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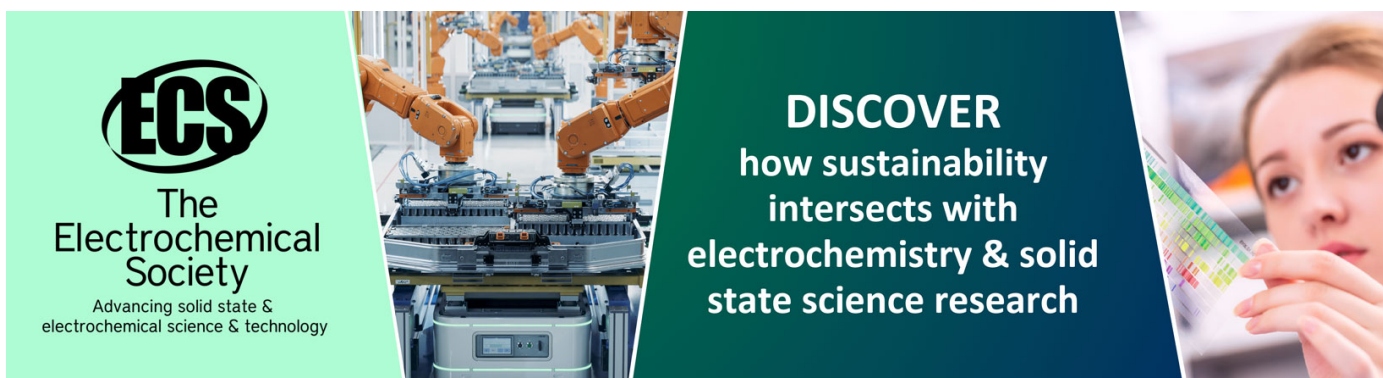
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To cite this article: Tianyi Guan *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **366** 012031

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The Study of Thin Film Capacitor on Loss and Current Distribution

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Abstract. The core structure of inverter DC-link bus film capacitor is too complex, it is more urgent to build the simulation model on capacitor core loss. Thus, in this paper, the current distribution and the loss distribution of thin film capacitor metal plate were analyzed, and then the mathematical expressions with current distribution and loss distribution were derived on the capacitor plate. On this basis, the concept of equivalent resistivity is put forward, and the loss model of equivalent capacitor core was established. By this method, the simulation model with capacitor core was simplified and verified by simulation. At the same time, the structure model of thin film capacitor core was established, and the influence of different core terminals and core shape were analyzed in the film capacitor.

1. Introduction

The capacitor plays an important role in the EV traction system, it is very important to choose the type of capacitor. Compared with the electrolytic capacitor, metalized film capacitor with high current capacity can withstand reverse voltage and long service life, no pollution and other advantages of acid [1], which is more suitable for using in a vehicle traction system. However, the film capacitor heating problem is the main reason for its service life, but want to understand the temperature of each part on the film capacitor, it is necessary to accurately know the loss of each part with the film capacitor. In view of the above problems, some papers concerned about the loss calculation in the film capacitor [2-3], but only the results of the loss calculation are given and the simulation is not verified. At the same time, the shape and the number of terminals have a great influence on the current distribution and the core loss distribution in the film capacitor, so the question should be analyzed.

In this paper, this thin film capacitor core will be divided into nine parts according to the internal structure. The current distribution and the loss distribution are analyzed, and the mathematical expressions are derived on the film capacitor plate. According to the concept of equivalent resistivity, the simulation model of thin film capacitor is established. The capacitor model is used to simulate the loss with the 87.8μF film capacitor. At the same time, the equivalent structure model of thin film capacitor core is established. The model can analyze the influence of capacitor terminal and capacitor core shape on the current distribution and loss distribution. Capacitors with lower height, larger diameter and multiple terminals have higher life expectancy.



2. Current distribution and loss distribution of thin film capacitor plates

2.1. Theoretical analysis

A common equivalent circuit model of thin film capacitor is shown in figure 1.

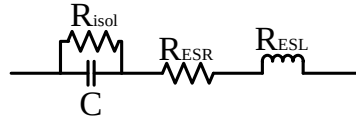


Figure 1. The equivalent circuit model of thin film capacitor[4-5]

R_{ESR} is the equivalent resistance of the film capacitor, and R_{ESL} is the equivalent inductance of the film capacitor. The capacitor loss can be expressed as,

$$P_{cap} = I_{crms}^2 \times R_{ESR} \quad (1)$$

I_{crms} is the RMS of thin film capacitor, this formula can only calculate the overall loss of the film capacitor, however, the loss of each part on the film capacitor cannot be obtained, it is necessary to understand the internal structure of the film capacitor.

