Design and Research on Tapped Inductor of Large Step-up Ratio DC/DC Converter

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Abstract. The design and manufacture of magnetic components such as inductors need to estimate theoretical parameters based on the working characteristics of circuit on the one hand, and select the magnetic core and winding method by experience to determine the manufacturing plan. The parameters and performance of magnetic components obtained by different winding methods are usually different, so the design results have certain uncertainty. In order to better obtain system indicators, a design method for the design of the tapped inductor of large step-up ratio DC/DC converter is proposed to calculate the key parameters such as the turn ratio and inductance of the tapped inductor. The optimized winding scheme method of the tapped inductor is proposed by combining electromagnetic field simulation and circuit simulation. The simulation results show that the theoretical parameters obtained under the proposed method are correct, and multiple performance indicators of the tapped inductance corresponding to the converter circuit under different winding modes can be obtained, which is convenient for the designer to find the best appropriate production plan according to actual needs.

1. Introduction

With the popularization and application of new energy such as photovoltaic and wind power, new energy power generation technology has made great progress. However, the generated voltage of new energy is usually low. To increase the voltage level, a boost converter is needed for electric energy conversion [1-4].

There are two types of boost converters: isolated and non-isolated. The isolated boost converter uses a transformer to boost the voltage. However, the turns ratio will affect the linearity of the transformer when the boost is relatively large. Moreover, the transformer is bulky and costly, and the conversion efficiency and power density of transformer are low [5-6]. In addition, the non-isolated converter is simple in structure, small in size, low in cost, and high in power density, but due to the influence of the parasitic parameters of the actual circuit, the boost ratio is also limited. In order to further improve the boost capability of the converter, some boost converters using coupled inductors have been proposed. These converters can obtain a larger boost ratio by setting an appropriate inductor turns ratio [7-9].

The non-isolated large step-up ratio DC/DC converter with tapped inductor can obtain both power density, conversion efficiency and high step-up ratio. Different tap positions have different boost capabilities in this converter. Therefore, the reasonable design of the tapped inductor plays a vital role in the overall performance of the boost circuit.

However, due to the strong nonlinearity of magnetic materials and the non-zero permeability of non-magnetic materials, it is difficult to design and manufacture magnetic components such as
actual inductors and transformers. It is usually necessary to rely on some empirical practices and use some empirical formulas [10-11], the design result has certain uncertainty. At the same time, the manufactured inductance parameters and parasitic parameters are also different with different winding methods. All these uncertainties and differences may cause the circuit to fail to work properly in severe cases. Therefore, on the basis of empirical methods, simulation software should be used to estimate component parameters and parasitic parameters under different inductor winding schemes.

In this paper, the design of non-isolated large step-up ratio DC/DC converter with tapped inductor, the Calculation method of the key parameters of the tapped inductance such as the turn ratio, inductance, and the current of the tapped inductor is proposed. In order to obtain the use effect of the designed inductance in the overall system under different winding schemes, the various data obtained by electromagnetic simulation under each scheme are brought into the converter circuit, and the relatively optimal is selected through system circuit simulation. And a method for optimizing the winding scheme of tapped inductors based on the combination of electromagnetic field simulation and circuit simulation is proposed.

2. Basic working principle of large step-up ratio DC/DC converter

2.1. Working mode of large step-up ratio DC/DC circuit

The circuit topology and the equivalent operating mode of large step-up ratio DC/DC converter are shown in Fig.1. In the figure, Cin is the input filter capacitor, Cf is the output filter capacitor, and Dd is power diode. Compared with the traditional Boost DC/DC converter circuit, this circuit uses a tapped coupled inductor instead of a tapless inductor, which makes the turns of the inductor in the magnetizing circuit and the demagnetizing circuit different, so that the inductance is different.

