Design of double loop controller for three-level boost converter

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Abstract. Three-level Boost Converter (TLBC) is widely used in new energy generation grid-connected technology. This topology not only reduces the voltage stress of the switching tube and the diode, but also has a smaller size, lighter weight and higher power density. However, it has the problem of midpoint potential shift. In this paper, a dual closed-loop controller is designed by establishing the AC small-signal model of the system. While stabilizing the output voltage, the upper and lower capacitor voltages are dynamically adjusted to ensure the balance of the midpoint potential. Finally, this paper establishes a simulation platform in MATLAB/Simulink and verifies the dual-loop controller scheme.

1. Introduction

New energy generation grid-connected technology gradually replaces fossil energy power generation as a hotspot for application and research, but new energy power generation is susceptible to uncontrollable factors such as weather, climate and environment [1]. The industry generally adopts a scheme of uncontrolled rectification, boost chopping and PWM inverter circuit cascading to solve the problem of voltage instability [2]. Among them, the boost chopper circuit often uses the Boost circuit, but in the high-voltage and high-power applications, the Boost circuit has high voltage stress of the switch transistor, difficulty in device selection, large current ripple, large loss, and low efficiency. Experts and scholars have designed a three-level Boost circuit (TLBC), whose switching tube voltage stress is half of the traditional Boost circuit. Under the same switching frequency condition and the same current ripple coefficient standard, the inductance of TLBC can be reduced to a quarter of the Boost circuit, thus reducing volume, weight, and increasing the power density [3]. At the same time, the current ripple is small, which can reduce the loss of the switching tube and the boosting inductor. However, in practical applications, due to the upper and lower output filter capacitors and the output load are not completely matched, the operating characteristics of the control circuit, the drive circuit and the switch tube are not completely synchronized, the midpoint potential of the three-level boost converter is easily offset, affecting the reliable operation of the system.

Therefore, this paper first analyzes the working principle of the three-level Boost circuit, and then establish the mathematical model of the system by the state space averaging method, and obtains the open-loop transfer function of the system. Based on this, the double-loop controller is designed to
solve the voltage equalization problem of the upper and lower capacitors while ensuring the voltage regulation requirement. Finally, a simulation model of the three-level Boost circuit was established in MATLAB/Simulink to verify the control scheme.

2. Working principle of TLBC

Fig.1 shows the topology of the TLBC circuit. $V_{dc}$ is the DC voltage input, $L$ is the boost inductor, $Q_1$ and $Q_2$ are the main power switch tubes. The two switch tubes operate at the same duty cycle and phase shift 180° in steady state. $D_1$ and $D_2$ are diodes, $C_1$ and $C_2$ are Output filter capacitors, $R_1$, $R_2$ are equivalent loads.

![Figure 1. Topology of the TLBC](image)

In the theoretical analysis, it is assumed that $Q_1$, $Q_2$, $D_1$, $D_2$, $L$, and $C_1$ and $C_2$ are ideal devices, and the equivalent loads $R_1$ and $R_2$ are completely equal, and $C_1$ and $C_2$ are completely equal and large enough.

The circuit can be divided into four working modes according to the switch state, as shown in Fig.2, respectively, $Q_1$, $Q_2$ are both on (a); $Q_1$ is on, $Q_2$ is off (b); $Q_1$ is off, $Q_2$ is on (c); $Q_1$, $Q_2$ are both off (d).

![Figure 2. Equivalent topology diagram under four working modes](image)

When TLBC is working, it is divided into two working conditions according to the duty cycle. When $D > 0.5$, its working mode changes under a-b-a-c; when $D < 0.5$, its working mode changes under b-d-c-d.

This paper mainly takes $D > 0.5$ as an example to analyze the working principle.

In mode(a), $Q_1$ and $Q_2$ are both turned on, $D_1$ and $D_2$ are turned off, $I_L$ is linearly rising, inductor $L$ stores energy, and $C_1$ and $C_2$ release energy respectively to supply energy to $R_1$ and $R_2$. 
In mode(b), Q1 is turned on, Q2 is turned off, D1 is turned off, D2 is turned on, L is released, and \( I_L \) is linearly decreased. \( V_{dc} \) forms a loop through L-Q1-C2R2-D2, and C1 releases energy to R1.

\[
\Delta i_{tb} = \frac{V_{dc} - \frac{V_o}{2}}{L} \cdot (1 - D) \cdot T_s
\]  

In mode(c), Q1 is turned off, Q2 is turned on, D1 is turned on, D2 is turned off, L releases energy, \( I_L \) decreases linearly, \( V_{dc} \) forms a loop through L-Q2-C1R1-D1, and C2 releases energy to R2.

\[
\Delta i_{tc} = \frac{V_{dc} - \frac{V_o}{2}}{L} \cdot (1 - D) \cdot T_s
\]  

When \( D < 0.5 \), at mode(b) L stores energy, and \( I_L \) rises linearly. At mode(c) L stores energy, and \( I_L \) rises linearly. At mode(d) L releases energy, and \( I_L \) decreases linearly. Refer to the analysis method when \( D > 0.5 \).

