control chip is LT3756 by Linear Company in America. The maximum output voltage for LT3756 is 100V, and the current sampling circuit is in the high voltage side of the circuit. The input voltage ranges for LT3756 is from 6v to 100V, which makes the chip suitable for many fields, and the schematic diagram is shown in Fig. 6.

The rated power for the prototype used in the laboratory is 100W. Considering both the applications and the costs, 250mA/3.3V LEDs by OSRAM are used. Here five LED branches are used. In Fig.6, R_{LED} is the sampling resistor for the constant current control circuit, its two sides are connected to ISP side and ISN side of LT3756. The voltage between ISP and ISN equals the voltage of 5kΩ resistor, then the voltage between ISP and ISN is 0.11V. As a result, the constant current control can be realized by designing the value of R_{LED}.

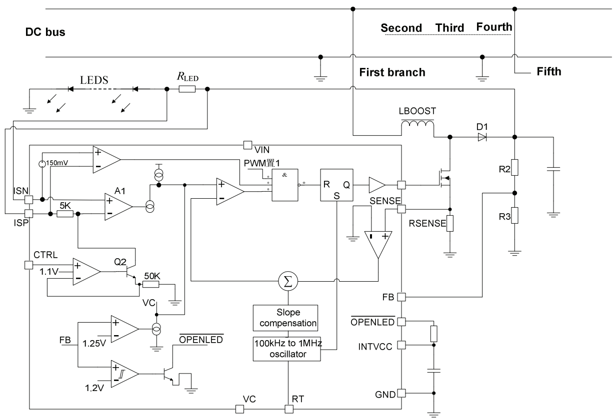


Fig.6 The circuit for constant current control

System design

The parameters of the lighting system are showed as follows: the AC input is 220V, V_0=48V, V_B=200V, the full power for the system is 100W, operation frequency is 100KHz, the maximum duty ratio is 0.4.Since the flyback circuit works in the DCM state, the charging time for the inductor in the secondary side of the transformer can be obtained:

(14) $$t_{dis}=\frac{nDT_sV_B}{V_0}$$

As the system works in DCM, the discharge time must less than (1-D)T_s, so the turn ratio must meet the equation (15) as follows.

(15) $$n<\frac{(1-D)V_0}{DV_B}$$

With the parameters given above, R_{e_fly} can be calculated and the inductor in the primary side of the transformer can be calculated from the equation (7).

As for the buck-boost circuit, in order to realize the power factor correction, it must also work in the DCM state. So we use the same analysis method as flyback, then L_b should meet (16):

(16) $$L_b<\frac{(1-D)T_sV_B}{I_{peak}}$$

For the constant current circuit, 100 kHz is also chosen to be the working frequency, and the constant current is 250mA. The inductance for the boost circuit should meet the equation (17).

(17) $$L_{Boost}=\frac{R_{SENSE}\times V_0\times(V_{LED}-V_0)}{V_{LED}\times 0.02\times f_{OSC}}$$

where V_{LED} is the voltage of the LED brunch.

The values of the main parameters for the lighting system are shown in table 1.

Table 1. The main parameters of the system

Component	Parameter
L_b	300uH
L_{boost}	375uH
T	n=1/4;L_{b_p}=288uH; the leakage inductance: 7uH
C_{bb}, C_B	330uF
C_1	4uF

Simulation and experimental results

Fig.7 shows the simulation schematic for the single-stage AC/DC converter with PSIM.

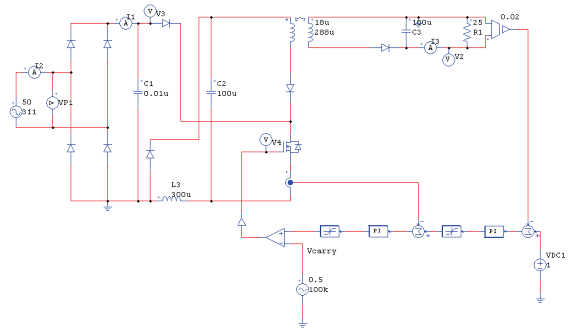
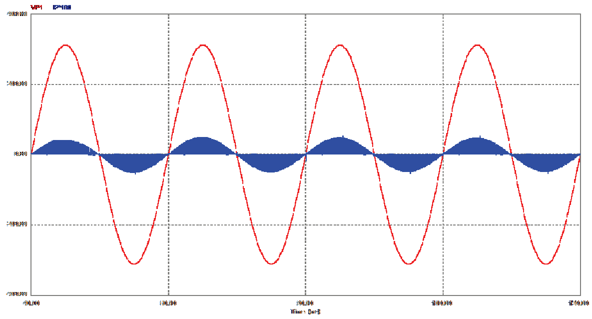


