Spice Modeling of LED Filament and its Simulation in Switch Drive Circuit

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Abstract

When designing the LED filament lamp device and driving circuit at the beginning, software simulation is an indispensable step. It is necessary to verify whether the circuit output results are consistent with the requirements through simulation. In this paper, first measure the volt-ampere characteristics of the actual 1W LED filament strip, and applied the six-segment linear approximation model method for Spice modeling. The simulated volt-ampere characteristics of the 1W model were consistent with the measured volt-ampere characteristics of the 1W LED filament strip. Then use the driver chip HV9910B to design the LED filament lamp switch constant current drive circuit. Combined with the piecewise linear equivalent method, 3W, 4W, 5W LED filament lamp loads are modeled, the detailed design process of the entire circuit is analyzed, and the output voltage, current, inductance output current, MOS output voltage and other parameters of the whole circuit are simulated and verified. The results show that the output voltages are 71V, 142V, 71V, and the output currents are 30.4mA, 20.7mA, 51.1mA respectively under the circuit topology of 3W, 4W, and 5W LED filament lamp. When the inductor current works in CCM mode, the duty cycle of MOS output voltage meets the requirements, and the circuit output results are consistent with the design requirements.

Keywords: *Spice model, LED filament lamp, Six-stage linear approximation model, Buck circuit, V-I characteristics, Voltage control switch, HV9910B, Switch driving circuit*

I. Introduction

Since Japan invented led filament lamp in 2008, after more than 10 years of development, the technology of LED filament lamp has been maturing, the industrial scale has made great breakthrough, and its market share is also increasing. It is considered as an ideal light source to replace traditional incandescent lamp due to its low energy consumption and high light efficiency. Many countries in the world are increasingly withdrawing from the stage of using incandescent lamp, The LED filament lamp with better performance began to enter a new generation of lighting market rapidly. However, the LED driving power supply does not match with its own photoelectric characteristics. The LED driving power supply is one of the most important links in the LED lighting technology, which directly affects the key indicators such as the luminous efficiency and life span of the LED lamp.

For a high-quality LED lighting product, not only need to design LED chip with long service life, but also need to have a high conversion efficiency and high stability LED drive system[1]. Led filament lamp drive circuit has two ways of constant current type and constant voltage type. In constant voltage drive, led uses constant voltage power supply. However, because the volt ampere characteristic curve is exponential, the small change of voltage at both ends will cause the large change of current[2]. Compared with the constant voltage drive, the constant current mode can avoid the driving current exceeding the maximum rated value, and the constant current driving mode can solve the current change problem caused by the forward voltage change caused by temperature and other factors, so that the brightness of LED is stable, the reliability is high, and the service life of the lamp is prolonged [3]. Therefore, the market basically adopts constant current driving mode. Constant current driving includes linear constant current and switching constant current driving methods. Linear constant current does not need to use switching power supply technology. The load is directly connected to the main power device, and the work efficiency is low. In some cases, it will produce voltage flicker, causing discomfort to human eyes, followed by stroboscopic flicker, which can be seen visually [4]. In the switching constant current drive circuit, the switching power supply technology is used to collect current from the load through the feedback principle to control the switching state of MOS transistor to maintain constant current drive, which has good current stabilizing effect and high work efficiency [5].

On the other hand, the circuit structure of LED filament lamp is different from that of ordinary LED lamp. The filament lamp uses LED filament [6], while the ordinary LED light source uses LED particles. The number of LED chips on a single filament is about 27, and the rated current of a single filament is about 10mA, so the power of a single filament is about 0.8W. In the initial design of LED filament lamp device and drive circuit, software simulation is an essential step which needs to design LED component module and power drive circuit. In the model simulation, in order to better predict the VI characteristic relationship of the LED lamp, the model equivalent method is used to replace the actual LED filament lamp. The equivalent model is established by the simple resistance equivalent method, approximate linear model [7], exponential model and piecewise linear approximation model. Exponential model can't simulate small signal in simple software; The simple resistance model method is only suitable for steady-state operation, but for LED small signal analysis, it will produce considerable error; The approximate linear model can only be matched in the linear region of the load V-I curve, but in the nonlinear region, the simulation results have a certain deviation from the actual test; The piecewise linear approximation model method can be used to analyze the V-I characteristics of LED filament lamp, and the V-I characteristics of the equivalent model output are consistent with the actual filament characteristic curve, which can more accurately describe the measured V-I curve[8]. In this paper, the piecewise linear approximation model method is used to establish the 1W power LED filament SPICE model. The 1W model is connected in different series and parallel modes, and the output state changes of the circuit under different power conditions are designed. The 3W, 4W and 5W LED filament lamp driving circuits are simulated, verified and analyzed respectively.