The internal structure of thin film capacitor core mainly includes four parts in figure 2: the sprayed layer, the metal plate layer, the margin area and the dielectric layer. The current distribution of the film capacitor can be obtained through the film capacitor structure.

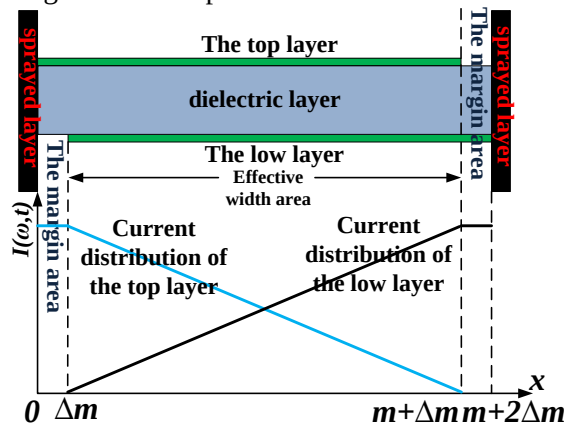


Figure 2. The current distribution of thin film capacitor plate

Δm is the margin width, m is the effective width of the metal plate, I is current density in the margin area, L is the plate length, ρ is the plate resistivity, d is the metal plate thickness.

The current density can be expressed in $[0, \Delta m]$ region as,

$$\begin{cases} I_{top} = I(\omega, t) \\ I_{low} = 0 \end{cases} \quad (2)$$

The current density can be expressed in $[\Delta m, m+\Delta m]$ region as,

$$\begin{cases} I_{top} = \left(-\frac{I(\omega, t)}{m}x + I(\omega, t)\left(1 + \frac{\Delta m}{m}\right) \right) \\ I_{low} = \left(\frac{I(\omega, t)}{m}x - I(\omega, t)\frac{\Delta m}{m} \right) \end{cases} \quad (3)$$

The current density can be expressed as in $[m+\Delta m, m+2\Delta m]$ region as,

$$\begin{cases} I_{top} = 0 \\ I_{low} = I(\omega, t) \end{cases} \quad (4)$$

The metal plate formula can be obtained at the dx width, the plate loss can be expressed in $[0, \Delta m]$ region as,

$$\begin{cases} d(P_{top}) = \frac{\rho}{L \times d} \times I^2(\omega, t) dx \\ d(P_{low}) = 0 \end{cases} \quad (5)$$

The plate loss can be expressed in $[\Delta m, m + \Delta m]$ region as,

$$\begin{cases} d(P_{top}) = \frac{\rho}{Ld} \times \left(\frac{I(\omega, t)}{m} x + I(\omega, t) \left(1 + \frac{\Delta m}{m} \right) \right)^2 dx \\ d(P_{low}) = \frac{\rho}{Ld} \times \left(\frac{I(\omega, t)}{m} x - I(\omega, t) \frac{\Delta m}{m} \right)^2 dx \end{cases} \quad (6)$$

The plate loss can be expressed in $[m + \Delta m, m + 2\Delta m]$ region as,

$$\begin{cases} d(P_{top}) = 0 \\ d(P_{low}) = \frac{\rho}{L \times d} \times I^2(\omega, t) dx \end{cases} \quad (7)$$

After the loss expression of the film capacitance is obtained, the equivalent resistivity of each part can be further calculated, which greatly simplifies the establish process of the simulation model on the film capacitor.

2.2. Deduction of equivalent resistivity

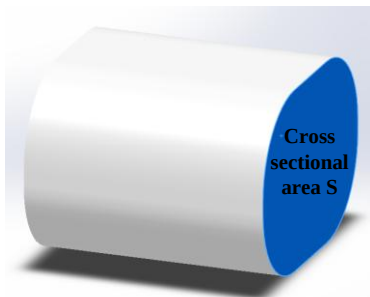


Figure3. The shape of the film capacitor core

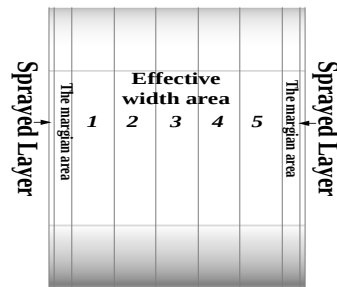


Figure4. The different regions of capacitor equivalent loss model

The equivalent core loss model can be established according to the equal loss principle. From the formula (2) (3) (4), it can be considered that the current in the equivalent model is equal to the sum of the current of the top and low plates.

