Simulation Research on Performance of Synchronous DC Converter Considering Temperature Rise Effect

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Abstract. In this paper, the effect of temperature rise of MOSFET on output performance of synchronous dc converter is studied. Firstly, the power loss calculation method and thermal resistance equivalent circuit of switching devices are analyzed, and mathematical modeling is carried out for the conduction mode and change rule of junction temperature, housing temperature and radiator temperature of switching devices, and the MOSFET temperature rise model is built in Matlab environment, and the temperature rise curves of different parts of MOSFET switching devices are obtained. By means of the model, the effect of temperature rise on the output and control signal of the synchronous DC converter is studied. The simulation results show that the effect of temperature rise on the switching device will increase the internal resistance of the switching device, decrease the gate opening voltage and reduce the output voltage. In the real circuit design, it is necessary to leave a margin for the above parameters to ensure an ideal output.

Keywords: Synchronous DC converter; Switching device; Switching loss; On-State loss; PWM control.

1. Introduction

The electric vehicle industry is an important development direction of China's national new energy strategy. The development of this industry can effectively reduce the carbon emissions of traditional vehicles and the atmospheric pollution of petrochemical energy. As a source of power for electric vehicles, charging facilities play an important role in transforming ordinary city power into battery energy storage. According to the classification of charging facilities, there are mainly AC charging facilities and DC charging facilities. Among them, DC charging facilities are used on a large scale because of their low power, low floor space and low requirements for external power points.

For DC charging facilities, it is usually expected that they can work in a constant voltage and constant current mode[1]. The entire charging process is close to the characteristics of the original battery, which requires that DC charging facilities have higher requirements for the selection of components and circuit design when they are manufactured.

Commonly, DC charging facilities are mainly composed of filter circuits, rectifier circuits, chopper circuits, voltage stabilizing circuits, etc. Among them, the chopper circuit assumes the main task of DC power conversion, which is the key to the design of DC charging facilities[2]. The conversion of the DC power supply is mainly divided into a boost conversion and a buck conversion, which respectively correspond to boosting a certain reference voltage to a certain required voltage point or lowering it to a certain required voltage point[3]. The main principle of DC conversion is to control the...
on-off of power electronic devices, add a DC voltage to the load intermittently and change the average value of the output voltage by changing the duty ratio, so it is also called a chopper circuit. The research of chopper circuit mainly has two directions: the research of circuit control strategy \(^{[4]}\) and the research of circuit switching device loss and design selection \(^{[5]}\). This type of research mainly analyzes the loss model of DC switching device MOSFET and considers the selection and optimization of circuit parameters in the case of loss. These studies have laid a theoretical foundation for the design optimization of DC converters. However, there are few studies on the changes in circuit output and control signals caused by losses.

Based on the above considerations, this article selects a wide range of synchronous buck DC converters as the research object \(^{[6]}\), and the temperature rise caused by the switching device losses of this circuit to conduct modeling research on the problem, to study the influence of temperature rise on the circuit output and the influence on the control signal.

The research results of this paper have guiding significance for the correct design of the control signal of synchronous DC converter and the selection of component parameters.

2. Working Principle of Synchronous Buck Converter

The synchronous buck converter, which uses two independent drivers to drive the upper-arm and lower-arm MOSFET switching devices, uses complementary conduction to realize the function of the BUCK converter, and is widely used in circuits that provide low voltage and high current \(^{[7]}\). For the above circuit, the main loss in the conversion process comes from the MOSFET (referred to as the VM tube), but when controlled by PWM, the duty cycle is different, resulting in different working times of the upper and lower arms, and the upper and lower tube losses of the VM tube are also different. For the Buck circuit with step-down output, since the input voltage is higher than the output voltage, the duty cycle is relatively small, resulting in the conduction time of the upper tube being significantly shorter than the conduction time of the lower tube. The conduction loss is mostly caused by the lower tube. For the lower tube, the main loss of the upper tube is the switching loss of the device.