II. Establishment of Piecewise Linear Approximation Model of LED Filament Strip

Before modeling and simulating the 1W LED filament strip, it is necessary to obtain the relevant parameters of the actual LED filament lamp. The actual 1W filament strip has a working current of 10mA-12mA, a working voltage of 70V, and an output power of 1W. The V-I curve characteristic diagram of LED filament can be observed by using Agilent's V-I tester, and its V-I characteristics are shown in Figure 1 below. It can be seen from the curve that when the input voltage reaches about 70V, the relationship between the output driving voltage and the current is approximately linear.

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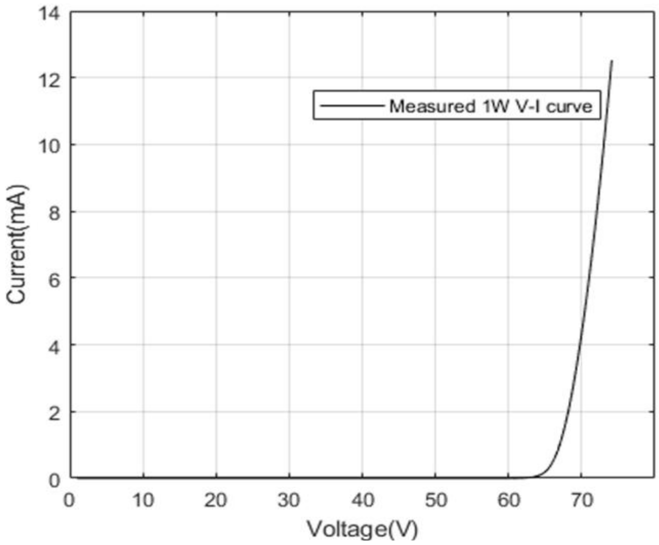

Fig1 : V-I characteristic curve of actual led filament lamp

According to the measured V-I characteristic diagram in Fig. 1, it is necessary to use the voltage current relationship in the curve to model the 1W filament strip model. In the model equivalent circuit, in order to better predict the relationship between led forward voltage and current, the superposition concept of segmented equivalent circuit and more branch equivalent models are used to obtain more accurate V-I characteristic curve of LED filament. Therefore, this paper uses six linear approximate model equivalent method to simulate led filament. Firstly, seven sets of V-I data values are collected from the curve. In order to make the model closer to the measured V-I characteristics, the sampling data includes two parts of data in the nonlinear interval and the linear interval. The sample data is shown in Table 1. According to the data in Table 1 and the formulas (1) to (6), the voltage and resistance values of the branch can be obtained, and the parameter values in the six segment linear model can be obtained. In the branch circuit, the ideal diode is replaced by a voltage controlled switch, which is used to simulate the unidirectional conductivity of the diode. The parameters of the voltage controlled switch are: turn off resistance: 10M Ω, Conduction resistance: 1U Ω, Threshold voltage: 10uv. The equivalent model is shown in Fig 2.

Table 1 The parameter value of six segment model

order number	Voltage	Current	Resistance
1	V_1=62.00V	I_1=0mA	R_1=19.85K
2	V_2=64.60V	I_2=0.131mA	R_2=5.73K
3	V_3=65.81V	I_3=0.403mA	R_3=3.56K
4	V_4=67.01V	I_4=1.01mA	R_4=2.92K
5	V_5=68.00V	I_5=1.85mA	R_5=2.46K
6	V_6=70.00V	I_6=4.36mA	R_6=1.61K
7	V_7=73.10V	I_7=10.18mA	

$$R_1 = \frac{V_2 - V_1}{I_2} \tag{1}$$

$$R_2 = \frac{V_3 - V_2}{I_3 - \frac{V_3 - V_1}{R_1}} \tag{2}$$

$$R_3 = \frac{V_4 - V_3}{I_4 - \frac{V_4 - V_2}{R_2} - \frac{V_4 - V_1}{R_1}} \tag{3}$$