It can be obtained by making the total loss of the top and low plates equal to the equivalent model loss on the margin area.

$$\begin{aligned} d(P_{top}) + d(P_{low}) &= \frac{\rho}{L \times d} \times I^2(\omega, t) dx = \frac{\rho_1}{S} I^2(\omega, t) dx \\ x &\in [0, m] \cup [m + \Delta m, m + 2\Delta m] \end{aligned} \quad (8)$$

then

$$\rho_1 = \frac{\rho S}{L \times d} \quad (9)$$

S is the cross sectional area of the core, as shown in figure 3, ρ_1 is the equivalent resistivity of the margin area.

It can be obtained by making the total loss of the top and low plates equal to the equivalent model loss on the effective width area.

$$d(P_{up}) + d(P_{low}) = (2x^2 + Ax + B) \frac{I^2(\omega, t) \rho}{m^2 L d} dx = \frac{I^2(\omega, t) \rho_2}{S} dx \quad x \in [m, m + \Delta m] \quad (10)$$

then

$$\rho_2 = (2x^2 + Ax + B) \times \frac{S \rho}{m^2 L d} \quad (11)$$

ρ_2 is the equivalent resistivity of the effective width area, A is $-2m-4\Delta m$, B is $(m+\Delta m)^2 + \Delta m^2$. According to (11), the effective width area resistivity of the equivalent model is the quadratic function about x . Therefore, the effective width area is divided into five parts along the axial direction, and the equivalent resistivity value is calculated. Then, the distribution of the effective width area can be fitted by the simulation data.

The equivalent resistivity of five parts can be expressed as:

$$\rho_{2i} = \frac{\int_{m_i}^{m_{i+1}} (2x^2 + Ax + B) \times \frac{S \rho}{m^2 L d} dx}{\frac{m}{5}} \quad i = 1 \cdots 5 \quad (12)$$

ρ_{2i} is the equivalent resistivity in i part of the effective width area.

$$\begin{cases} m_1 = \Delta m \\ m_{i+1} = m_i + \frac{m}{5} \end{cases} \quad i = 1 \cdots 5 \quad (13)$$

Through the above analysis, the capacitor can be divided into nine parts in figure 4, and the different parts have corresponding equivalent resistivity.

2.3. Simulation results

87.8uF capacitor core parameters are shown in Table 1.

Table 1. The Capacitor core parameter

	Material	Width (mm)	Resistivity ($\Omega \cdot m$)	Thickness (nm)	Length (m)
Sprayed layer	SnZn-2+SZSC-3	0.55	$8.307 \cdot 10^{-8}$	—	—
Metal plate	Zn+Al	25	$7 \cdot 10^{-8}$	2.08	550.35
Margin area (mm)		Effective width area (mm)		Cross section area (m^2)	
2		23		$\pi(24.05 \cdot 10^{-3})^2$	

The equivalent resistivity of each part can be obtained according to the capacitor parameters.

$$\begin{aligned} \rho_1 &= 1.11 \times 10^{-4} \Omega \cdot m & \rho_{21} &= 2.01161 \times 10^{-6} \Omega \cdot m \\ \rho_{22} &= 1.42759 \times 10^{-6} \Omega \cdot m & \rho_{23} &= 1.23299 \times 10^{-6} \Omega \cdot m \\ \rho_{24} &= 1.42759 \times 10^{-6} \Omega \cdot m & \rho_{25} &= 2.01161 \times 10^{-6} \Omega \cdot m \end{aligned} \quad (14)$$

The model shown in figure 5 is added with a current excitation source of 10A and 10kHz. As seen in figure 6 and figure 7, the loss of the terminal end in the spray layer is the largest, indicating the most serious heating here. The loss in the effective width region is decreasing along the radial direction from the capacitor terminal side. Generally, the loss distribution of the effective width area along the radial is related to terminals shape, so the radial loss distribution has no regularities.