3. MOSFET Loss Analysis

From the analysis of the working principle in the previous section, it can be seen that the losses of MOSFET devices are mainly two kinds of on-state losses and switching losses, where the on-state losses are mainly related to the junction temperature of the MOSFET, the duty cycle of the switch, and the on-state current; It is related to factors such as parasitic capacitance, junction temperature, collector current, and switching frequency. In general, the ratio of the MOSFET's cut-off power loss and drive power loss is very small, which can be ignored in the discussion \(^{[8]}\).

On-state loss is the power loss generated when the MOSFET device is turned on and the loop current flows through the internal resistance of the device. From Ohm's theorem, the voltage between the source and drain stages of the MOSFET can be Equation 1 calculates:

\[
V_{DS} = R_{DS}I_D
\]  

(1)

In the formula, \(V_{DS}\) and \(I_D\) are the drain-source voltage and on-state current of the MOSFET in the on-state, \(R_{DS}\) is the resistance in the on-state. This value is a variable determined by the junction temperature and the on-state current, usually provided by the manufacturer can be found in the Datasheet. The on-state resistance loss can be calculated by the following formula:
In the above formula, $\alpha$ is the duty cycle, which is controlled by the PWM controller, and $T$ is the absolute temperature.

\[
P_{HR} = aI_D^2R_{DS}(T/300)^{2.3}
\]  

(2)

The MOSFET turn-on process is divided into 4 stages. The solid line is $V_{GS}$, and the rising solid line is the gate during turn-on driving voltage, the falling solid line is the gate driving voltage during turn-off. MOSFET current $I_D$, drain-source voltage $V_{DS}$ change relationship is shown in Figure 2.

Figure 2. MOSFET turn-on curve

The MOSFET conduction loss $P_{HR}$ is concentrated in the t1-t3 phase, while in the t1-t2 phase, $V_{DS}$ remains unchanged, and the current increases approximately linearly to the full-load current $I_D$. During the period from t2 to t3, the MOSFET conductive channel is gradually formed, $V_{DS}$ decreases approximately linearly, and the full load current $I_D$ remains unchanged. At this time, the lead-through loss $P_{HR}$ is:

\[
P_{HR} = 0.5 V_{DS}I_D(t_3 - t_1)f_{sw}
\]  

(3)

$f_{sw}$ is the switching frequency.

Similarly, in the synchronous buck converter, the on-state resistance loss of the lower arm MOSFET is as follows:

\[
P_{LR} = (1 - a)I_D^2R_{DS}(T/300)^{2.3}
\]  

(4)

During the t0 ~ t1 stage of the turn-on process of the lower-arm MOSFET, the conductive channel is in the off state, and all the current flows through the body diode. From t1 to t2, the amplitude of $V_{DS}$ and diode freewheeling voltage $V_f$ are equal, the MOSFET channel current increases linearly and the body diode freewheeling current maintains the MOSFET total full-load current $I_D$ unchanged. With the opening of the MOSFET channel from t2 to t3, the $V_{DS}$ voltage decreases linearly from $V_f$ to $R_{DS}I_D$. At this time, the MOSFET is fully turned on, and the loss $P_{LR}$ during the turn-on process is as follows:

\[
P_{LR} = V_fI_D(t_3 - t_0)f_{sw} + V_fI_D(t_2 - t_1)f_{sw} + 0.5(V_f + I_fR_{DS})I_D(t_3 - t_2)f_{sw}
\]  

(5)

In the circuit of Figure 1, the diode loss is mainly composed of two parts, the on-state loss and the switching loss, where the on-state loss means that the diode is in the on-state, Due to the forward voltage and current withstand, this current generates work on the internal resistance of the diode, and its value can be calculated by equation (6)\cite{9}

\[
P_{CD} = u_{F0}I_{Fav} + R_DI_{Frms}^2
\]  

(6)