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$$R_4 = \frac{V_5 - V_4}{I_5 - \frac{V_5 - V_3}{R_3} - \frac{V_5 - V_2}{R_2} - \frac{V_5 - V_1}{R_1}} \tag{4}$$

$$R_5 = \frac{V_6 - V_5}{I_6 - \frac{V_6 - V_4}{R_4} - \frac{V_6 - V_3}{R_3} - \frac{V_6 - V_2}{R_2} - \frac{V_6 - V_1}{R_1}} \tag{5}$$

$$R_6 = \frac{V_7 - V_6}{I_7 - \frac{V_7 - V_5}{R_5} - \frac{V_7 - V_4}{R_4} - \frac{V_7 - V_3}{R_3} - \frac{V_7 - V_2}{R_2} - \frac{V_7 - V_1}{R_1}} \tag{6}$$

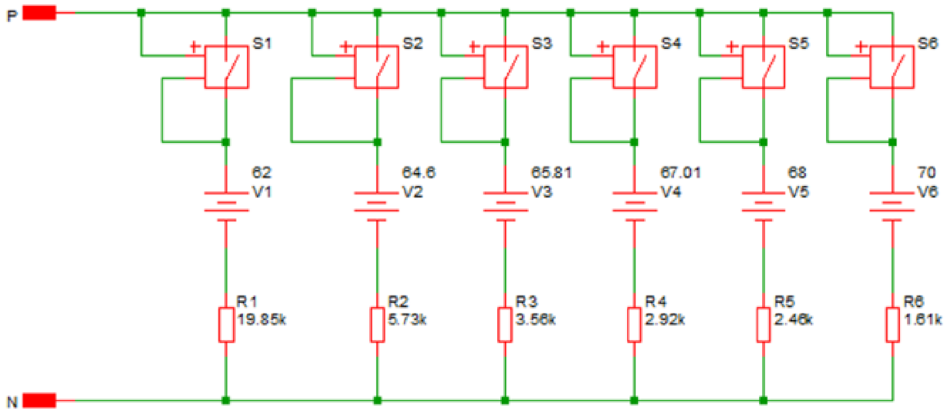

Fig 2:Equivalent diagram of LED six segment linear model

After the six-segment model is established, it needs to be packaged into a device for performance simulation analysis. In Fig3, (a) is a simulation VI characteristic curve. The forward drive voltage and current conform to the exponential relationship. In order to further verify the accuracy of the model, The model curve needs to be compared with the measured curve. Fig3(b) is the VI characteristic comparison chart. In the linear and non-linear regions, the VI characteristic of the simulation curve is consistent with the actual test curve. It conforms to the V-I characteristics of the 1W filament strip. Therefore, in the design of the circuit principle, a six-segment linear approximate model can be used to replace the actual LED filament strip as the circuit load.

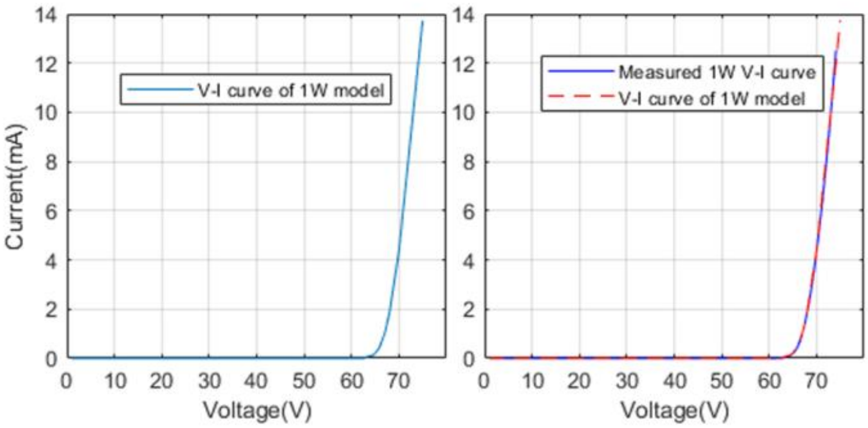

Fig3: V-I characteristic diagram of actual and model

III. Design of LED Switch Constant Current Source Circuit

3.1 Introduction of HV9910B chip

HV9910B is a general-purpose LED drive controller, which can drive the external input with a DC voltage of 8-450V and convert it to a constant current output. The output constant current drive current has a wide range, from tens of mA to more than 1A. The output current can be changed by adjusting the external resistance. The implementation method is simple. The chip does not require additional external components, and the circuit drive efficiency is high. It can drive both low-power LED and high-power LED, and has a very wide range of applications.