### 3. Mathematical model establishment of TLBC

Under the premise of low-frequency small-signal disturbance assumption, four kinds of topology circuits in one switching period are combined and linearized by the switching period averaging operator, and the state equation which characterizes the dynamic characteristics of the converter is obtained, that is, the AC small-signal model of the converter [4].

The mathematical modeling approach is as follows: writes the state equation of the various modes of the system in a cycle, and finds the average amount over a period. Introducing small signal disturbances to the equation of state, and eliminating the second perturbation term and DC component. Through the matrix solution and the Laplace transform, finally obtain the transfer function of the system.

Taking \( D > 0.5 \) as an example, the inductor current \( I_L \) and the two capacitor voltages \( V_{c1}, V_{c2} \) are taken as state variables. Form a three-dimensional variable \( X(t) = [i_L(t), u_{c1}(t), u_{c2}(t)]^T \). Taking \( V_{dc} \) as the input variable, taking the inductor current \( I_L \) and the output voltage \( V_o \) as the output variables \( Y = [I_L, V_o]^T \). Write the state space equation:

\[
\dot{X}(t) = AX(t) + Bu_{dc}(t)
\]

\[
Y(t) = CX(t)
\]

among them \( C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \)  

(1) The coefficient matrix of the state equation for modal a is:

\[
A_1 = \begin{pmatrix}
0 & 0 & 0 \\
0 & -\frac{1}{R_1C} & 0 \\
0 & 0 & -\frac{1}{R_2C}
\end{pmatrix} \quad B_1 = \begin{pmatrix}
\frac{1}{L} \\
0 \\
0
\end{pmatrix} \quad \text{action time is} (D-1/2)T_s
\]  

(2) The coefficient matrix of the state equation for modal b is:
The coefficient matrix of the state equation for modal $c$ is:

\[
A_4 = \begin{bmatrix}
0 & -\frac{1}{L} & 0 \\
\frac{1}{C} & -\frac{1}{R} & 0 \\
0 & 0 & -\frac{1}{R} \\
\end{bmatrix}
\quad B_4 = \begin{bmatrix}
\frac{1}{L} \\
0 \\
0 \\
\end{bmatrix}
\] action time is $(1-D)T_S$. \hspace{1cm} (7)

Average the state variables in one cycle:

\[< X >_{T_S} = [(D-\frac{1}{2})A_1 + (1-D)A_2 + (D-\frac{1}{2})A_3 + (1-D)A_4] < X >_{T_S} + \left[ \frac{1}{L} \begin{bmatrix} 0 & 0 \end{bmatrix} \right]^T < V_{dc} >_{T_S} \]

\[< Y >_{T_S} = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 1 \end{bmatrix} < X >_{T_S} \] \hspace{1cm} (8)

Introduce the small signal disturbances:

\[I_L = I_{L1} + I_{L2} \quad V_{c1} = V_{c1} + V_{c2} \quad V_{c2} = V_{c2} + V_o \]

\[V_{dc} = V_{dc} + V_{dc} \] \hspace{1cm} (9)

Eliminate the secondary small signal component and the DC component, and then obtain:

\[< X >_{T_S} = \begin{bmatrix}
\frac{1-D}{L} & -1-D \\
\frac{1-D}{C} & 0 \\
-1-D \\
\end{bmatrix} < X >_{T_S} + \left[ \frac{1}{L} \begin{bmatrix} 0 & 0 \end{bmatrix} \right]^T < V_{dc} >_{T_S} + \begin{bmatrix}
0 \\
\frac{1}{C} \\
\frac{1}{C} \\
\end{bmatrix} \begin{bmatrix} I_L \\ U_{c1} \\ U_{c2} \end{bmatrix} \] \hspace{1cm} (10)

After the Laplace transform, the open-loop transfer function of the system can be obtained under the assumption that the input voltage interference is zero:

\[G_{(s)dc} \mid_{s \rightarrow 0} = \frac{\frac{1}{2}L \cdot S + \frac{L \cdot S \cdot (1-D)^2 \cdot R}{R}}{LC \cdot S^2 + \frac{L}{R} \cdot S + (1-D)^2 \cdot R} \] \hspace{1cm} (11)

The modeling method for $D<0.5$ is similar, and the open-loop transfer function is consistent after calculated.

4. **Control strategy of TLBC**

The control goal of TLBC is to ensure the equalization of the upper and lower capacitors while stabilizing the output voltage, that is, to ensure the midpoint potential balance. Therefore, this paper designs two loops, which are voltage regulator loop and voltage equalization loop. The voltage regulator loop ensures that the output voltage is stable to the expected value. The voltage equalization loop dynamically adjusts the upper and lower capacitor voltages to ensure the midpoint potential balance.
balance. The two loops work cooperatively.