In formula (6), $u_{F0}$ is the diode voltage drop when conducting; $R_D$ is the on-state resistance of the diode; $I_{Fav}$, $I_{Frms}$ respectively correspond to the effective current of the diode during the working time and the average current can be calculated according to equations (7) and (8)

\[
I_{Fav} = \frac{1}{2\pi} \int_0^\pi I_{in} (1 - \alpha) d\phi
\]  

(7)

\[
I_{Frms}^2 = \frac{1}{2\pi} \int_0^\pi I_{in}^2 (1 - \alpha) d\phi
\]  

(8)
Another loss of the diode is the switching loss. When the diode is turned on, it will withstand a higher on-voltage. After \( t_f \) time, it will be reduced to the inherent forward voltage drop of the diode. During the turn-on period, the diode losses generated by the tube:

\[
P_{on} = 0.5 f_{sw} t_f (U_{FR} - U_F) \quad (9)
\]

\( U_{FR} \) is the highest voltage the diode can withstand when it is turned on. This value can be obtained from the datasheet provided by the diode manufacturer.

### 4. Temperature Rises Mechanism

The loss of the synchronous DC converter in the working process will exist in the form of heat in a closed space, which will lead to the problem of temperature rise in MOSFET. The temperature change is affected by many factors: such as the volume of the device packaging methods, and air circulation. In order to accurately calculate the temperature rise problem caused by losses, the literature [10-11] established the thermal resistance equivalent circuit by introducing the concept of thermal resistance from the perspective of the circuit. The model is shown in Figure 3.

**Figure 3. Temperature rise model**

The relationship between thermal resistance, power loss and temperature rise is:

\[
R = \frac{\Delta T}{P} \quad (10)
\]

In the circuit analysis, the power loss of each part of the MOSFET can be treated as a current source[12]; the thermal resistance is equivalent to resistance, and the temperature rise effect is equivalent to voltage. The thermal resistance equivalent circuit shown in Figure 4 can be obtained model.

**Figure 4. Thermal resistance equivalent circuit**

In Figure 4, \( T_{jt} \) and \( T_{jd} \) are the junction temperature of MOSFET and diode respectively. \( T_c \) and \( T_s \) are the MOSFET case temperature and the heat sink temperature. \( T_a \) is the ambient temperature; \( P_T \) and \( PD \) are the equivalent losses of MOSFET and diode respectively. \( R_{thjc} \) and \( R_{thjd} \) are the thermal resistance between the MOSFET and the diode silicon to the case; \( R_{thca} \) is the thermal resistance between the device case and the atmosphere; \( R_{thha} \) is the thermal resistance between the case and the heat sink. \( R_{shs} \) is the heat resistance between the heat sink and the environment. From this equivalent circuit, the temperature at each point can be obtained. In the above equivalent circuit, the internal thermal resistance of the MOSFET and the internal resistance of the diode can be available from the data sheet provided by the MOSFET and the diode. The thermal resistance parameters of the 1XFH88N30PMOSFET device and the diode DPG60C400HB selected in this article are shown in Table 1:
Table 1. Thermal resistance parameters of MOSFET and diode

| Node-to-shell thermal resistance(K/W) | MOSFET | Rthje | 0.21 |
| Shell to radiator thermal resistance(K/W) | MOSFET | Rthes | 0.21 |
| Node-to-shell thermal resistance(K/W) | MOSFET | Rthje | 0.95 |
| Shell to radiator thermal resistance(K/W) | Diode | Rthes | 0.25 |

5. Model Building
According to the above loss and temperature rise mechanism, using the components provided in the Simscape toolbox of Matlab to build the temperature rise simulation model shown in Figure 5. In this model, the actual heat transfer situation, node and shell are considered. The heat transfer method between the junction and the shell is conduction; The heat relationship between the housing and the heat sink is in the form of heat exchange. In the parameter configuration, the contact area, the package size of the device and the temperature test data of each part of the device are required. These data can be obtained from the datasheet provided by the manufacturer once the device model is determined [13].

