IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received September 10, 2021, accepted September 29, 2021, date of publication November 26, 2021,
date of current version December 20, 2021.

*Digital Object Identifier 10.1109/ACCESS.2021.3118042*

# Research on Five-Loop Simplified Scaling Model for Dry-Type Air-Core Reactors With Inter-Turn Short Circuit Fault

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This work was supported by the National Natural Science Foundation of China under Grant 51977122.

**ABSTRACT** In order to simplify the research method of the spatial magnetic field distribution (SMFD) of dry air-core reactors (DARs) in the case of inter-turn short circuit fault, the concept of simplified scaling model was put forward, and the optimal simplified scaling model for different inter-turn short circuit fault was calculated by using the least square method. Firstly, in order to simplify the calculation, 7 typical directions describing the SMFD of DARs were determined based on the similarity degree of magnetic induction intensity in each direction. Then, the simplified scaling model parameters corresponding to different short circuit positions and degrees were studied, and the variation rule was described by using the method of fitting function. Finally, the original model and the simplified scaling model of the DARs in the case of inter-turn short circuit were established respectively in the laboratory. The results show that the optimal structure relative height obtained by experiment is 30% and 20% respectively, which is the closest to the parameters obtained by computer simulation, i.e.,28% and 20.3%.

**INDEX TERMS** Dry-type air-core reactor (DAR), inter-turn short circuit fault, spatial magnetic field distribution (SMFD), five-loop simplified scaling model, optimal structure.

## I. INTRODUCTION

Dry-type Air-core Reactors(DARs) are important power equipment in power system, with the role of compensating reactive power, limiting short circuit current and filtering high harmonic [1]–[5]. However, once the inter-turn short circuit fault occurs in them, the huge short circuit current will damage the DARs, or even cause fire [6]–[10]. When the current passes through, there will be a magnetic field around the DARs that changes with the different working state of the DARs, which is called the Space Magnetic Field(SMFD). The SMFD can accurately and sensitively reflect the inter-turn short circuit fault of the DARs [11]–[16]. Therefore, it is of great significance to monitor and analyze the SMFD so as to detect inter-turn short circuit fault effectively and reliably.

For the DARs with inter-turn short circuit fault, the SMFD of the DARs can be obtained directly by field measurement [17], but the cost of making the DARs prototype is very high, and the experimental process is dangerous. In order to avoid the above problems, it is necessary to establish an equivalent model which can simulate the inter-turn short circuit fault in different positions and degrees of DARs.

So far, two equivalent models of DARs based on similarity theory have been established to study the SMFD, which are the Scaling Models and the Simplified Scaling Models. These two equivalent models can simply calculate the SMFD in all directions of the DARs, which means that the equivalent model of the DARs in the case of inter-turn short circuit fault can also be established.

The Scaling Models can be obtained by tightly winding a single layer of wire along the axis. In the Scaling Models, the SMFD can be obtained from the geometric similarity expansion after deriving the similarity principles of DARs [18], [19]. Because a scale model can only simulate inter-turn short circuit fault at a certain position or degree,

The associate editor coordinating the review of this manuscript and approving it for publication was Baoping Cai.

a large number of scale models will be needed to simulate inter-turn short circuit fault at different positions or degrees, which will consume a lot of time and experimental materials in the laboratory. In order to reduce the workload of analyzing the SMFD by the simplified model, a simpler simplified model of the DARs is required.

The Simplified Scaling Models are simpler than the Scaling Models, which are composed by three loops of superimposing three coaxial coils along the axial direction. Yu *et al.* [20], [21] established SINGLE model, 3FIXED model and FLEXIBLE model to calculated magnetic flux densities along five typical traverses, and found that the FLEXIBLE model was more satisfying. Han *et al.* [22] built accurate simplified three-loop scaling model by optimizing the structural parameters, which made the SMFD along the typical directions be more similar to the original DARs. These results show that the simplified scale model can be used to study the SMFD of the DARs with inter turn short circuit fault. For different inter-turn short circuit faults, the SMFD under this condition can be equivalent only by adjusting the position of the coils in the simplified scaling model, which greatly reduces the time spent in the experimental research process compared with the scaling model.

When the number of coils in the simplified scaling model is too small to reflect the geometry of the DARs, then the equivalent effect will be reduced [14]. This is due to the fact that the original model was a tightly wound solenoid, with the magnetic field mainly concentrated in the axial direction, while the equivalent model had a large gap between the coils, which would lead to an increase in the radial magnetic flux leakage. The influence of magnetic flux leakage on the calculation accuracy can be alleviated by increasing the number of coils. Since the simulation of the SMFD in the case of inter-turn short circuit fault had higher requirements on the calculation accuracy, the five-ring simplified scaling model was selected under the condition of taking the simulation time into account.

In this paper, the mathematical expressions of magnetic induction intensity in typical directions of the original model and the simplified model were derived according to Biot-Savar law, and the simplified scaling model of the five loops was determined when the DARs work normally. Then, the short-circuit position and the short-circuit degree of the original model were adjusted, and the optimal structure in the case of various inter-turn short-circuit faults was obtained through the least square simulation. Finally, the magnetic field measurement platform of the simplified scaling model was established, and the measurement results were statistically analyzed to verify the effectiveness of the optimized scaling model.

