Characteristic Analysis of Inductor in Pulsed Power Supply Changing with Shape Ratio

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INTRODUCTION

As the key technology and energy source of electromagnetic emission, the pulse power supply is of high voltage, pulsed high current and high power. Solenoid inductor is a key component of pulse power supply, which plays a role in limiting discharge current and adjusting pulse width. With the development of pulsed power supply, increasingly higher requirements are placed on inductor, which require inductor to have lower resistance, occupy less space, and lower external magnetic field strength.

In the published literature, formulas for calculating inductance are "forward" formulas, meaning calculate the inductance value from the given dimensions such as size, shape, and number of turns. "Backward" formulas for calculating inductance has no unique solution, a few large turns, or many small turns will deliver the same inductance value, a lot of research has done on their optimal forms. James Clerk Maxwell stated that when the total length and thickness of the wire being given, if the channel in which the coil is wound has a square transverse section, the mean diameter of the coil should be 3.7 times the side of the square-section of the channel, the form of a coil for which the coefficient of self-induction is a maximum. Grover considers a range of practical examples including the "Most Economical Coil Shape" which is the "given piece of wire" optimum. Takaaki Ibuchi gave the optimal design sizes of a single-layer solenoid to minimize copper loss for a given wire diameter and inductance value. In the design process of the solenoid inductor, given the inductance value, it is necessary to consider not only the resistance of the inductor, but also various factors such as volume, stress and external magnetic field.

In this paper, a solenoid inductor calculation model was established, and the formula for calculating the inductance value, volume, formula, resistance, and external magnetic field of the solenoid inductor was given. By changing the number of solenoid coil turns, that is, changing the shape parameter of the inductor, calculate the volume, resistance, stress and magnetic field strength of the inductor under different shape ratios, and Analyze and discuss its changes.

CALCULATION MODEL

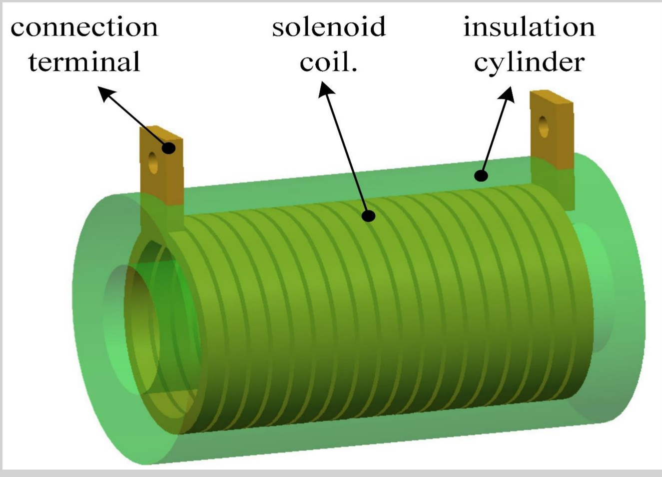


Fig. 1 Three-dimensional perspective of the solenoid inductor

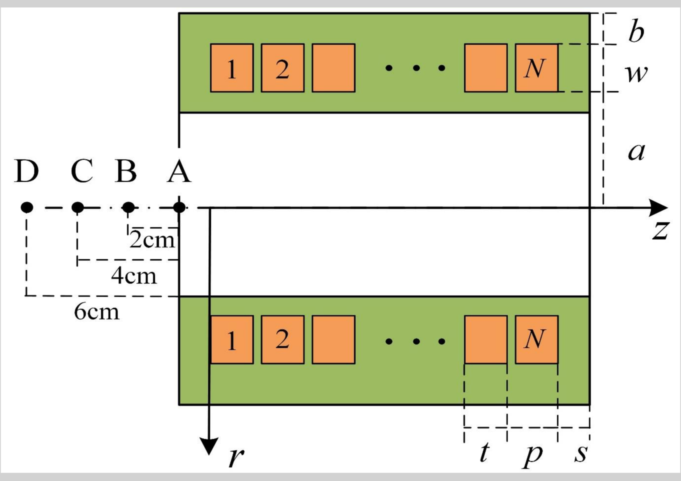


Fig. 2 Calculation model of the solenoid inductor

Table. 1 List of principal symbols

Symbols	Meaning
a	The inner radii of circular loops
p	The distance between two adjacent loops(pitch of spiral coil)
t	The cross-sectional dimension of copper wire in axial direction
w	The cross-sectional dimension of copper wire in radial direction
N	The number the loops
b	Outside insulation thickness in radial direction
s	End insulation thickness in axial direction