3.2 Design of 4W Buck Driver Circuit

Taking driving 4 1 W LED filament lamps as an example, the design output voltage is 142V, and the driving current is 20mA. Fig4 shows the step-down constant current HV9910B chip as the driving circuit. The circuit design includes five main modules: power supply module, rectifier filter module, buck module, buck constant current circuit module and LED load module. The input signal is 220 V commercial power, which is connected with the input terminal of HV9910B through bridge rectifier circuit. C1, C2 and C3 filter out high-frequency fine ripple. Buck module mainly consists of HBV9910B chip and external circuit. In the buck structure, the input voltage is greater than the output voltage, and the duty cycle is $d = V_{out} / V_{in}$. If D ＜ 0.5, the constant frequency mode is adopted. The frequency is determined by the resistance of RT terminal. The switch of MOS transistor is in the fixed mode. The turn-on and cut-off time of MOS transistor are determined by the ratio of input voltage to output voltage and the working frequency. When R1 voltage is less than 250mv, MOS is turned on, and the voltage of MOS transistor is high, D1 is cut-off, and the load, the inductor L1 and the resistor R3 form a loop. The inductance L1 stores energy, the R3 can detect the current flowing through the L1, and convert the current into voltage, then feed back the voltage to CS terminal. When the detected voltage is greater than 250mv, MOS tube is cut-off, the output is low level. The energy storage inductor L1, D1, and the load form a loop structure to work. When the output current of the inductor is less than a certain value, the detection voltage of the CS terminal is less than 250mv, and the MOS tube is on. The work is repeated continuously. After the resistance R3 converts the detected current into voltage, the internal comparator controls the working state of the MOS tube, so as to effectively control the output current of the LED, and keep the output current in a constant current state.

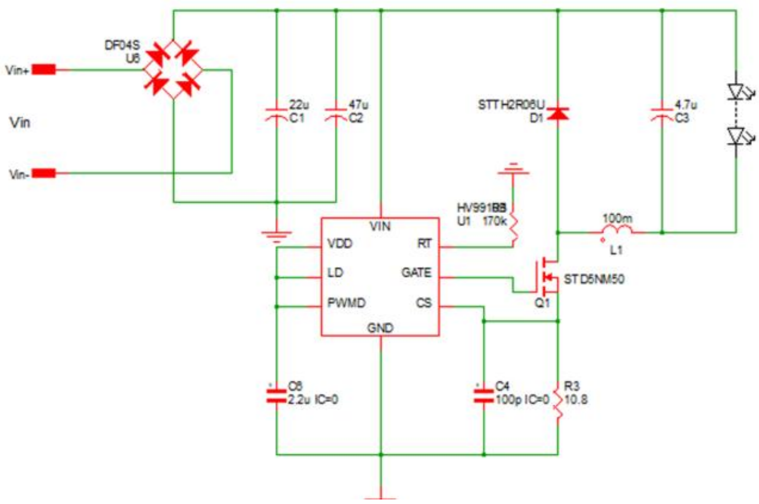

Fig4: Schematic diagram of HV9910Bdrive circuit

3.2.1 Selection of switching frequency and resistance R1

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As shown in the driving circuit diagram in Fig4, the frequency of the oscillator in HV9910B is determined by the resistance value connected to the R_T pin. The calculation formula is as follows [9]:

$$f = \frac{25000}{R_T(K\Omega) + 22} \tag{7}$$

HV9910B has two working modes: constant frequency mode and shutdown time. The working mode is determined by the ratio of the output voltage of the driver to the input voltage. When the input voltage is less than the output voltage, it enters the shutdown mode. When the input voltage is greater than the output voltage, Enter the constant frequency mode. This circuit is a buck architecture. The output voltage is always less than the input voltage, so the constant frequency mode is adopted, and the duty cycle D<0.5 is required. The duty cycle is the ratio of the input voltage to the output voltage. In the design, the constant working frequency f is 130KHZ, so the resistance R1=150K can be calculated by formula (7). The resistance value determines the operating frequency of the circuit.