## II. FIVE-LOOP SIMPLIFIED MODEL AND CALCULATION OF SMFD

Since the several parallel packages structure of DARs can be equivalent to a single package structure, the original model could be a signal package DAR [23]. As shown in Fig.1, a 300 turn solenoid was chosen as the original model, and 7 typical directions were selected to describe the spatial magnetic field distribution of the DARs.

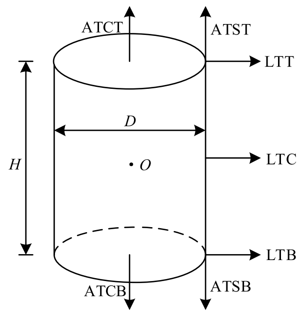


**FIGURE 1. Original model of a single package DAR. ATCT: axial traverse, center, top, ATST: axial traverse, side, top, ATCB: axial traverse, center, bottom, ATSB: axial traverse, side, bottom, LTT: lateral traverse, top, LTC: lateral traverse, center, LTB: lateral traverse, bottom.**

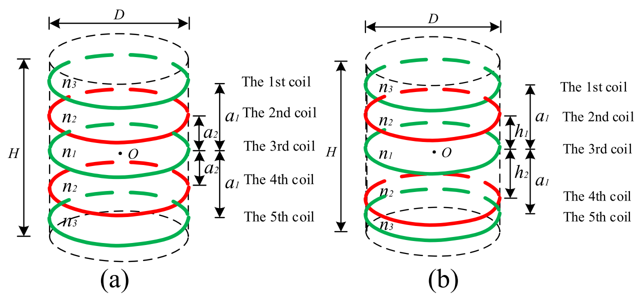


**FIGURE 2. Simplified scaling model under normal conditions and in the case of inter-turn short circuit fault of a single package DAR. (a) under normal conditions. (b) in the case of inter-turn short circuit fault.**

As shown in Fig.2(a), the simplified scaling model of the single package structure in Fig.1 was constituted by 5 coaxial coils. When the DAR was in normal operation, the positions of the 5 coils are symmetrical. The 1st and 5th coils with $n_3$ turns have a distance of $a_1$ to center point $O$, and the 2nd and the 4th coils with $n_2$ turns have a distance of $a_2$ to center point $O$, and the 3rd coil with $n_3$ turns is located at the center point $O$.

As shown in Fig.2(b), the positions of the five coils in the simplified scaling model are no longer symmetric due to the asymmetrical SMFD caused by the DARs in the state of inter-turn short circuit fault. The 1st and 5th coils with $n_3$ turns have a distance of $a_1$ to center point $O$. The 2nd coil with $n_2$ turns have a distance of $h_1$ to center point $O$. The 4th coil with $n_2$ turns has a distance of $h_2$ to center point $O$, and the 3th coil with $n_1$ turns is located at the center point $O$. The total turns of the simplified scaling model is $n = n_1 + n_2 \times 2 + n_3 \times 2$.

**TABLE 1. Parameters of original model.**

| Parameters | Symbol |
|---|---|
| Axial Height | $H$ |
| Basal Diameter | $D$ |
| Line Width | $W$ |
| Total Number of Turns | $N$ |
| Current | $I$ |

**TABLE 2.** Parameters of simplified model in normal condition.

| Parameters | Symbol |
|---|---|
| Axial Height | $H$ |
| Basal Diameter | $D$ |
| Line Width | $W$ |
| Total Number of Turns | $N$ |
| Current | $I$ |
| Turns of the 3rd coil | $n_1$ |
| Turns of the 2nd and the 4th coil | $n_2$ |
| Turns of the 1st and the 5th coil | $n_3$ |
| Distance of the 1st and the 5th coil to point $O$ | $a_1$ |
| Distance of the 2nd and the 4th coil to point $O$ | $a_2$ |

**TABLE 3.** Parameters of simplified model in the fault state.

| Parameters | Symbol |
|---|---|
| Axial Height | $H$ |
| Basal Diameter | $D$ |
| Line Width | $W$ |
| Total Number of Turns | $N$ |
| Current | $I$ |
| Turns of the 3rd coil | $n_1$ |
| Turns of the 2nd and the 4th coil | $n_2$ |
| Turns of the 1st and the 5th coil | $n_3$ |
| Distance of the 1st and the 5th coil to point $O$ | $a_1$ |
| Distance of the 2nd coil to point $O$ | $h_1$ |
| Distance of the 4th coil to point $O$ | $h_2$ |
| Relative position percentage of the 2nd coil | $\rho_1$ |
| Relative position percentage of the 4th coil | $\rho_2$ |
| Percentage of short circuit position | $L$ |
| Percentage of short circuit degree | $M$ |

The parameters of the original model and the simplified model are shown in Table 1, Table 2 and Table 3 respectively. The expressions of $\rho_1, \rho_2, L$ and $M$ in Table 3 are as follows:

$$\rho_1 = h_1/H \times 100\% \tag{1}$$

$$\rho_2 = h_2/H \times 100\% \tag{2}$$

$$L = \frac{l}{H} \times 100\% \tag{3}$$

$$M = \frac{m}{N} \times 100\% \tag{4}$$

where, $l$ represents the distance from the center of the short-circuit position to the bottom of the model, and m represents the number of turns in which a short circuit fault occurred.