Fig.7 Schematic of the single-stage AC/DC converter in the simulation

Fig.8 shows the simulation results of the single-stage AC/DC converter.Fig.8 a) shows the waveforms of the input voltage and the current of L_b. It's obvious that the buck-boost circuit works in the DCM state, and it can realize the PFC function. Fig.8 b) shows the waveform of the output voltage for the single-stage AC/DC converter, then the output voltage is 48V with little ripple.


a)

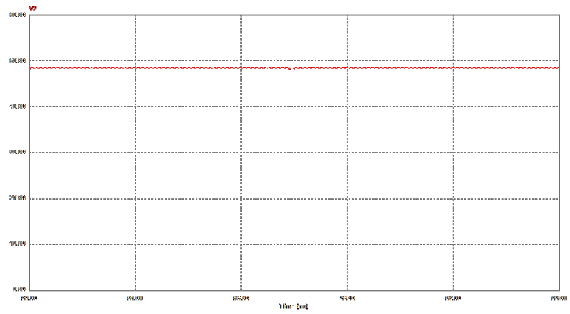

b)
Fig.8 Simulation results of the single-stage AC/DC converter

Fig.9 shows the simulation schematic for the constant current circuit, and the software is LTspiceIV by LINEAR company. Fig.10 a) and Fig.10 b) show output voltage and output current of the boost topology based on the peak current control. It is obvious that the system responses fast to the steady state after powered on. The output voltage is 80V, and the constant current is 250mA in the steady state.

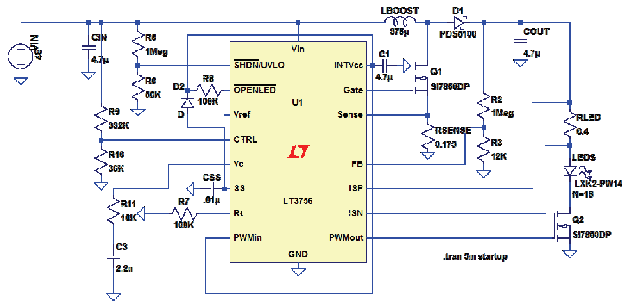
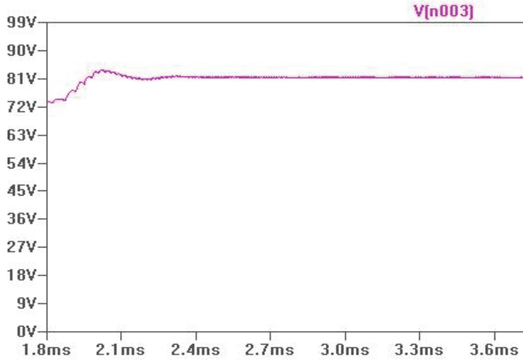
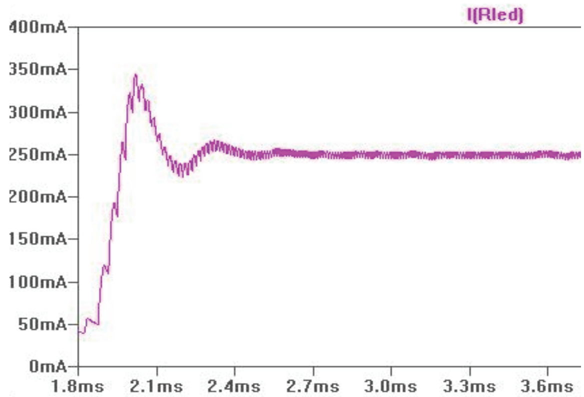


Fig.9 Simulation results of the system



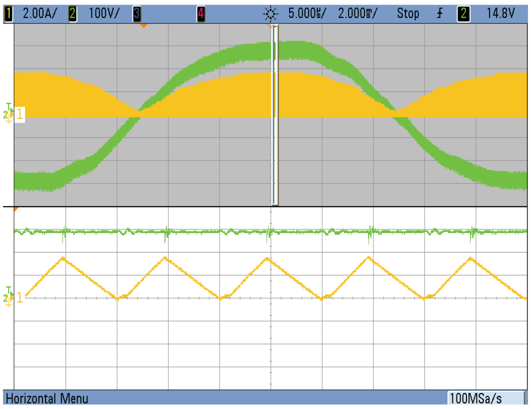
a)



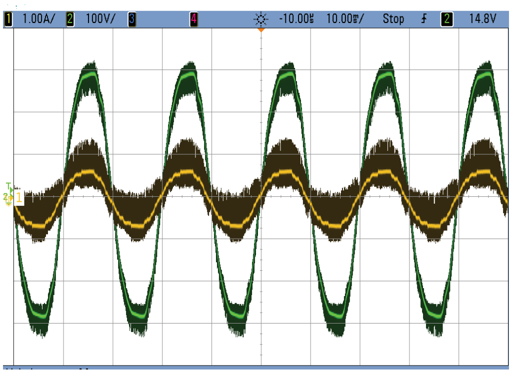
b)