CALCULATION EQUATIONS

Calculation Equation of the Inductance Value

The inductance of the designed inductor should conform to the requirement of inductor electrical parameters. The inductance of the solenoid inductor is given by

$$L=\frac{\mu_0}{w^2t^2}\sum_{n_2=1}^{N}\sum_{n_1=1}^{N}\int_0^{\pi}\cos\theta\,\mathrm{d}\theta\int_a^{a+w}r_2\mathrm{d}r_2\int_a^{a+w}r_1\mathrm{d}r_1\int_{(n_2-1)p}^{(n_2-1)p+t}\mathrm{d}z_2\int_{(n_1-1)p}^{(n_1-1)p+t}\frac{\mathrm{d}z_1}{R}$$

where

$$R=\sqrt{r_1^2+r_2^2-2r_1r_2\cos\theta+(z_2-z_1)^2}$$

Where μ_0=4π×10−7 H/m is the permeability of free space (vacuum), r_1, r_2, z_1 and z_2 are the cylindrical coordinates corresponding to the radii and azimuths of coil n_1 and coil n_2, and θ corresponds to the angular coordinate in a cylindrical coordinate system.

Calculation Equation of the Inductor Volume

As the requirements for miniaturization of pulse power source modules become higher and higher, the inductance needs to occupy as little space as possible. The volume of inductance is:

$$V=\pi\left[(N\text{-}1)\,p+t+2s\right](a+w+b)^2$$

Calculation Equation of the Inductor Maximum Stress

The resultant force of radial magnetic force of each ring of the solenoid coil is zero, so only the axial magnetic force is considered. The axial magnetic force of the first turn of the solenoid circle with the highest axial magnetic force is:

$$F_{z\max}=\sum_{n=2}^{N}\frac{\mu_0I^2}{w^2t^2}\int_0^{\pi}\cos\theta\,\mathrm{d}\theta\int_a^{a+w}r_1\mathrm{d}r_1\int_a^{a+w}r_1\mathrm{d}r_2\int_{(k-1)p}^{(k-1)p+t}\mathrm{d}z_1\int_{(n-1)p}^{(n-1)p+t}\frac{(z_2-z_1)\mathrm{d}z_2}{R^3}$$

Where the symbols I is the maximum electric currents imposed coils. The maximum stress on the insulation cylinder is:

$$\sigma_{z\max}=\frac{F_{z\max}}{\pi\left(w^2+2aw\right)}$$

The maximum stress calculated should be less than the ultimate compressive strength of epoxy resin, will not cause the inductor material failure.

Calculation Equation of the Inductor Magnetic Intensity

The strong magnetic field generated by the pulse inductor during the discharge process has greatly restricted the development requirements for the miniaturization of pulse power supply. The magnetic strength at point (r, z) is:

$$\boldsymbol{B}(r,z)=\frac{\mu_0I}{4\pi wt}\sum_{n=1}^{N}\int_a^{a+w}r_1\mathrm{d}r_1\int_{-\pi}^{\pi}\mathrm{d}\theta\left[\int_{(n-1)p}^{(n-1)p+t}\frac{(z_2-z_1)\cos\theta}{R^3}\mathrm{d}z_1\boldsymbol{e}_r+\int_{(n-1)p}^{(n-1)p+t}\frac{r_1-r_2\cos\theta}{R^3}\mathrm{d}z_1\boldsymbol{e}_z\right]$$

Calculation Equation of the Inductor Resistance

The low-resistance inductor can improve the emission efficiency of pulse power supply and reduce the absorbed heat. It makes sense to minimize the resistance of the inductor. The resistance of inductance is:

$$R_L=\rho\frac{l}{S}=\rho\frac{\sqrt{\left[\pi N(2a+w)\right]^2+\left[(N-1)p\right]^2}}{wt}$$

SOLENOID INDUCTOR CHARACTERISTICS AS A FUNCTION OF SHAPE RATIO

In this section, by changing the number of turns of the coil, that is, changing the shape ratio of the spiral coil, we discuss the characteristics dependence on the shape ratio for 10μH, 20μH, 30μH, 40μH and 50μH solenoid inductor. The fix parameters are w=12mm, b=s=t=10mm, p=12mm, I=100kA.