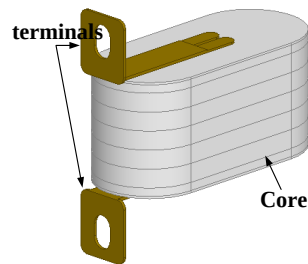


Figure 5. The simulation model of film capacitor core

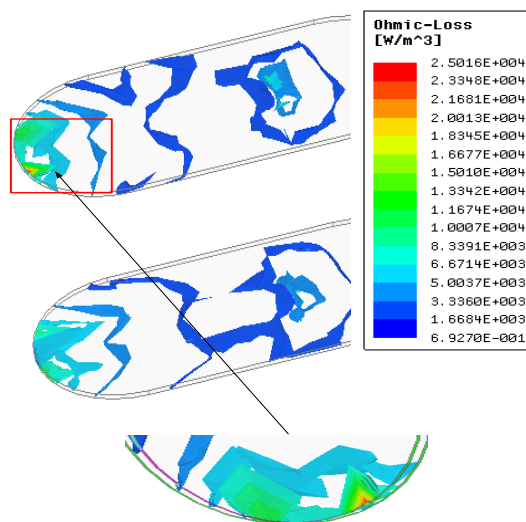


Figure 6. The loss nephogram of the spraying layer

The simulation results show that the loss of the sprayed layer is much larger than that of the effective width area.

In order to observe more intuitively the loss distribution of the capacitor in the axial direction, a loss path can be added to the capacitor model, as shown in figure 8.

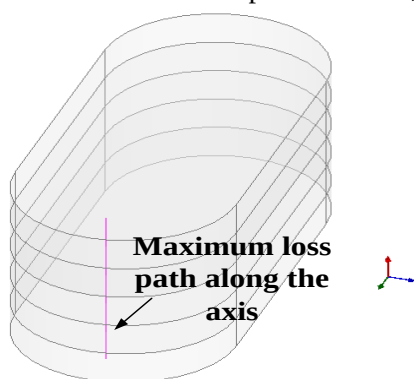


Figure 8. The model loss path

It can be seen from the path loss curve in figure. 9 that the five parts of the equivalent model is symmetrically distributed, and the curve is fitted to the quadratic curve as the loss distribution of the actual core.

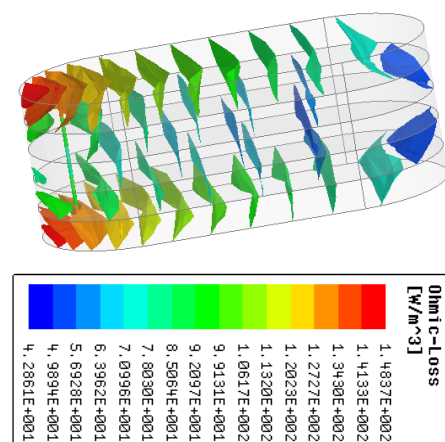


Figure 7. The loss nephogram of effective width area

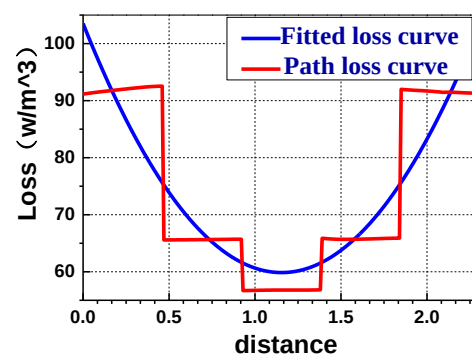


Figure 9. The path loss curve and fitted loss curve

3. The influence of size and terminals on the capacitor core

3.1. Model establishment

The thickness of the winding layer is a few nanometers, and the winding layer reaches thousands of layers. The entity capacitor model cannot be established, so the capacitor model is made up of a few layers to investigate the effect of different factors on the current and loss inside the core. At the same time, in order to simplify the analysis, the two winding layer can be equivalent to the cylinder with close contact.

The capacitance of a film capacitor can be expressed as,

$$C = 2 \frac{\epsilon_1 \epsilon_0 w l}{d} \quad (15)$$

C is the capacitance value, d is the film thickness, ϵ_1 is the dielectric constant of film, ϵ_0 is the dielectric constant of vacuum, w is the effective width, l is the winding length of capacitor core. In order to analyze the influence of different sizes on the current distribution, it is necessary to ensure that the capacitance value of different capacitors are equal, the product wl should be equal.

Three different dimension capacitor core models are established in figure 10 and figure 11, w_i is the effective width of No. i core model. l_i is the winding length of No. i core model. n_{ij} is the diameter of No. j layer in No. i core model.