According to the transfer function obtained above, the compensation link of the voltage regulator loop is designed. The structure diagram of the voltage stabilizing loop is shown in Fig.3. The mathematical model of the TLBC system has a zero point on the right half plane of the S axis, similar to the Boost circuit. When designing the compensation link of the voltage stabilizing loop, the lead-lag network can be designed to correct it. When designing the compensation link, a pole with a frequency equal to the system zero frequency should be designed to eliminate the influence of the zero point of the unstable system [5-6]. The Bode diagram of the amplitude-frequency characteristic of the compensated system crosses the 0dB line at -20dB/dec. The compensated system gain crossover frequency $f_g$ is less than 1/5 of the switching frequency $f_s$. It can be designed with reference to the frequency domain method in classical control theory.

Due to the structure of TLBC, in the actual engineering, the incomplete matching of the switching tube and the driving circuit could cause the midpoint potential is unbalanced, so that the voltage stress of the switching tube is not equal, which affects the normal operation of the circuit [7-8]. In order to solve this problem, it is necessary to design a pressure equalization loop for the system and implement a pressure equalization strategy.

When the system is in modal b, $C_2$ discharges, $V_{c2}$’s voltage drops, and its amount of energy increase and decrease is related to the duty-time of $Q_1$; when the system is in mode c, $C_1$ discharges, $V_{c1}$’s voltage drops, and its amount of energy increases and decreases is related to the duty-time of $Q_2$. The control principle of the equalizing ring is: collecting the voltage difference between the two capacitors as the error control amount to obtain the duty signal correction value $\Delta d$ of the two switching tubes, thereby correcting the duty signal $d$ of the upper and lower switching tubes, that is, adjusting the modal b and the modal c act time to finally achieve the capacitor voltage equalization. The pressure equalization ring uses classic PI control.

Fig.4 shows the block diagram of the TLBC double closed-loop control system. Collect the voltages $V_{c1}$ and $V_{c2}$ of the upper and lower capacitors. The value of $V_{c1}+V_{c2}$ is used as the voltage stabilizing loop’s feedback, compared with the reference rated output value. through the compensation link $G_{c}(s)$, get the output value ‘d’; $V_{c1}-V_{c2}$ is used as the input of the voltage equalizing loop controller, get the output value $\Delta d$, and added and subtracted with the ‘d’ separately from the voltage stabilizing loop, and the obtained result is compared with the carrier signal to obtain the driving signals $d_1$ and $d_2$ of the two switching tubes $Q_1$ and $Q_2$. 

**Figure 3.** Structure diagram of voltage stabilizing loop.
5. Experimental verification of TLBC

This paper simulates the system based on MATLAB/Simulink. Fig. 5 shows the overall simulation model. The main power loop uses the continuous mode, and the control part introduces the interrupt by function generator simulate actual digital control scheme, which makes the simulation result closer to reality and greatly improves the speed of simulation calculation. The voltage stabilizing loop’s reference is set to a ramp reference can effectively reduce the inductor current spike.

The design requirements: output power is 100KW, rate input voltage is 360V, output voltage is 900V, switching frequency is 50KHz, output voltage ripple <20%, and inductor current ripple factor <20%. Parameter design value: The boost inductor L=145μH, the capacitance value C=1mF, the equivalent resistance value R=4.05Ω, the voltage equalization loop K_p=0.1, K_I=0.1.

The working waveform is shown in Fig. 6. Fig. 6(a) shows the output voltage ripple of 90V, the voltage ripple frequency is equal to the switching frequency, and Fig. 6(b) shows the inductor current ripple 40A with a ripple frequency that is twice of the switching frequency. Fig. 6(c) shows the drain-source voltage of the switch, the two tubes are alternately turned on, and the voltage stress is 1/2 of the Boost converter. Fig. 6(d) shows the output waveform when load is not matched (R_1=4.05Ω R_2=10Ω). Fig. 6(e) shows voltage equalization loop’s action waveform when the load is not matched.
(a) Waveforms of output voltage and two capacitor’s voltage in rate condition

(b) Waveforms of Switching tube’s driving voltage and inductor current $I_L$
(c) Waveform of Switching tube’s drain source voltage

(d) Output waveform when load is not matched ($R_1=4.05\,\Omega, R_2=10\,\Omega$)
6. Conclusion

This paper introduces the working principle and mathematic modal of the three-level Boost converter and its controller design method. The mathematical model of the system is obtained according to the state space averaging method. In order to achieve the expected goal of the system, a cooperative working double loop controller is designed. The voltage regulator loop ensures the output voltage of the system, and the dynamic pressure of the voltage equalizing loop realizes the voltage equalization of the upper and lower capacitors of the system. Finally, the TLBC system of the converter is simulated on the MATLAB/Simulink platform. The simulation results show that the designed dual-loop controller can achieve the balance of the midpoint potential and ensure the stability of the output voltage.

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