The shape ratio of solenoid inductor as the following equation:

$$\beta=\frac{NP}{2a+w}$$

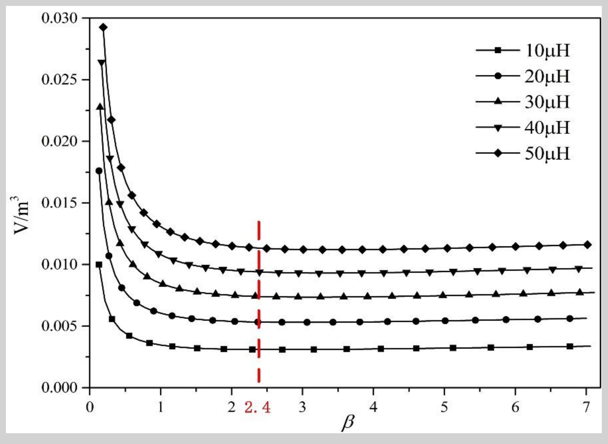


Fig. 3 Volume as a function of shape ratio

Figure 3 shows the volume dependence on the shape ratio for solenoid inductor. The results shown in Fig. 3 indicate that the volume of solenoid inductor reaches a minimum and remains constant when β is greater than 2.4. When β is less than 2.4, the smaller the value of β, the larger the volume of the inductor. When β is 0.13, the volume of solenoid inductor is more than double that when β is greater than 2.4. It can also be seen in Fig. 3 that the minimum volume of the inductor is in a multiple relationship with the inductance value of the inductor.

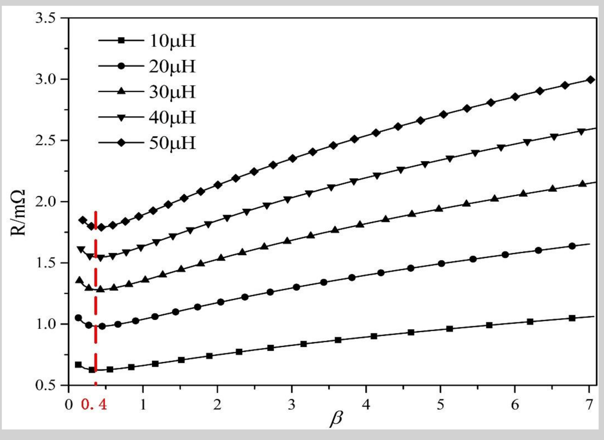


Fig. 4 Resistance as a function of shape ratio

The calculated resistance is shown in Fig. 4. Resistance is minimum at a solenoid shape ratio is 0.4. When β is greater than 0.4, the resistance value of the inductor increases as shape ratio β increases. The resistances of the five inductors are more than half larger when β is 7 than when β is 0.4. It can be seen that the shape ratio has a greater impact on the resistance of the inductor. It can also be seen in Fig. 4 that the larger the inductance value, the greater the resistance value of the inductor.