The No.1 core model is made up of four metal layers.

$$l_1 = \pi(n_{12} + n_{14}) = \pi(0.51 + 1.03) = 4.84 \text{ mm} \quad (16)$$

$$l_1 \times w_1 = 4.84 \times 8 = 38.7 \text{ mm}^2 \quad (17)$$

The No.2 core model is made up of six metal layers.

$$l_2 = \pi(n_{22} + n_{24} + n_{26}) = 9.7 \text{ mm} \quad (18)$$

$$l_2 \times w_2 = 9.7 \times 4 = 38.8 \text{ mm}^2 \quad (19)$$

The No.3 core model is made up of eight metal layers.

$$l_3 = \pi(n_{32} + n_{34} + n_{36} + n_{38}) = 16.21 \text{ mm} \quad (20)$$

$$l_3 \times w_3 = 16.21 \times 2.4 = 38.9 \text{ mm}^2 \quad (21)$$

The product wl are equal basically, the capacitance of three capacitor models are equal.

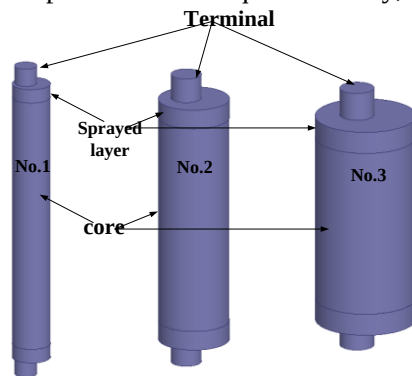


Figure 10. The three capacitor core model

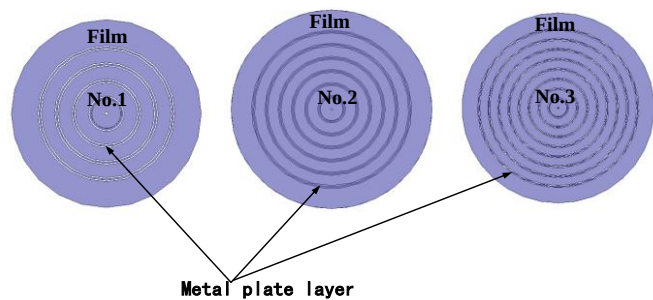


Figure 11. capacitor film and metal plate layer

3.2. Simulation result on different size capacitors

The excitation used in the simulation is a current source with 10A and 10kHz. Capacitor model materials are shown in Table 2.

