A Slot Shape Optimization Method for Reducing Motor Stray Losses (Postprint)

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Abstract

Altering slot geometry, as a simple and readily implementable method, is widely applied in the optimization of various performance characteristics of electric motors. This paper investigates an optimal design methodology for rotor slot shapes aimed at reducing motor additional losses. The study first analyzes the relationship between individual rotor slot dimensions and additional losses, performs function fitting to obtain a set of dimensions corresponding to the minimum additional losses, and subsequently iteratively adjusts the dimensional variables according to other motor design requirements to derive optimal slot geometry parameters. This research can provide a reference approach for the optimal design of electric motors.

Full Text

Preamble

A Slot Optimization Method for Reducing Motor Additional Losses

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Abstract

Modifying slot structure is widely employed for optimizing various motor performance metrics due to its simplicity and ease of implementation. This paper investigates an optimization design for rotor slot geometry aimed at reducing motor additional losses. The study first analyzes the relationship between individual rotor slot dimensions and additional losses, performs function fitting to identify the dimension set corresponding to minimum additional loss, and then iteratively adjusts these dimensional variables according to other motor design requirements to obtain optimal slot parameters. This research provides a valuable reference approach for motor optimization design.

Keywords: Additional loss, slot optimization, finite element analysis
Classification: TM315

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1 Introduction

Additional losses in motors encompass all losses beyond fundamental iron losses, fundamental copper losses, and mechanical losses. Due to their complex origins and computational difficulties, current motor design practices rarely establish direct correlations between additional losses and motor dimensions. However, slot geometry dimensions are in fact closely related to motor additional losses. Therefore, this paper discusses an optimization design methodology for rotor slot geometry specifically targeting the reduction of motor additional losses.

2 Calculation Method for Additional Losses

Motor additional losses include harmonic losses in various components and fundamental losses generated by partial leakage flux. Since analytical methods involve numerous empirical coefficients and cannot account for effects such as skin effect, this paper employs the finite element method to calculate motor additional losses, considering only the additional losses in stator/rotor cores and rotor bars.

2.1 Additional Losses in Stator and Rotor Cores

As hysteresis losses in additional losses are negligible compared to eddy current losses, they are omitted. Based on the two-term iron loss model, the total additional losses in the iron core can be expressed as [**?**]:

$$Pc_{ex} = E_{r,n}^2 + E_{\theta,n}^2$$

where n represents the harmonic order (with $n = 1$ denoting the fundamental), and $E_{r,n}$ and $E_{\theta,n}$ are the radial and axial electric field intensities of the n-th harmonic, respectively. k is a correction coefficient with the following expression.

2.2 Additional Losses in Rotor Bars

According to [**?**], the total eddy current loss in rotor bars can be calculated as:

$$P_{eddy\_bar} = L \sum S_{\Delta} J_{\Delta v}^2$$

where S_Δ is the area of each bar element, and $J_{\Delta v}$ is the v-th harmonic current value in each small element of the bar (with $v = 1$ representing the fundamental current).

3 Influence of Rotor Slot Dimensions on Additional Losses

Based on the above analysis, motor additional losses are primarily generated by harmonics and leakage magnetic fields, while variations in rotor slot dimensions affect both the permeance harmonics in the air-gap magnetic field and rotor leakage flux. Since direct analytical establishment of the relationship between individual slot dimensions and additional losses is not feasible, this study compares results across multiple motor models with varying slot dimensions.

Using pear-shaped rotor slots as an example, this paper simulates and calculates motor models with different dimensional variables including rotor slot opening width and height, slot shoulder height, upper-to-lower slot width ratio, and slot depth-to-width ratio. The main motor parameters are listed in Table 1 , the rotor slot geometry is shown in Figure 1 [Figure 1: see original paper], and the calculation results are presented in Figure 2 [Figure 2: see original paper].