3.2.2 Inductance calculation of L1

The inductance calculation result of inductor L1 depends on the input AC voltage, the output voltage and current of LED, the working frequency and other related parameters. When the working frequency increases, the inductance value decreases, which increases the switching loss in the circuit. It is generally assumed that the ripple current allowed by LED is ± 15%, the ripple range can be received is 30%, and the maximum allowable current is 15% of the average current. The calculation is shown in formula (8):

$$L = \frac{V_{o\max} \times (1 - \frac{V_{o\max}}{\sqrt{2} \times V_{acnom}})}{0.3 \times I_{o\max} \times f_s} \tag{8}$$

Substituting the corresponding data into the formula, the inductance value can be 100mH.

3.2.3 Current limiting resistor Rcs

The calculation formula of the current limiting resistor R_{cs} is:

$$R_{CS} = \frac{0.25}{1.15 \times I_{o\max}} \tag{9}$$

Where 0.25 represents the threshold voltage inside the chip. When the maximum ripple current is 15% of the average current, the maximum current can be calculated as 20mA*1.15=23mA. Substituting it into the formula, the resistance value of the current limiting resistor is 10.8 ohms.

3.2.4 Other parameter settings

A bypass capacitor must be connected between VDD and GND. When the MOSFET is turned off, VDD is a constant voltage of 7.5V. In this state, the high-frequency pulse charges the gate current. The typical value of C3 is 2.2UF. This circuit design does not use PWM to change the voltage, so the PWM pin is grounded, and the capacitors C1 and C2 are used to absorb the high-frequency ripple current generated by the circuit and filter the noise signal in the circuit.

IV. Load Connection Mode of LED Filament Lamp

The circuit load mainly includes 3W, 4W and 5W led filament lamps with different power. The load connection mode takes 1W equivalent model as the basic unit, and the 1W model can be connected in parallel or in series to form different power loads. The working voltage at the input end of the circuit is 220 V, and the working parameters and connection requirements of the circuit are shown in Table 2.

Table 2 Load parameters and connection mode table

Output power	Output voltage	Output current	Connection mode	Oscillation frequency	Duty cycle
3W	71V	30mA	Three parallel	100KHz	23%
4W	142V	20mA	Two parallel two series	130KHz	46%

5W	71V	50mA	Five parallel	100KHz	23%

V. Result Analysis

5.1 Analysis of output voltage and current of LED filament lamp switch driver circuit

Fig5 shows the output voltage and current waveforms of the 4W load. It can be seen from the figure that the voltage of the 4W LED load is about 142V and the current is 20.4mA. In the same way, the simulation shows that the output voltage of the 3W LED load is about 71V and the current is about 30.4mA. The output voltage of the 5W LED load is about 71V, and the current is about 51.1mA. Under the three load conditions, the current fluctuation is very small, and the output is almost constant current. The load output voltage and current are basically consistent with the parameters in Table 2, and the simulation is consistent with the actual requirements.