For the original model, when the incoming current is $I$, the magnetic induction intensity of $P(x, y, z)$ in the space can be calculated by the following formula:

$$\begin{cases} \overrightarrow{B_x} = \sum_{l=0}^{N-1} \frac{\mu_0 IR}{4\pi} \int_0^{2\pi} \frac{(z-lW)\cos\theta}{r^3} \vec{i}\, d\theta \\ \overrightarrow{B_y} = \sum_{l=0}^{N-1} \frac{\mu_0 IR}{4\pi} \int_0^{2\pi} \frac{(z-lW)\sin\theta}{r^3} \vec{j}\, d\theta \\ \overrightarrow{B_z} = \sum_{l=0}^{N-1} \frac{\mu_0 IR}{4\pi} \int_0^{2\pi} \frac{R - x\cos\theta - y\sin\theta}{r^3} \vec{k}\, d\theta \end{cases} \tag{5}$$

where $r = ((x - R\cos\theta)^2 + (y - R\sin\theta)^2 + (z - lW)^2)^{1/2}$.

The five-loop simplified model and the original model are in the same coordinate system. The number of turns for each of the five coils is $\boldsymbol{n} = [n_3, n_2, n_1, n_2, n_3]$. When the DAR was in normal operation, the positions of the 5 coils are $\boldsymbol{h} = [H/2 + a_1, H/2 + a_2, H/2, H/2 - a_2, H/2 - a_1]$ respectively. When the DAR was in the state of inter-turn short circuit fault, the positions of the 5 coils are no longer symmetrical, and the positions can be expressed as $\boldsymbol{h} = [H/2 + a_1, H/2 + h_1, H/2, H/2 - h_2, H/2 - a_1]$. In the case of ignoring the influence of winding pitch angle, the SMFD can be calculated by superposition principle. The magnetic induction intensity of point $P$ in space is calculated as follows:

$$\begin{cases} \overrightarrow{B_x} = \sum_{l=1}^{5} \frac{\mu_0 IR \cdot n(l)}{4\pi} \int_0^{2\pi} \frac{(z-h(l))\cos\theta}{r^3} \vec{i}\, d\theta \\ \overrightarrow{B_y} = \sum_{l=1}^{5} \frac{\mu_0 IR \cdot n(l)}{4\pi} \int_0^{2\pi} \frac{(z-h(l))\sin\theta}{r^3} \vec{j}\, d\theta \\ \overrightarrow{B_z} = \sum_{l=1}^{5} \frac{\mu_0 IR \cdot n(l)}{4\pi} \int_0^{2\pi} \frac{R - x\cos\theta - y\sin\theta}{r^3} \vec{k}\, d\theta \end{cases} \tag{6}$$

where $r = ((x - R\cos\theta)^2 + (y - R\sin\theta)^2 + (z - h(l))^2)^{1/2}$.

## III. SIMULATION OF OPTIMAL STRUCTURE FIVE-LOOP SIMPLIFIED MODEL IN NORMAL CONDITION

The object of research is a single package structure with 300 turns, whose outside diameter is $D = 124$mm and line width as $W = 0.6$mm. Because the wire is tightly wound, the height of the simplified model of DARs is $H = 180$mm, and the height to diameter ratio of the model is $H/D = 1.45$.

For the purpose of ensuring the correct size and accuracy of the simplified scaling model, the number of turns of the simplified model in this paper is still 300, and the current of the original model and the simplified scaling model should be equal at this time, with the amplitude $I = 1.5$A and the frequency $f = 50$Hz. The line width, base diameter and height of the simplified scaling model are the same as those of the original model. The effects of eddy current, skin effect and background magnetic field are ignored.

According to the references [22], when the DAR is working normally, the optimal simplified scaling model can be determined by selecting four 4 monitoring directions (ATCB, ATSB, LTC and LTB) through the principle of minimum error.

The optimal simplified scaling model can be determined by obtaining the minimum square sum of the errors of the original model and the simplified scaling model in each typical direction. For a point in space, the error of magnetic induction intensity between the original model and the simplified scaling model can be expressed as:

$$e = |B_o| - |B_s| \tag{7}$$

where $B_o$ represents the magnetic induction intensity of the original model, and $B_s$ represents the magnetic induction intensity of the simplified scaling model.