Fig.10 Simulation results of the constant current circuit

In the experiment, a 100W prototype is made, and 250mA/3.3V highlight LEDs from OSRAM compny are used in the experiment, with five branches, 24 LEDs each. The test waveforms are shown as follows.



a)



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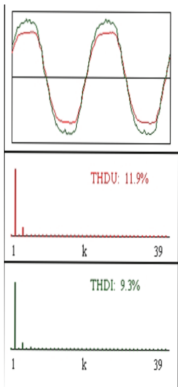
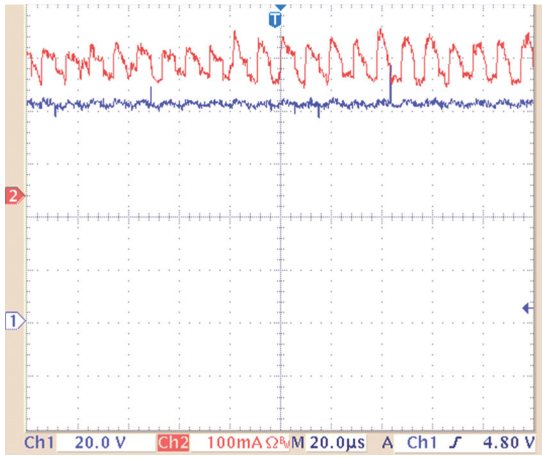


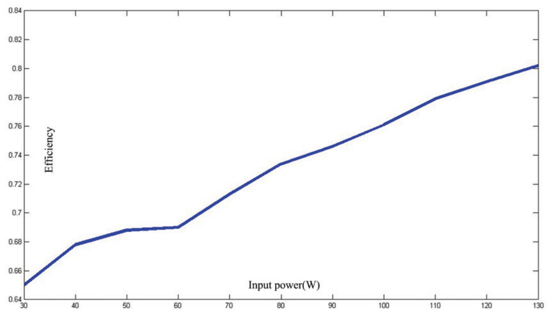
spectrum k	voltage %	current %	spectrum k	voltage %	current %
0	0.0	0.0	1	100.0	100.0
2	0.0	0.6	3	11.8	8.3
4	0.0	0.4	5	1.0	2.4
6	0.0	0.7	7	0.5	1.5
8	0.0	0.1	9	0.5	0.6
10	0.0	0.3	11	0.4	0.9
12	0.0	0.0	13	0.9	1.4
14	0.0	0.3	15	0.7	0.9
16	0.0	0.1	17	0.7	1.1
18	0.0	0.6	19	0.4	0.7
20	0.1	0.5	21	0.1	0.1
22	0.0	0.5	23	0.2	0.4
24	0.0	0.2	25	0.1	0.1
26	0.0	0.2	27	0.0	0.3
28	0.0	0.1	29	0.0	0.2
30	0.0	0.3	31	0.1	0.4
32	0.0	0.1	33	0.0	0.2
34	0.0	0.1	35	0.0	0.1
36	0.0	0.2	37	0.0	0.1
38	0.0	0.1	39	0.0	0.3

c)

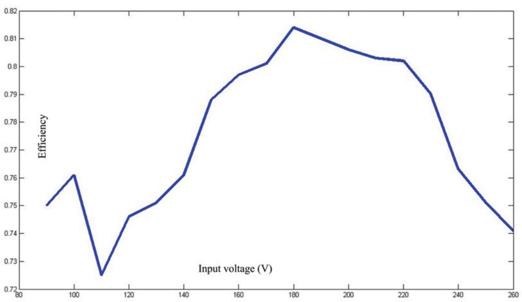


d)

Fig.11 The test waveforms in the experiment



a)



b)

Fig.12 Test results with input voltage range and output power range

Fig.11 a) shows the waveforms of the input voltage and the current of L_b, it's obvious that the buck-boost circuit is in the DCM state with the peak input voltage, so the buck-boost is in the DCM state for the whole working period. Fig.11 b) shows the waveforms of the input voltage and the input current, and it's evident that the input current can follow the input voltage, which realize the PFC function. Fig.11 c) shows the harmonic content of the input current, the THD of the system in the full load is 9.3% and the power factor is 0.995, which is satisfied with IEC 61000-3-2 class C. Fig.11 d) shows the waveforms of the output current and the output voltage of the system, and the output voltage is 80V and the constant current is 250mA.

Fig.12 a) shows the relationship between the input power and the efficiency of the system, the efficiency range from 65% to 80.2% when the input power ranges from 30W to 130W. Fig.12 b) shows the relationship between the input voltage and the efficiency of the system, the efficiency range from 74.1% to 81.4% when the input voltage ranges from 90V to 260V.

Conclusion

A single-stage LED driver for street lighting is presented in this paper. The driver is integrated by a power factor correction circuit with a DC/DC convertor, which decreases the costs and increases the reliability and efficiency of the system. The system can work reliability through experiment, the power factor is 0.995 and the efficiency is 80.2% in full load.

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