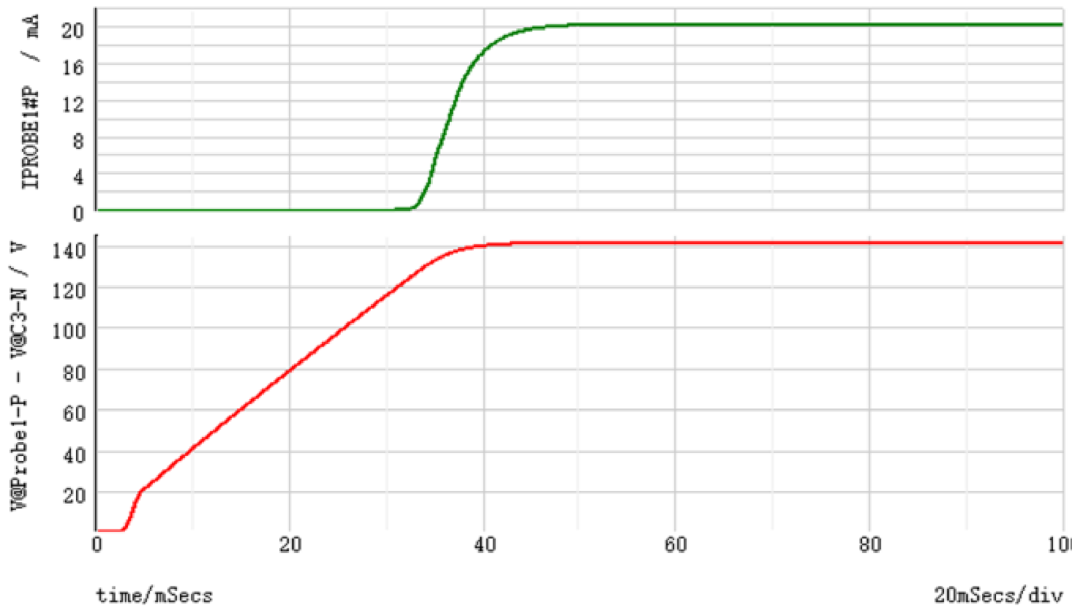

Fig5: Simulation waveform of output voltage and current of 4W LED load

5.2 Analysis of inductive current of LED filament lamp switch driver circuit

There are CCM mode and DCM mode in switching mode power supply. The current waveform of the inductive current L1 determines the operating mode of the switch drive circuit, and the simulated waveform of the inductive current is shown in Fig6. From the simulation waveform, it can be seen that the output waveform of inductive current is sawtooth wave. In Fig6 (a), the average inductive current of 3W load is about 30.5mA, and the amplitude of oscillation current is about 8.3mA. In Fig6 (b), the average inductive current of 4W load is about 20.6mA, and the amplitude of oscillation current is 5.3mA. In Fig6 (c), the average inductive current of 5W load is about 51mA, the oscillation amplitude is 13.7mA. The inductive current of the three circuits is always greater than 0. The circuit works in CCM mode. Compared with DCM mode, the ripple of the LED output current in CCM mode is smaller, and the output circuit remains in constant current mode.

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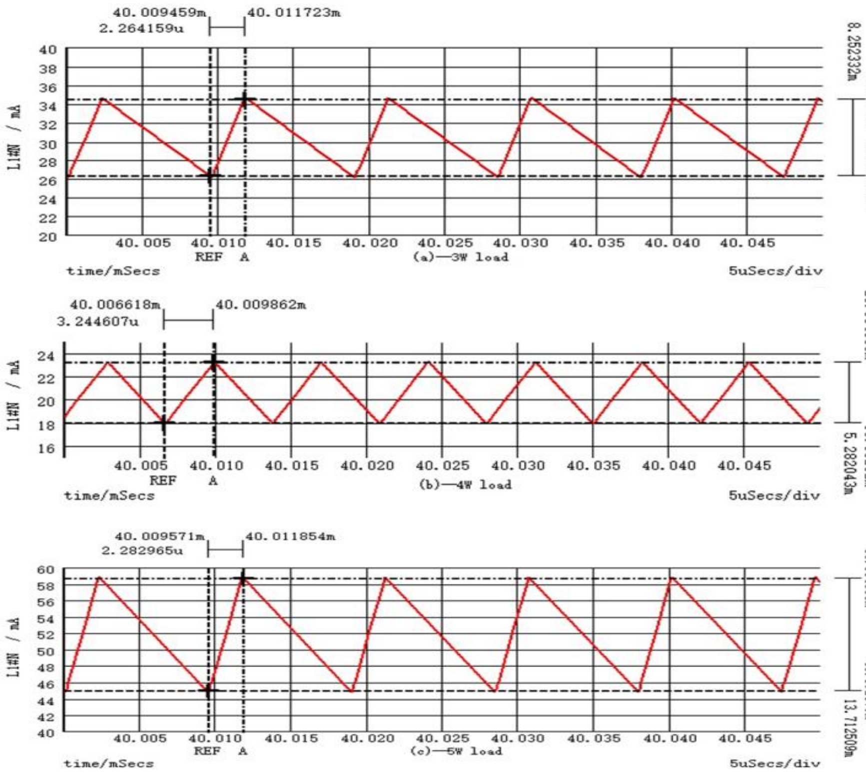

Fig6: Current simulation waveform of inductor L1

5.3 Analysis of simulation results of MOS gate driving voltage in LED filament lamp switch driving circuit

The simulation waveform of MOS gate driving voltage is shown in Fig7. The driving circuit adopts constant frequency operation mode where the duty cycle is required to be less than 50%, and the duty cycle is determined by the ratio of input voltage and output voltage. Fig7 (a) shows the output voltage waveform of MOS transistor gate under 3W load, and its duty cycle is about 23%. Fig7 (b) shows the output voltage waveform of MOS transistor gate under 4W load, and its duty cycle is about 46%. Fig7(c) shows the output voltage waveform of MOS transistor gate under 5W load, and its duty cycle is about 23%. Through the above gate voltage waveform simulation analysis, it can be seen that under three load conditions, the gate driving voltage duty cycle is consistent with the duty cycle requirements given in Table 2, and the duty cycle is less than 50%, which ensures that the current ripple size is within a certain range, and the output current works in constant current mode, which meets the requirements of constant frequency mode in this design.