Taking ATC direction as an example, 50 equidistant points between (0, 0, 0) and (0, 0, -*D*) are selected, and the magnetic induction intensity of each point in the original model and the simplified scaling model is calculated. The square loss function in the ATC direction is shown as follows:

$$Q_{ATC} = \sum_{i=1}^{n} e_i^2, \quad n = 50 \tag{8}$$

When $Q_{ATC}$ is the smallest, the corresponding simplified scaling model is the optimal simplified model in the direction of ATC. However, 4 typical directions must be considered in order to determine the optimal simplified scaling model. The sum of $Q$ values in 4 directions is expressed as follows. When $Q$ gets the minimum value, the corresponding simplified model is the optimal simplified scaling model.

$$Q = Q_{ATCB} + Q_{ATSB} + Q_{LTC} + Q_{LTB} \tag{9}$$

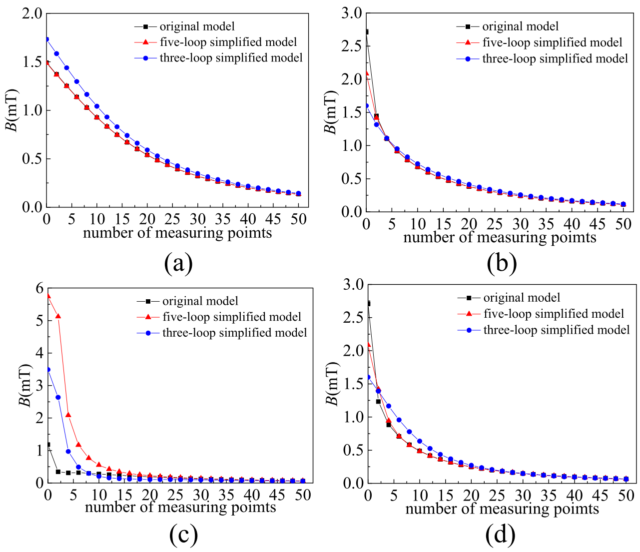


**FIGURE 3. Magnetic induction intensity of the original model,the optimal five-loop simplified model and the optimal three-loop simplified model in four typical directions. (a) ATCB direction. (b) ATSB direction. (c) LTC direction. (d) LTB direction.**

Through calculation, the minimum value of $Q$ is $6.4577 \times 10^{-8}$, and the optimal structural parameter is $n_1 = 110$, $n_2 = 65$, $n_3 = 30$, $a_1 = 83.4$mm, $a_2 = 55.2$mm. However, for the same original model, the error of the optimal structure of the three-ring simplified model is $1.0607 \times 10^{-7}$. The distribution of magnetic induction intensity in 4 typical directions of the original model, the five-ring simplified model and the three-ring simplified model is shown in Fig. 3. It can also be seen that the five-ring simplified model is superior to the three-ring simplified model in terms of magnetic field equivalence. For five-ring simplified model, the SMFD in ATCB, ATSB and LTB directions are very similar to those in the original model, except that the SMFD in the near-field region in the LTC direction are significantly different from those in the original model. The structural differences between the original model and the simplified scaling model lead to the different SMFD. Since the original model is a tightly wound solenoid, the magnetic field is mainly distributed inside the model. However, the simplified model is only composed of five independent coils, and the gaps between the coils lead to large magnetic leakage in the near-field region in the LTC direction, which results in the difference in SMFD in the LTC direction. After calculation, there is only a large error within the distance of 0-$H/5$ in this direction. In practical application, because the large primary equipment is generally located a little farther from the DARs, the errors in the near field area can be ignored.

## IV. SIMULATION OF OPTIMAL STRUCTURE FIVE-LOOP SIMPLIFIED MODEL IN INTER-TURN SHORT CIRCUIT FAULT STATE

In the case of inter-turn short circuit fault, in order to explore the influence rule of short circuit position on the structure of simplified scaling model, 10% short circuit turns were selected, that is, 30 turns, and the short circuit position was adjusted from bottom to top. In order to explore the influence rule of short circuit degree on the structure of the simplified scaling model, the number of short circuit turns was 2%-15%, that is, 5-45 turns, and the short circuit position was 45mm from the bottom of the DARs.

In order to reduce the number of variables, the simplified model in the case of inter-turn short circuit fault can be obtained by adjusting the position of the 2nd coil and the 4th coil in the simplified model under normal conditions. That means that the optimal simplified model in the case of inter-turn short circuit can be determined by calculating the values of $\rho_1$ and $\rho_2$. For the DARs with inter-turn short circuit fault, because the SMFD is asymmetric, 7 directions in a symmetrical position are selected to measure it, that is, ATCT, ATST, ATCB, ATSB, LTT, LTC and LTB.

In this case, to calculate the parameters of the optimal simplified model, it is necessary to minimize the sum of errors in 7 directions. The expression is as follows:

$$Q = Q_{ATCT} + Q_{ATST} + Q_{ATCB} + Q_{ATSB} + Q_{LTT} + Q_{LTC} + Q_{LTB} \tag{10}$$

When the parameters of inter-turn short circuit fault are $L = 25\%$ and $M = 10\%$, the optimal structural parameter is $\rho_1 = 28\%$, $\rho_2 = 20.3\%$. As is shown in Fig.4, the errors in the near-field region in the LTC direction are still ignored, and the equivalent errors in other positions are all less than 0.01mT, which indicates that the SMFD of the simplified model in 7 typical directions is very similar to the original model.