By running this model, the temperature change curves at different time points shown in Figure 6 can be obtained. From the change curve in Figure 6, it can be seen that the maximum temperature of the lower arm is higher than that of the upper arm, which is the same as the previous analysis of the article consistent, because the conduction time of the lower bridge arm is long [14], and the conduction loss is large. It can be seen from Figure 6 that the maximum temperature of the device is about 340K. The corresponding temperature is about 30 degrees Celsius, and the temperature of each part is close to the change curve provided by the manufacturer. These phenomena indicating that the temperature model can represent the real temperature changes and the simulation model is effective.
Figure 6. Temperature rise simulation results

Mask the completed temperature rise simulation model to facilitate the subsequent call when modeling the Buck converter. According to the working principle of the synchronous buck converter, the circuit model simulation diagram shown in Figure 7 is constructed. This circuit model completes the function of a DC 30V power supply into a DC 15V step-down circuit. By adding the temperature rise change component to the MOSFET switching device, the influence of the temperature rise on the conversion circuit is studied\(^\text{(15)}\). In Figure 7, \( R = 10 \) ohm and heat source is a standard reference temperature. During simulation, it can be adjusted according to the parameters of different switching devices.

Figure 7. Synchronous Buck converter simulation model

In the circuit of Figure 7, the simulated heat sources 1, 2 respectively represent the influence of the upper and lower arms of the temperature rise effect; PWM control is used to generate the MOSFET gate switching signal, and the variable load module simulates the external environment with periodic changes load. PI control is used to achieve closed-loop control of the circuit to ensure the quality of the output current.
Figure 8. Corresponding diagram of output voltage and PWM signal
Figure 8 is the corresponding relationship between the output voltage and the control signal. As can be seen from the figure 8, when the PWM control signal is high, the MOSFET switch is turned on, and the level of output is 15V. The presence of capacitor C makes the output stable at around 15V. Only every time the PWM control signal changes, there is a small change in the output voltage, which fluctuates within a range of ± 3%. At the same time, for the PWM signal, the ideal control signal source output is a rectangular wave, but the actual output waveform has a certain amount of tailing. This is because the actual electronic components cannot achieve the ideal switching characteristics[16]. In addition, the PWM control signal can be seen that the duty cycle of the model is a number less than 1, which is consistent with the previous theoretical analysis.

Figure 9. Comparison of output under different models
Figure 9 is a simulation of the output comparison with temperature rise effect and without temperature rise effect. It can be seen from the figure that when the temperature rise effect is not considered, the voltage value output by the simulation model is higher than the model considering the temperature rise effect. This is explained by the internal resistance of the switching device increases due to the increase in temperature. From Ohm's theorem, for a series circuit, the increase in internal resistance means that the current flowing in the circuit will decrease; For the load, due to its resistance as the current changes, the current on the load decreases, so the voltage on the load (output voltage) decreases. Therefore, the design of the actual circuit needs to increase the design of voltage regulation in order to ensure the constant output voltage[17].
Comparing Figure 10, the gate-source voltage in Figure 11 can be seen that when the temperature rise effect is not considered, the gate turn-on voltage is higher than the gate turn-on voltage that considers the temperature rise effect. It is mainly due to the increase in temperature that accelerates the flow of electrons inside the device, so that only a small turn-on voltage can work. It can be seen from Figures 10 and 11 that the temperature rise effect is not obvious to other aspects of the device except that it has a relatively obvious influence on the gate turn-on voltage.

6. Conclusion
The article selects the MOSFET switching device in the synchronous DC converter as the research object. The calculation method of power loss of switching devices and the equivalent circuit of thermal resistance are derived. According to the conduction mode and change law of the junction temperature, case temperature and heat sink temperature of the switching device, a temperature rise model of the MOSFET is built in the Matlab environment. With the help of this model, the influence of the output and control signal of the synchronous buck converter was studied. Finally, it is concluded that the temperature rise effect will increase the internal resistance of the device, the gate turn-on voltage will decrease, and the output voltage will decrease.

The model proposed in this paper can be used to both size the inductance L and smoothing capacitor C, as well as to design the feedback controller.

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