The large step-up ratio DC/DC converter has two working modes of magnetization and demagnetization in CCM mode, as shown in Fig.1(b) and Fig.1(c) respectively. In the magnetizing mode, the switch S is turned on, the tapped inductor L1 (corresponding to the coil N1) is magnetized through the loop formed by S and Ui, the current rises, and the inductor L2 (corresponding to the coil N2) has no current. At this time, the output filter capacitor Cf supplies power to the load; In the demagnetization mode, the switch S is turned off, and the tapped inductance L is demagnetized through the loop formed by the diode Dd, the output load and Ui. The current of L drops, and the currents of L1 and L2 are equal. At this time, the input source Ui and the tapped inductance L jointly supply power to the load.

2.2. Calculation of boost ratio

In the CCM mode, during the switch-on period of the switch tube S in a high-frequency switching period Ts, the tapped inductance is in the magnetizing stage, as shown in Fig.1(b)

\[
N_1 \frac{d\phi}{dt} = U_i - N_1 \frac{\phi}{L_1} \cdot r
\]

(1)

\[
C_f \frac{dU_o}{dt} = - \frac{U_o}{R_L}
\]

(2)
where $\phi$ is the magnetic flux of tapped inductance, and $r$ is the equivalent resistance including the resistance of the inductor winding, the power switch and the on-state resistance of the diode $D_d$. When the switch $S$ is off, the tapped inductance is in the demagnetization phase, as shown in Fig.1(c)

$$\left(N_1 + N_2\right) \frac{d\phi}{dt} = U_i - \left(N_1 + N_2\right) \frac{\phi}{L_1 + L_2} - U_o$$  

$$C_i \frac{dU_o}{dt} = \left(N_1 + N_2\right) \frac{\phi}{L_1 + L_2} - \frac{U_o}{R_s}$$

Since in a high-frequency switching cycle, the inductance flux and the average value of the output voltage does not change, let $\frac{d\phi}{dt} = 0$ and $\frac{dU_o}{dt} = 0$, from (1)-(4), the boost ratio $M$ can be obtained as

$$M = \frac{U_o}{U_i} = \frac{1+nD}{1-D+\frac{r}{R_s} + \frac{rD}{R_s(1-D)(1+n)^2}}$$

Where $D$ is the duty cycle of the on-time of $S$, and $n = \frac{N_2}{N_1}$ is the turns ratio of the two coils of the tapped inductor. In the ideal situation ($r=0$), the converter boost ratio $M$ is:

$$M = \frac{U_o}{U_i} = \frac{1+nD}{1-D}$$

From (6), the boosting capability of the circuit can be further enhanced by adjusting the turns ratio $n$.

3. Calculation of related parameters of tapped inductor

3.1. Calculation of inductance

Fig.2 shows the waveform of the tapped inductor current of large step-up ratio DC/DC converter in CCM mode. In the figure, the current of $L_2$ is equal to the current of $L_1$ in the demagnetization phase. When the maximum duty cycle and boost ratio are determined, it can be obtained from (6)

$$n = \frac{M-1}{D-M}$$

In the steady state, the magnetic potential balance can be obtained:

$$N_1 \cdot \Delta i_L = (N_1 + N_2) \cdot \Delta i_2$$

Where $\Delta i_L$ and $\Delta i_2$ are the change of the inductance current in the magnetizing phase and the demagnetizing phase, then

$$\Delta i_L = \frac{U_i DT_s}{L_i} = \frac{D(1-D) U_i T_s}{(1+nD)L_i}$$

Fig.2 Waveform of tapped inductor current

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Fig.2 Waveform of tapped inductor current
The average current through the diode is equal to the output average current \( I_o \), and the diode current is the tapped inductor current in the demagnetization phase. Therefore, in conjunction with (10), the output average current \( I_{OB} \) in critical mode can be obtained as

\[
I_{OB} = I_{L2avg} = \frac{1}{2} \cdot \frac{1}{1+n} \cdot \frac{D(1-D)}{(1+nD)L_i} \cdot U_o
\]  

(11)

Where \( IL2avg \) is the average current of the inductor \( L2 \).