### A. SIMULATION OF SMFD AT DIFFERENT SHORT CIRCUIT POSITIONS

In the simulation, the percentage of short circuit degree is $M = 10\%$, and the variation range of the percentage of short circuit position is $5\% < L < 95\%$. When the short circuit position changes, the relationship between $\rho_1$ and $\rho_2$ in the

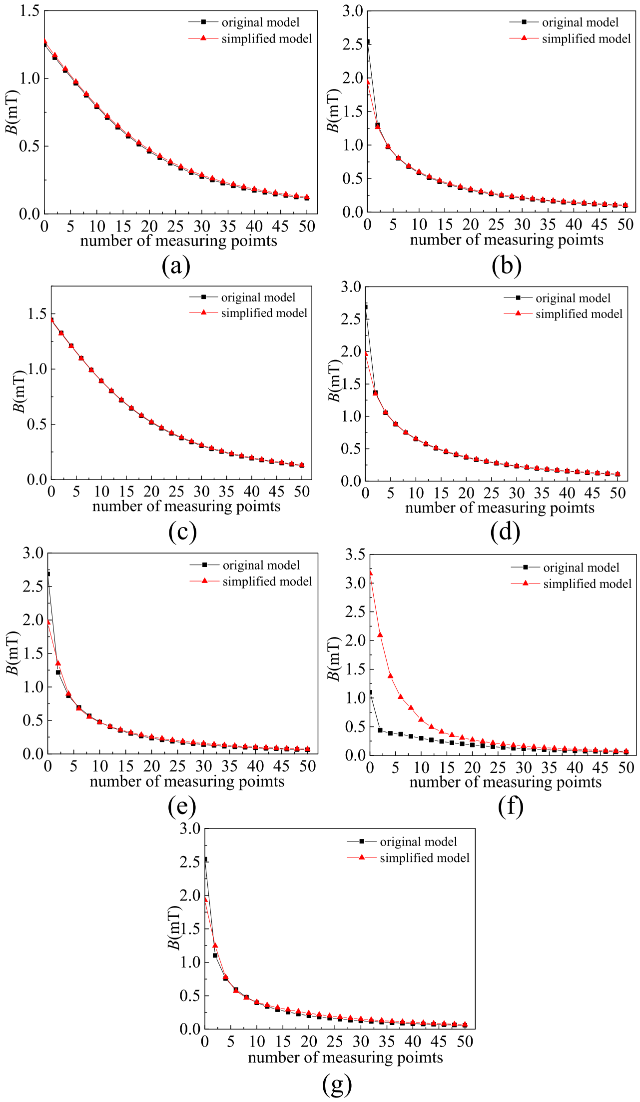


**FIGURE 4.** Magnetic induction intensity of the original model and the optimal five-loop simplified model in seven typical directions. (a) ATCB direction. (b) ATSB direction. (c) ATCT direction. (d) ATST direction. (e) LTT direction. (f) LTC direction. (g) LTB direction.

simplified scaling model is shown in the Fig.5. Taking the short circuit position as the $z$-axis, different colors represent different short circuit positions.

When the short circuit position is determined, $\rho_1$ and $\rho_2$ of the simplified model are positively correlated, and $\rho_2$ increases with the increase of $\rho_1$. At the same time, the optimal model corresponding to different short circuit positions can also be calculated, which means that the structural parameters ($\rho_1$, $\rho_2$) of the optimal simplified model will be uniquely determined. The black curve in Fig.5 shows the ($\rho_1$, $\rho_2$) corresponding to the optimal model for inter-turn short circuit at different positions. Projecting the black curves onto the $xOz$ and $yOz$ planes respectively, the two curves obtained are shown in Fig.6. It could be found that with the short-circuit position moving up, the 4th coil is gradually away from the center, and the 2nd coil is gradually close to