Table 2. Capacitor model material

Metal plate layer	Al
Terminal	Cu
Thin film	polythylene
Sprayed layer	Zn

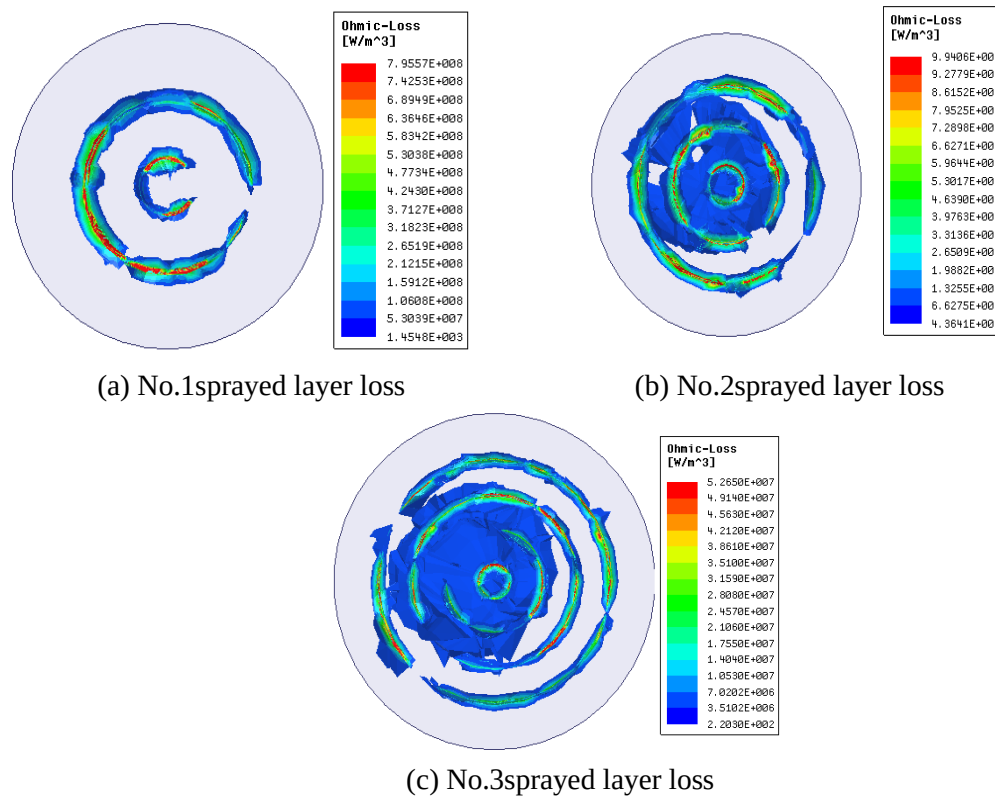


Figure 12. The loss nephogram of the sprayed layer

3.2.1. Loss on sprayed layer. The location of maximum loss in the sprayed layer is shown in figure 12. No.1 capacitor sprayed layer maximum loss is $7.9 \times 10^8 \text{ W/m}^3$. No.2 capacitor sprayed layer maximum loss is $9.9 \times 10^7 \text{ W/m}^3$. No.3 capacitor sprayed layer maximum loss is $5.2 \times 10^7 \text{ W/m}^3$. The maximum loss area of the No.1 capacitor sprayed layer is the largest in the three capacitors model.

3.2.2. Loss on metal plate layer. P_{ij} is the metal plate loss distribution on No. j layer, No. i capacitor core model. The metal plate layer losses are compared in different capacitors. In order to research the maximum loss relationship in different metal layers, A scatter diagram can be drawn.

It can be concluded that the capacitor with lower height and larger diameter can produce less loss in the capacitor, can reduce the heat conduction path and can reduce the heat inside core under identical capacitance circumstance from figure 13.

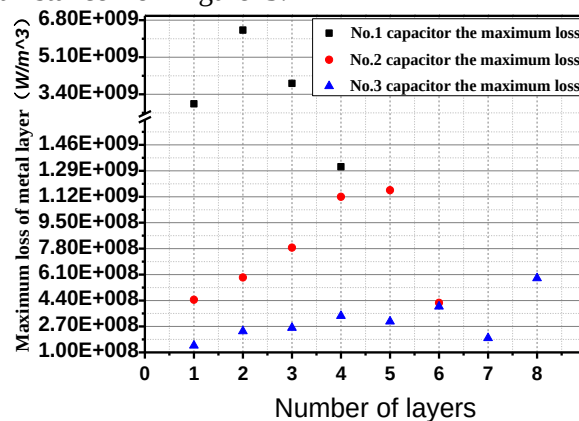
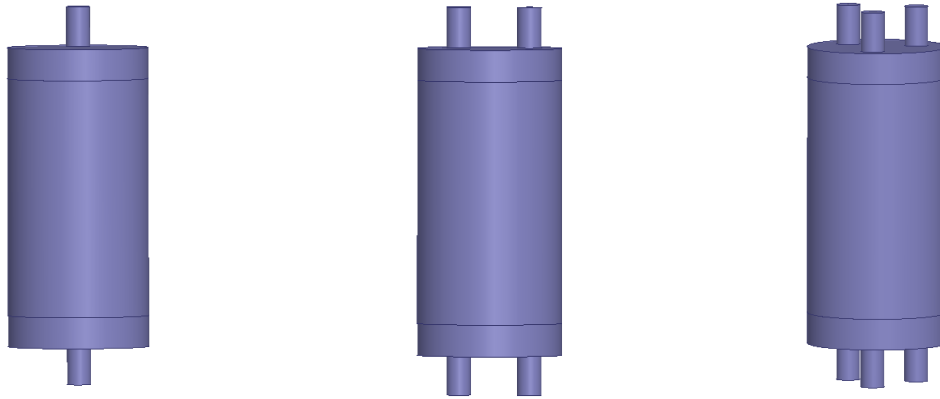


Figure 13. The maximum loss of the different capacitor on metal plate layers

3.3. Simulation result on different terminal capacitors

In order to research the terminaleffect on the capacitor loss distribution, the core model was established in figure 14, in which only the number of terminals changed, while the material and size of the three capacitor cores did not change. Capacitance values are equalon the three capacitor core models.