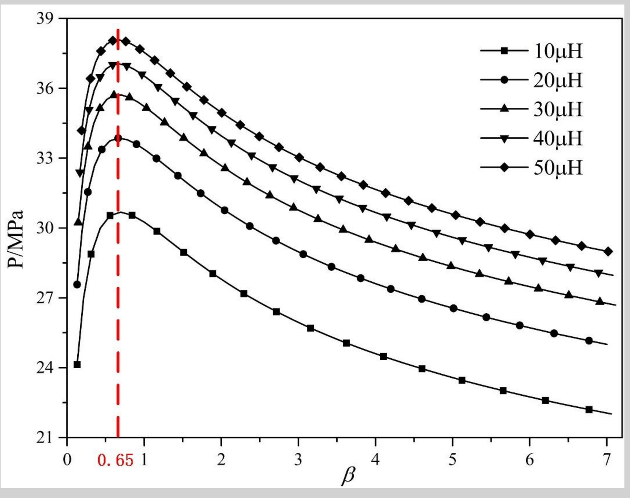
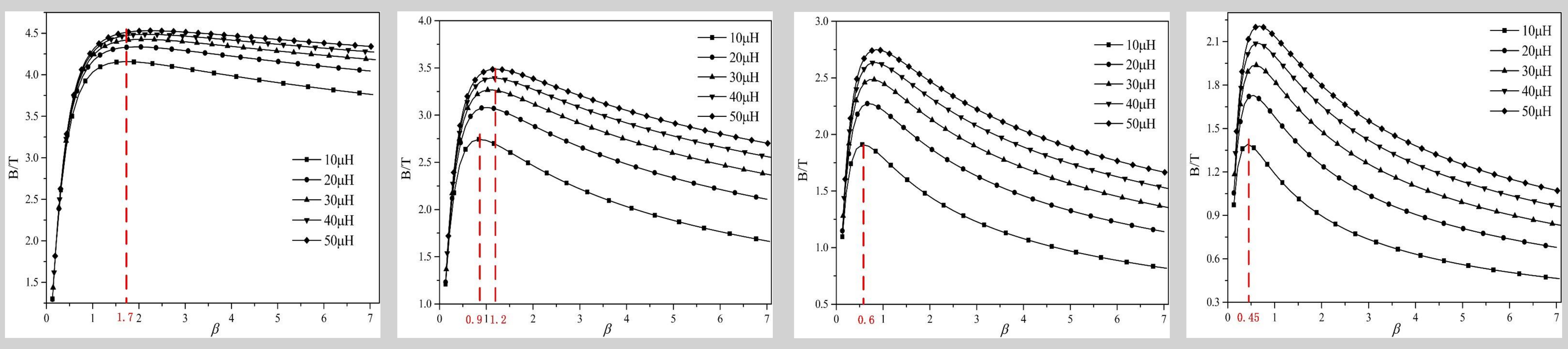


Fig. 5 Stress as a function of shape ratio

Figure 5 shows the maximum stress dependence on the shape ratio for solenoid inductor. It can be seen from Fig 5 that when β is about 0.65, the maximum stress on the insulation cylinder is the largest. The maximum stress value of the five inductors is more than half when the shape ratio β is 0.65 than when β is 7. Therefore, when the mechanical properties of the insulation material of the inductor cannot meet the design requirements of the inductor, the shape parameters ratio β of the inductor can be adjusted to meet the design requirements.



(a) (b) (c) (d)

Fig. 6 External magnetic intensity as a function of shape ratio

Figure. 6 (a), (b), (c), and (d) are the magnetic intensity on the inductance axis at the inductor end, 2cm, 4cm and 6cm away from the inductor end respectively (points of A, B, C and D in fig. 2. As shown in Figure 6, with the same shape ratio β, the larger the inductance value, the greater the external magnetic intensity of the inductor. It can be seen from Figure 6(a) that the magnetic intensity on the inductance axis at the inductor end (point A) is maximum when the shape ratio β is 1.7. When the shape ratio β is greater than 1.7, the magnetic intensity at point A gradually decreases as the shape ratio β increases. At the same position, the larger the inductance value, the larger the shape ratio β at the maximum magnetic intensity. When the inductance value is 10μH, the shape ratio β at the maximum magnetic intensity at points A, B, C and D are 1.7, 0.9, 0.6, and 0.45 respectively. Therefore, the farther away from the inductor, the smaller the shape ratio β at the maximum magnetic intensity.

CONCLUSION

In this paper a calculation model of solenoid inductor is established, and gives the calculation formulas for the inductance, volume, resistance, maximum stress, and external magnetic intensity of solenoid inductor.

The volume, resistance, maximum axial stress and magnetic intensity of five kinds of inductors under different shape ratios are calculated, and their variation laws are analyzed.

It is obtained that when the shape ratio of the inductor is greater than 2.4, the volume of the inductor reaches a minimum and remains unchanged, the inductor has the smallest resistance when the shape ratio is 0.4. When the shape ratio of the inductor is about 0.65, the maximum stress of the inductor is the largest, when the shape ratio of the inductor is about 1.7, the magnetic intensity on the inductance axis at the inductor end.

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