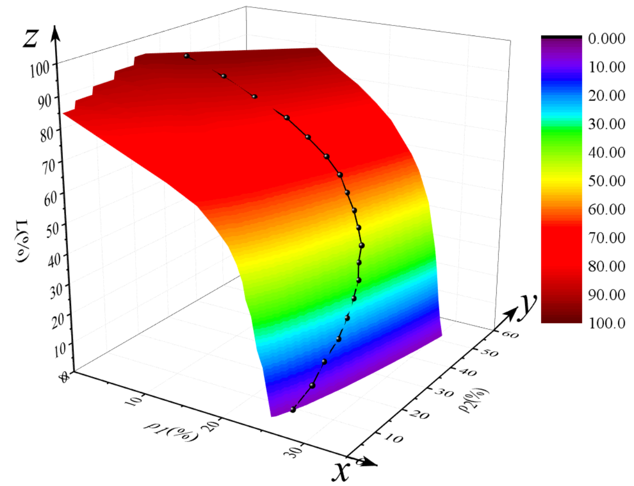


**FIGURE 5.** Relationship between $\rho_1$ and $\rho_2$ as short circuit position varies.

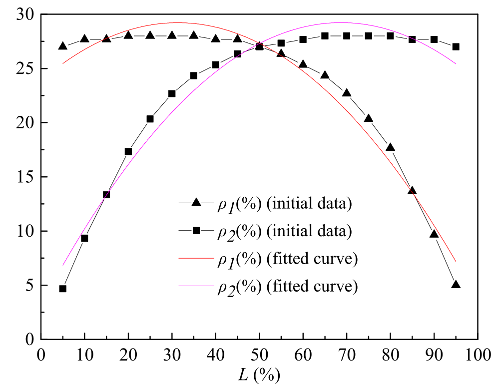


**FIGURE 6.** Relationship between $\rho_1$, $\rho_2$ *and L.*

the center. The change trend of $\rho_1$ and $\rho_2$ is symmetrical and opposite. When the inter-turn short circuit fault occurs in the center of the DARs, $\rho_1$ happens to be equal to $\rho_2$. This is because that the spatial magnetic field is still symmetrically distributed in this case, which requires that the position of the coils must be symmetrical.

$\rho_1$ and $\rho_2$ can be expressed by fitting functions as follows:

$$\begin{cases} \rho_1(\%) = -0.00544L^2 + 0.34047L + 23.88614 \\ \rho_2(\%) = -0.00551L^2 + 0.75791L + 3.185415 \end{cases} \tag{11}$$

$R^2$ generally represents the degree of correlation between the predicted value and the actual value, as shown below:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \tag{12}$$

where total sum of squares $SS_{tot} = \sum_i^n (y_i - \bar{y})^2$, residual sum of squares $SS_{res} = \sum_i^n (y_i - f_i)^2$, and the mean value of actual value $\bar{y} = \frac{1}{n}\sum_i^n y_i$.

As shown in Fig.7, When the inter-turn short circuit fault occurs in the middle part of the DARs, the $R^2$ will

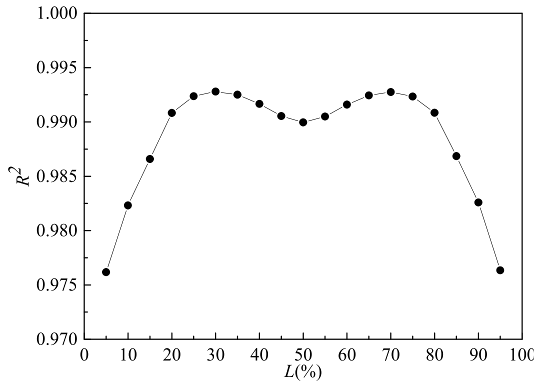


**FIGURE 7.** $R^2$ **as a function of** $L$**.**

increase significantly, and the prediction effect is better at this time. However, when the asymmetry degree of SMFD is the highest, $R^2$ is still above 0.975, which indicates that the overall prediction effect is relatively accurate.

### B. SIMULATION OF SMFD WITH DIFFERENT SHORT CIRCUIT DEGREE

In the simulation, the percentage of short circuit position is $L = 25\%$, and the variation range of the percentage of short circuit degree is $1.67\% < M < 15\%$. When the short circuit degree changes, the relationship between $\rho_1$ and $\rho_2$ in the simplified scaling model is shown in the Fig.8. Taking the short circuit degree as the $z$-axis, different colors represent different short circuit degree.

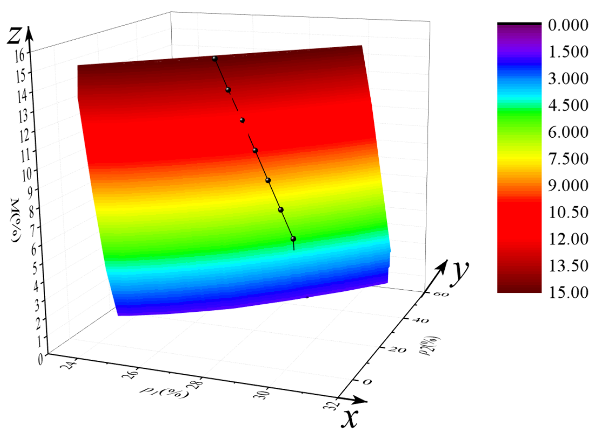


**FIGURE 8.** **Relationship between** $\rho_1$ **and** $\rho_2$ **as short circuit degree varies.**

When the short circuit degree is determined, $\rho_1$ and $\rho_2$ of the simplified model are positively correlated, and $\rho_2$ increases with the increase of $\rho_1$. For different degree of inter-turn short circuit fault, the optimal structural parameters($\rho_1$, $\rho_2$) of the simplified model can be uniquely determined. The black curve in Fig.8 shows the ($\rho_1$, $\rho_2$) corresponding to the optimal model for inter-turn short circuit with different degree. Projecting the black curves onto the $xOz$ and $yOz$ planes respectively, the two curves obtained are shown in Fig.9. With the increase of short circuit degree, both $\rho_1$ and $\rho_2$ show a trend of gradual decrease, and the decrease degree of $\rho_2$ is greater. If the two curves are extended in the opposite direction, it will be found that their intersection happens to be on the $z$-axis. It means that, the DARs will produce symmetrical SMFD without an inter-turn short circuit fault, which requires that the position of the coils must be symmetrical, that is, $\rho_1$ is equal to $\rho_2$.