To make the converter work in CCM mode, \( I_{OBmax} < I_{omin} \) must be satisfied, so

\[
I_{OBmax} = \frac{1}{2} \cdot \frac{1}{1+n} \cdot \frac{D_{min}(1-D_{min})}{(1+nD_{min})I_{omin}} \cdot U_o \leq I_{omin}
\]  

(12)

Then the inductor \( L1 \) can be obtained as

\[
L_i \geq \frac{1}{2} \cdot \frac{1}{1+n} \cdot \frac{D_{min}(1-D_{min})}{(1+nD_{min})I_{omin}} \cdot U_o
\]  

(13)

### 3.2. Calculation of tapped inductor current

According to Fig.2, the peak current of the tapped inductor can be calculated as

\[
i_L^{max} = \frac{(1+n)I_o}{1-D} + \frac{1}{2} \cdot \frac{D(1-D)}{(1+nD)\cdot L_o} \cdot U_o
\]  

(14)

The effective value of inductor current \( IL1rms \) during magnetization and the effective value of inductor current \( IL2rms \) during demagnetization are respectively:

\[
IL_{1rms} = \sqrt{\int_{0}^{2\pi} i_L^2(t) dt} = \sqrt{\frac{D}{3} \left[ \frac{D(1-D) \cdot T_o \cdot U_o}{(1+nD) \cdot L_o} \right]^2 + \frac{3(1+n)^2 P_o^2}{(1-D)^2 U_o^2}}
\]  

(15)

\[
IL_{2rms} = \sqrt{\int_{0}^{2\pi} i_L^{12}(t) dt} = \sqrt{\frac{1}{3} \left[ \frac{1}{4} \cdot \frac{1}{1+n} \cdot \frac{D(1-D) \cdot T_o \cdot U_o}{(1+nD) \cdot L_o} \right]^2 + \frac{3P_o^2}{(1-D)^2 U_o^2}}
\]  

(16)

\[
IL_{rms} = \sqrt{\frac{P_{L1}^2 + P_{L2}^2}{I_{L2}^2}} = \sqrt{\frac{1}{3} \left[ (nD+2nD+1) \right] \left[ \frac{1}{4} \cdot \frac{1}{1+n} \cdot \frac{D(1-D) \cdot T_o \cdot U_o}{(1+nD) \cdot L_o} \right]^2 + \frac{3P_o^2}{(1-D)^2 U_o^2}}
\]  

(17)

Where \( P_o \) is the converter output rated power.

### 4. Design of a tapped energy storage inductor

#### 4.1. Core selection

In the development of soft magnetic materials, the metal soft magnetic powder core not only retains some of the excellent characteristics of metal soft magnetic and ferrite soft magnetic, but also overcomes some of the defects of the two to the greatest extent. Therefore, so far, the metal soft magnetic powder core is a soft magnetic material with the best comprehensive performance [12-13].

There are many types of core shapes, the more common ones are EE type, EI type, UI type, RM type and ring type. Among them, the ring type core has high permeability, low loss, strong anti-interference, and has a higher coupling coefficient when it is making coupled inductors [12].

Based on the above analysis, the magnetic core selected in this paper is a toroidal core made of soft metal powder. The magnetic permeability of the inductor peak current is 60% of the initial value, and the maximum magnetic field strength at this time is \( H_m \). Calculate area product by AP
method as

$$AP = \frac{L^2 \cdot i_{i, \text{max}}^2 \times 10^4}{0.6 \cdot \mu_0 \cdot H_{\text{m}} \cdot j \cdot K_u}$$  \hspace{1cm} (18)

Where j is the wire current density, \(\mu_0\) is the initial permeability of the magnetic core, Ku is the window utilization coefficient, and Ku is 0.4. Consult the data sheet and select a core whose actual area product AP1 is greater than AP.

4.2. Calculation of turns
The initial inductance of the magnetic ring is AL0. When the peak current drops to 60% of the initial value, the turns of the tapped inductance coil N1 is

$$N_1 = \frac{L_0}{60\% \cdot A_{L0}}$$  \hspace{1cm} (19)

The turns of the tapped inductance coil N2 is n·N1.