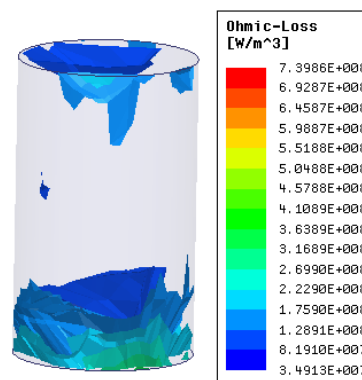
(a) No.1 capacitor model

(b) No.2 capacitor model

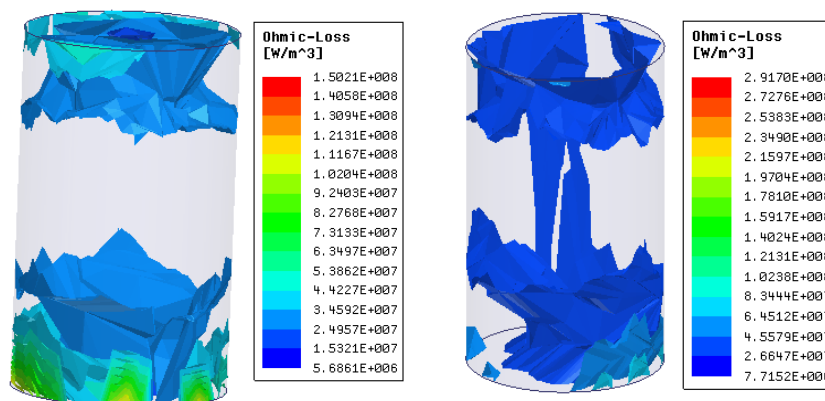
(c) No.3 capacitor model

Figure 14.The Capacitor core models with different terminals

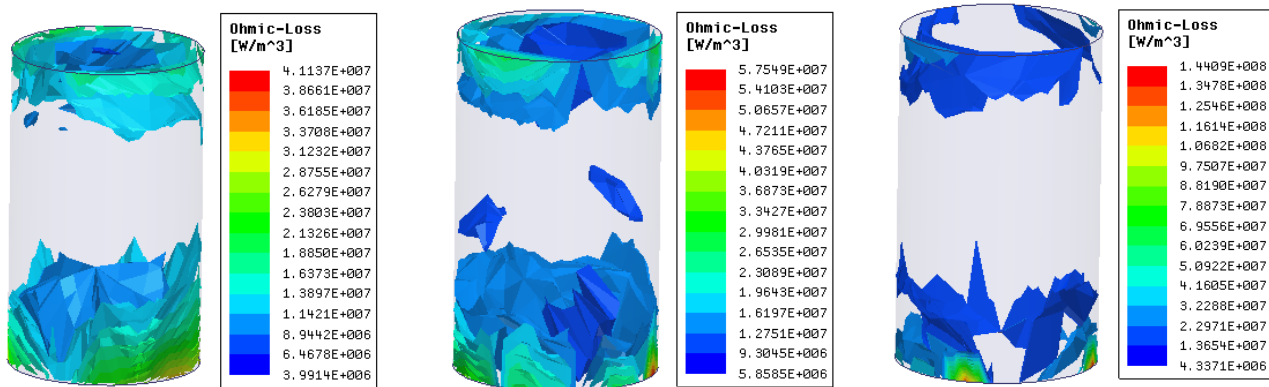
The excitation used in the simulation is a current source with 10A and 10kHz.



(a) Terminal loss nephogram of No.1 capacitor



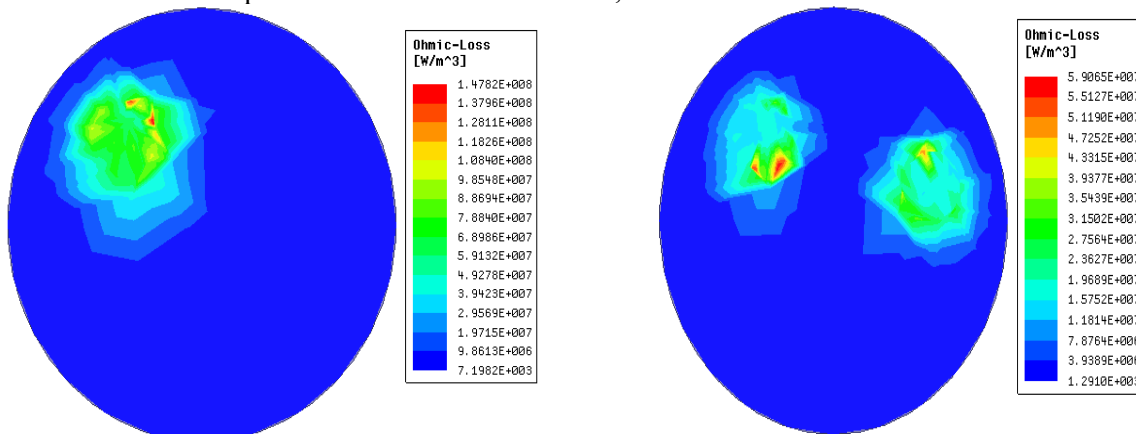
(b) Terminal loss nephogram of No.2 capacitor