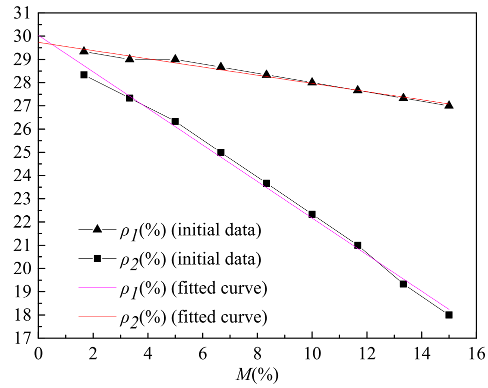


**FIGURE 9.** **Relationship between** $\rho_1$**,** $\rho_2$ ***and M.***

$\rho_1$ and $\rho_2$ can be expressed by fitting functions as follows:

$$\begin{cases} \rho_1(\%) = -0.17667M + 29.73149 \\ \rho_2(\%) = -0.78667M + 30.03703 \end{cases} \tag{13}$$

when there is no inter-turn short circuit fault in the DARs, i.e., $M = 0$, the relation between $\rho_1$ and $\rho_2$ is $\rho_1 = \rho_2 = 30.67\%$. As shown in Fig.9, when $M = 0$, $\rho_1 = 29.73\%$, and $\rho_2 = 30.04\%$, which shows that the equivalent result of the simplified model for the SMFD is accurate.

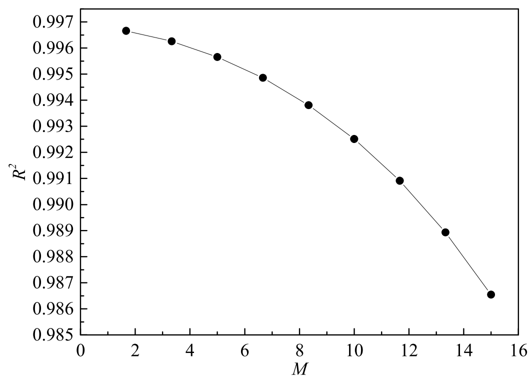


**FIGURE 10.** $R^2$ **as a function of** $M$**.**

Fig.10 shows the relationship between $R^2$ and $M$. It can be found that $R^2$ gradually decreases, with the increase of short circuit degree. However, $R^2$ always remains above 0.985, which indicates that the accuracy of the simplified model in predicting the magnetic field is relatively high.

## V. EXPERIMENT

As is shown in Fig.11, the magnetic field measurement model of the DARs was made in the laboratory. There is a scaling model of DARs in normal operation, as is shown in Fig.11(a), which is a solenoid with 300 turns wound by copper enameled

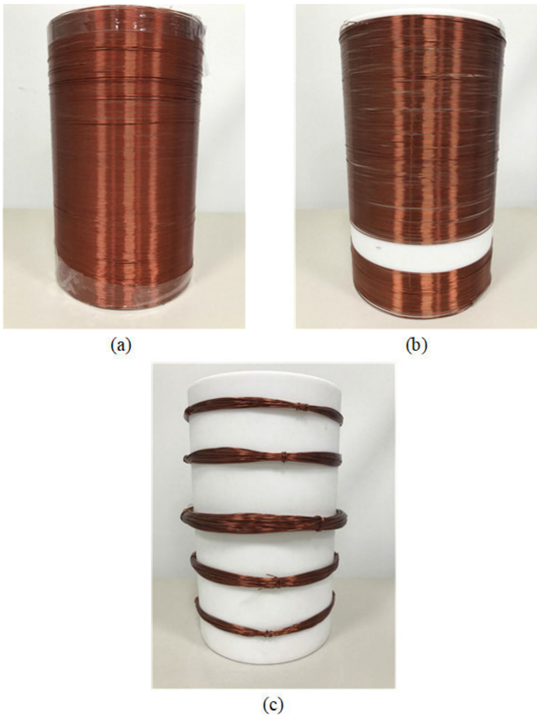


**FIGURE 11.** **Original model with normal working condition, Original model with Inter-turn short circuit fault and simplified model of a single package DAR. (a) Original model with normal working condition. (b) Original model with Inter-turn short circuit fault. (c) simplified model.**

wire with a wire diameter of 0.6mm, i.e., $H = 180$mm. As is shown in Fig.11(b), the method of making the scaling model of DARs with inter-turn short circuit fault is to remove the corresponding number of turns on the basis of the model in Fig.11(a). In this experiment, the short-circuit position is 45mm from the bottom, and the short-circuit degree is 10%, that is, 30 turns. In order to facilitate the experiment, the five-ring simplified scaling model composed of five coils is shown in Fig.11(c). The parameters of the simplified scaling model are $\rho_1 = 40\%$ $\rho_2 = 30\%$, $\rho_1 = 40\%$ $\rho_2 = 20\%$, $\rho_1 = 40\%$ $\rho_2 = 10\%$, $\rho_1 = 30\%$ $\rho_2 = 20\%$, $\rho_1 = 30\%$ $\rho_2 = 10\%$, and $\rho_1 = 20\%$ $\rho_2 = 10\%$ respectively.