4.3. Inductance value calculation
The magnetic field strength at the peak of the inductor current is:

$$H_{\text{m}} = \frac{0.4 \pi N_1 L_{1, p}}{L_e}$$  \hspace{1cm} (20)

Where le is the effective magnetic path length of the magnetic core. According to the manual, when the magnetic permeability of the magnetic ring has dropped to k\% of the initial value, the corresponding inductance can be obtained

$$L_{1, p} = k\% \cdot A_L \cdot N_1^2$$  \hspace{1cm} (21)

Compare the designed actual inductance L1, if $$L_1 \geq L_{1, p}$$, it shows that the design requirements are met.

4.4. Winding design
High-frequency current has a strong skin effect. In order to eliminate the influence of the skin effect, the diameter of the wire must not exceed twice the penetration depth. The penetration depth of the copper wire when a 100kHz current flows is equal to 0.2093mm, so the selected wire diameter should be less than 0.4186mm. Taking the current density j=500A/cm², the multiple strands of 0.4mm copper wire can be chosen. The actual window utilization factor can be obtained as

$$K_u = \frac{S_1 \cdot N_1 + S_2 \cdot N_2}{Q}$$  \hspace{1cm} (22)

Where SL1 and SL2 are the wire cross-sectional areas of L1 and L2, and Q is the window area of the magnetic core. If Ku<0.4, it means that the wire meets the requirements, otherwise it needs to be reselected.

5. Simulation verification

5.1. Simulation Parameters
Table 1 is the circuit parameters of the large step-up ratio DC/DC converter designed in this paper.

| Rated Parameters         | Value     |
|--------------------------|-----------|
| Input Voltage Uᵢ/V      | 40–50     |
| Output Voltage Uₒ/V     | 400       |
| Output Power Pₒ/W       | 1000      |
| Input Capacitance Cᵢ/μF | 100       |
| Output Filter Capacitor Cₒ/μF | 40     |
| Switching Frequency fₛ/Hz | 100k     |
In the above input voltage working range, the boost ratio range of the converter is 8-10. In order to take into account the switching loss and the current mutation rate, and combined with equations (7), the turns ratio n is selected as 2, and the corresponding duty cycle range is 0.7-0.75. According to (13) and considering a certain margin, select the inductance L1 to be 0.01mH, and the inductance L2 to be 0.04mH.

5.2. Simulation analysis of three winding modes of tapped energy storage inductor

Select the magnetic ring with the core model NPH158060, and the parameters of the magnetic core and inductance wire are shown in Table 2 [13]. According to equations (14)-(22), it can be obtained as iL1max=45A, IL1rmsmax=27.04A, IL2rmsmax=5.2A, Bm=0.38T, AP=2.66, 12 turns for N1, 24 turns for N2, Ku=0.348<0.4. The actual AP1>AP, so the magnetic core parameters meet the design requirements.

Table 2 Magnetic core parameters

| Core Parameters Value                                                                 |
|----------------------------------|----------------------------------|
| Initial Permeability μ0/G1 Oe⁻¹   | 60                               |
| Initial Inductance A1/0/nH/turn²   | 122                              |
| Coating Outer Diameter*Inner Diameter*Height/mm | 40.94*21.27*17.89 |
| The Effective Magnetic Path Length is L/cm | 9.51                             |
| Cross-sectional Area S/cm²       | 1.5372                           |
| Window Area Q/cm²                | 3.55                             |
| Actual AP/cm²                   | 5.457                            |
| The Wire Cross-sectional Area of L1: S1₁/mm² | 8.04                           |
| The Wire Cross-sectional Area of L2: S1₂/mm² | 1.13                           |

Substitute the above-mentioned parameters into Maxwell software, establish three-dimensional inductance models under three different winding modes, as shown in Fig.3.

(a) Ordinary winding model
(b) Sandwich winding model
(c) Cross-winding model

Fig.3 Three-dimensional model of tapped inductors under three different windings

Table 3 shows the inductance parameters of the three different winding modes under the peak current.