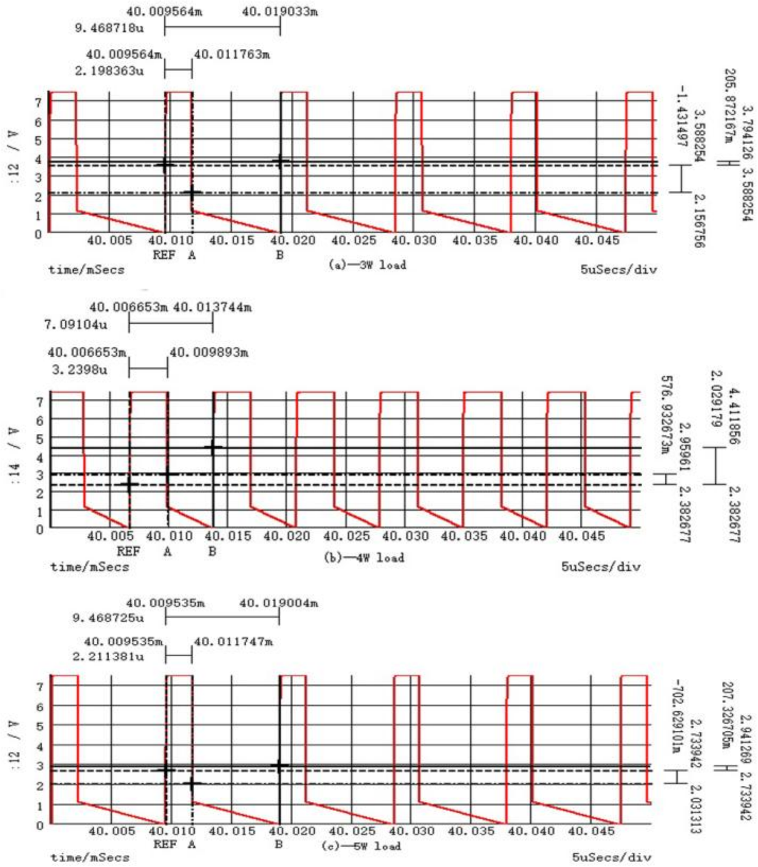

Fig7: Simulation waveform of MOS tube gate driving voltage

5.4 Summary of parameter comparison

To sum up, under the three load modes, the voltage, current, working mode and gate voltage duty cycle are consistent with the design requirements. According to the design requirements and simulation results, the parameter values of the three LED filament lamp switch driving circuits are shown in Table 3.

Table 3 Parameter comparison of three kinds of LED driving circuit

power	Ideal output voltage	Actual output voltage	Ideal output current	Actual output current	oscillation frequency	resistor R1	Inductor L1	Current limiting resistor	Duty cycle
3W	71V	71V	30mA	30.4mA	100KHZ	228k	61mH	7.3	23%
4W	142V	142V	20mA	20.7mA	130KHZ	170k	100mH	10.8	46%
5W	71V	71V	50mA	51.1mA	100KHZ	228k	37mH	4.3	23%

VI. Conclusion

In this paper, the calculation method of the six-segment linear approximation model equivalent method is discussed. Comparing the actual measurement results with the results of six segment linear approximate model, it is concluded that the V-I characteristics of six segment linear approximate model are almost consistent with the actual measurement curve. Secondly, the six-segment linear model circuit is packaged, and the packaged devices are connected in series or parallel to model filament lamps with different powers of 3W, 4W, and 5W respectively. The driving circuit adopts the HV9910B chip, and the external circuit parameters of the circuit are appropriately modified to provide a constant current driving circuit for different loads. Through modeling and simulating with Spice software, the main parameters of the output voltage, current, inductive current waveform, and duty cycle are consistent with the actual situation, which meets the circuit design requirements. It is proved that, in the simulation, LED filament lamps of different powers can be equivalent with the piecewise linear approximation model, which is very convenient in actual design and application. But there are also some shortcomings, such as not considering the influence of temperature parameters on LED filament, which need to be further verified.

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