The magnetic field measurement diagram is shown in Fig.12. The voltage regulator with an output frequency of $f = 50$Hz provides the current in the model, and the current is measured by the multi-meter in the loop. The Tesla meter is used to measure the intensity of magnetic induction around the model. In the measurement process, it was found that the magnetic induction intensity in the direction of LTC was less than 0.2mT, which was greatly affected by the error. The magnetic induction intensity in the four directions of ATCT, ATST, ATCB and ATSB have similar changing trends, and the magnetic induction intensity in the direction of LTT and LTB have similar changing trends. In order to reduce the complexity of the experiment, ATCT and LTT directions were selected to represent the spatial magnetic field distribution.

During the experiment, the magnetic induction intensity of the original model and the simplified model in the range of 10cm in the direction of ATCT and LTT were measured at equal spacing. In order to ensure the accuracy of the data, the method of repeated measurement 10 times and then averaging was selected. The SMFD of the original model and the 6 simplified models are shown in Fig.13. It can be found that the variation trend of magnetic induction intensity in ATCT and LTT directions of the simplified model with $\rho_1 = 30\%$ $\rho_2 = 20\%$ is the most similar to that of the original model. The parameters of the optimal model in the experiment are very close to the optimal model parameters $\rho_1 = 28\%$ $\rho_2 = 20.3\%$ obtained by computer simulation, which means that the accuracy of the simulation results is verified by the experiment.

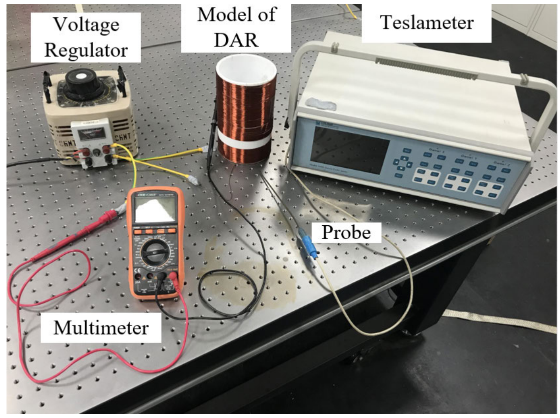


**FIGURE 12.** **Connection diagram of experimental equipment.**

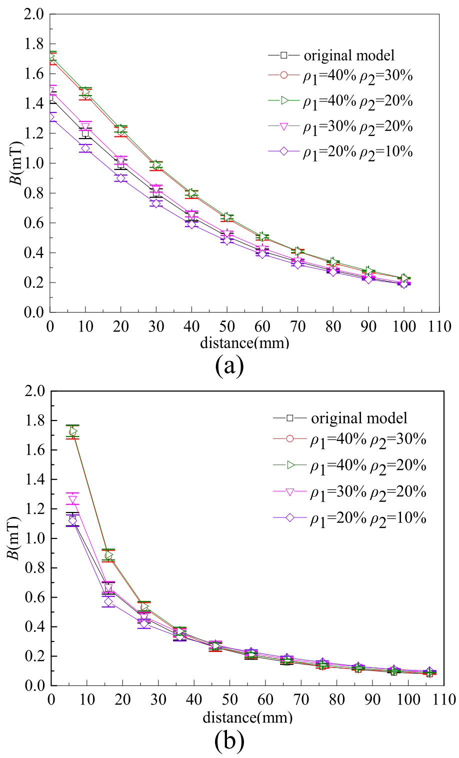


**FIGURE 13.** **SMFD measurement results of the six simplified models and the original model in two directions. (a) ATCT direction. (b) LTT direction.**

## VI. CONCLUSION

A five-ring simplified scaling model was proposed to study the SMFD of DARs when inter-turn short circuit fault occurs. By comparing the magnetic induction intensities in several typical directions of the simplified model, the conclusions of simulation and experiment are as follows:

(1) When the short circuit position changes, the change trend of the position of the 2nd coil and the 4th coil is symmetric and opposite, and the variation rule of their positions with respect to the short circuit position can be described by equation (11). As the short circuit position changes, $R^2$ is above 0.975, which indicates that the overall prediction effect is relatively accurate.

(2) When the short circuit degree changes from small to large, both the 2nd coil and the 4th coil gradually move away from the center. The variation rule of the positions of the two coils on the short-circuit degree can be described by equation (13). With the increase of the short circuit degree, the value of $R^2$ is always above 0.985, which ensures the prediction accuracy of the simplified scaling model.

(3) By measuring the magnetic induction intensity in the typical direction, it is found that the SMFD of the simplified model is closer to the original model when $\rho_1 = 30\%$ $\rho_2 = 20\%$, which is also the closest to the parameter obtained by computer simulation, i.e. $\rho_1 = 28\%$ $\rho_2 = 20.3\%$. Therefore, the accuracy of the simulation is verified by experiments.

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