Table 3 Inductance parameters of three different winding methods

| Winding Method        | L₁/mH | L₂/mH | M/mH | Coupling Coefficient | L/mH | Parasitic Resistance r/Ω |
|-----------------------|-------|-------|------|----------------------|------|--------------------------|
| Ordinary Winding      | 0.0121| 0.0507| 0.0242| 0.978                | 0.1112| 0.03404                  |
| Sandwich Winding      | 0.0123| 0.0490| 0.0243| 0.991                | 0.1099| 0.02921                  |
| Cross-winding         | 0.0121| 0.0483| 0.0239| 0.990                | 0.1081| 0.02443                  |

Calculated by (21), L1p=0.12mH, and it can be seen from Table 3 that L1>L1p which meets the design requirements. As Table 3 shown that the inductive coupling coefficient under the ordinary winding method is lower, and the parasitic resistance is larger which will cause the loss to increase. Moreover, the sandwich winding model and the cross-winding model have larger coupling coefficients, lower parasitic resistance, and better performance.
5.3. Simulation analysis of three ways of winding inductors in converter circuits

Substitute the inductance parameters in Table 3 into the Psim simulation circuit to obtain the converter performance indexes corresponding to the inductances of the three different winding models. Fig.4(a), Fig.4(b) and Fig.4(c) are the steady-state simulation results under the three winding model when the input voltage is 45V. It can be seen from Fig.4 that the output voltage is stable at 400V, and the inductor current magnetic flux is continuous.

Fig.4 Simulation results of a DC/DC converter with a large boost ratio when the input voltage is 45V

Organize the results into Table 4. From Table 4, the following conclusions can be drawn:

1) Under different input voltages, among the three winding models, the most efficient converter is the cross-winding model, and the lowest is the ordinary winding model inductance, which because of the parasitic resistance of the inductor model. The larger the parasitic resistance, the greater the loss and the lower the efficiency of converter.

2) The switching voltage stress of the sandwich winding model is the smallest, the ordinary winding model is the largest, which corresponds to the coupling coefficient.

3) It can be calculated from equations (14) - (16) that when the input voltage is 45V, the inductor current peak value is 40.81A, and the effective value is 24.11A. As Table 4 shown that the simulation result is a larger than the theoretical value, mainly due to the parasitic resistance of the inductor and other components, which leads to the loss of converter efficiency. Therefore, a certain margin needs to be considered when designing.

4) Among the three different winding models, the ordinary winding model has the lowest coupling coefficient, the largest parasitic resistance, the lowest efficiency, the largest effective value of the inductor current, and the largest switch tube voltage stress. It is nearly the worst winding method. The sandwich winding model and the cross winding model have similar inductance performance. The cross winding model has the highest efficiency, but other performance are lower than the sandwich winding model. And the actual winding is difficult, which is only suitable for occasions with high efficiency requirements. The sandwich winding model has good inductance performance, and the actual winding is not difficult, and it can basically meet various occasions.

Table 4 Circuit simulation results when the input voltage is 45V

| Winding method   | $V_s/V$   | $I_{L_{max}}/A$ | $I_{L_{rms}}/A$ | Output Voltage Ripple | Effectiveness $\eta$ |
|------------------|-----------|-----------------|-----------------|-----------------------|----------------------|
| Ordinary winding | 164.43    | 44.76           | 26.77           | 0.30%                 | 91.55%               |
| Sandwich winding | 163.98    | 45.01           | 26.17           | 0.35%                 | 93.87%               |
| Cross-wound      | 164.13    | 45.90           | 26.19           | 0.38%                 | 93.98%               |
6. Conclusion
Based on the results and discussions presented above, the conclusions are obtained as below:

1) The working principle of the large step-up ratio DC/DC converter is analyzed, and the design ideas of the tapped inductor turns ratio and inductance is proposed in this paper. The main parameters of tapped inductor is deduced, and the selection and design of the tapped inductors are carried out.

2) Through the combined simulation analysis of Maxwell and Psim, the effectiveness and feasibility of the tapped inductor design are verified, the performance of three different winding inductor models are compared, and the method for the optimized design of tapped inductors and software simulation optimization is provided.

3) The simulation results show that different winding methods bring different inductance parameters, which affect the overall performance of the converter system. A relatively suitable design plan can be determined according to actual design requirements.

Acknowledgments
This work was financially supported by the Natural Science Foundation Project in Fujian Province (2018)01757).

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