(c) Terminal loss nephogram of No.3 capacitor

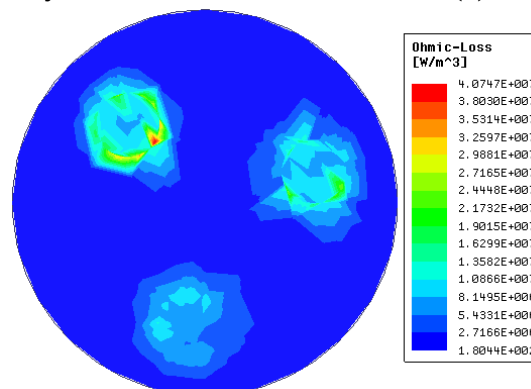
Figure 15. Loss distribution nephogram of different capacitor terminals

3.3.1. Terminal loss. In figure 15, the maximum loss of No.1 capacitor terminal is $7.39\text{e}+008\text{w/m}^3$, The maximum loss of No.2 capacitor terminals are $2.91\text{e}+008\text{w/m}^3$, The maximum loss of No.3 capacitor terminals are $2.91\text{e}+008\text{w/m}^3$. With the number of terminals increases, the maximum loss of capacitor terminal can be reduced, the local overheat of terminal is reduced.



(a) No.1 sprayed layer loss

(b) No.2 sprayed layer loss



(a) No.3 sprayed layer loss

Figure 16. The loss nephogram of the sprayed layer

3.3.2. Loss on sprayed layer. In figure 16, The maximum loss of No.1 capacitor sprayed layer is $1.4782\text{e}+008\text{w/m}^3$, the maximum loss of No.2 sprayed layer is $1.4782\text{e}+008\text{w/m}^3$, the maximum loss

of No.3 capacitorsprayed layer are $1.4782+008w/m^3$.The simulation result show that incrementalterminalquantities can reduce the maximum loss on sprayed layer, which makes the loss distribution more uniform, and the local overheatingare reduced on sprayed layer.

3.3.3. Loss on metal plate layer.In order to research the influence of terminal on the film metal layer more intuitively, Scatter diagram can be drawn from the maximum loss of the metal layer with different capacitance models.

It can be obtained from figure17 that the maximum loss value is $8.9e+009w/m$ on the second layer with the No.1capacitor model³,which is obviously higher than the maximum loss of other metal layers. It can be concluded that when the number of terminal is one, the current distribution on the metal plate layer will be more inhomogeneous,which will lead to obvious hot spot in the capacitor.

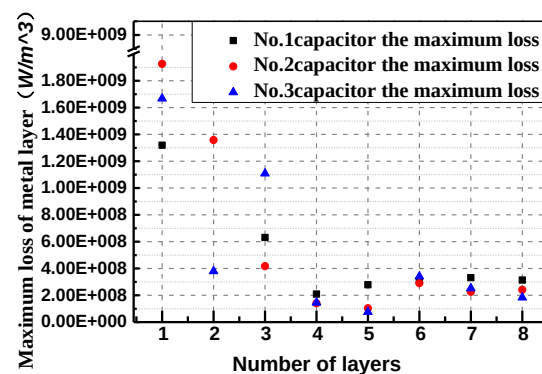


Figure 17.The maximum loss of the different capacitor on metal plate layers

4. Conclusion

In this paper, a method establishing the loss model is proposed on thin film capacitor, First of all, The concept of equivalent resistivity is put forward, which solves the problem on establishing film capacitor loss model. At the same time, the loss distribution of different film capacitor cores is compared by simulation, The simulation result show that the capacitor core with larger diameter and lower height has less loss, multi-terminal capacitor can make core loss distribution be more uniform and can reduce hot spots.

Acknowledgments

This work was supported by National Key R&D Program of China, and the project number is 2016YFB100700.

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