Table 1 Main specifications of the motor

Parameter	Value
Rated power (kW)	1000
Rated voltage (kV)	10
Stator outer diameter (mm)	-
Stator inner diameter (mm)	-
Rotor outer diameter (mm)	-
Core length (mm)	-
Number of stator slots (double-layer winding)	-
Silicon steel sheet conductivity (S/m)	2.2×10
Bar conductivity (S/m)	4.7×10

Figure 1 Rotor slot shape and its geometry dimension variables

Figure 2 Additional loss curve along with rotor slot opening

The variation of additional losses with rotor slot opening and slot opening height is shown in Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper], while the variations with slot depth-to-width ratio and upper-to-lower slot width ratio are shown in Figures 5 [Figure 5: see original paper] and 6 [Figure 6: see original paper], respectively.

Figure 3 Additional loss curve along with rotor slot opening height

Figure 4 Additional loss curve along with rotor shoulder height

Figure 5 Additional loss curve along with the depth-width ratio of rotor slot

Figure 6 Additional loss curve along with the upper and lower width ratio of rotor slot

Analysis of these figures reveals that total motor additional losses decrease with increasing rotor slot opening width but increase with slot opening height, primarily due to rotor leakage flux effects. In contrast, the variation trends of additional losses with different rotor slot shoulder heights, depth-to-width ratios, and upper-to-lower width ratios are less pronounced. Therefore, this paper applies fitting functions to model the relationship between each variable and additional losses. The fitted functions are as follows:

$$P_{ad} = 11803.9 b_{s1}^{-0.16}$$

$$P_{ad} = 10804.7 h_{s1}^{0.28}$$

$$P_{ad} = 12791.7 - 833.9 h_{s2} + 120.1 h_{s2}^2$$

$$P_{ad} = 13941.6 - 1260.7 k_1 + 137.2 k_1^2$$

$$P_{ad} = 6314.1 + 15673.6 k_2 - 10176.6 k_2^2$$

4 Optimization Method

After establishing the correspondence between rotor slot dimensions and additional losses, the slot optimization design procedure is summarized in the flow chart shown in Figure 7 [Figure 7: see original paper].

Figure 7 Flow chart of slot optimization design

The dimensions determined from the fitting functions correspond to the minimum additional loss values but may not satisfy other performance requirements in motor design. The determination of rotor slot geometry in motor design must satisfy the following constraints:

1. The rotor tooth and yoke must possess sufficient mechanical strength and rigidity.
2. The magnetic flux density in teeth and yoke must be appropriate, typically 1.25-1.6 T in teeth and approximately 1.0 T in yoke.
3. The current density in rotor bars must be suitable, generally ranging from 2.0×10 to 4.5×10 A/m^2.

Furthermore, rotor slot optimization targeting additional loss reduction should essentially maintain the motor’ s starting and other operational performance characteristics. Based on these requirements, secondary iterative adjustments to the slot dimensions yield the optimized motor geometry.

Applying this method to the motor model in this study produces the following optimized slot dimensions: $b_{s1} = 3.5$ mm, $h_{s1} = 1$ mm, $b_{s2} = 7.92$ mm, $h_{s2} = 3.5$ mm, $b_{s3} = 6.6$ mm, and $h_{s3} = 42.9$ mm. A comparison of additional losses before and after slot optimization is presented in Table 2 .

Table 2 Corresponding additional loss before and after slot optimization

Motor Model	Stator & Rotor Core (W)	Rotor Bars (W)	Total Additional Loss (W)
Before Optimization	-	-	-
After Optimization	-	-	-

The comparison reveals that while stator and rotor core losses increase slightly after optimization, rotor bar losses decrease significantly, resulting in a 21% reduction in total additional loss compared to the pre-optimization design.

The current and torque characteristics before and after optimization are also analyzed. The torque and stator current curves are shown in Figures 8 [Figure 8: see original paper] and 9 [Figure 9: see original paper], respectively. The results indicate that the starting torque decreases slightly after slot optimization, while the maximum torque increases and the rated operating torque remains essentially unchanged. Both starting current and rated operating current remain virtually unchanged. Therefore, this optimization method essentially preserves other motor performance characteristics.

Figure 8 Torque-speed curve of motors before and after the optimization

Figure 9 Stator current-speed curve of motors before and after the optimization

5 Conclusion

This paper presents a slot optimization method for reducing motor additional losses, using a 1000 kW, 10 kV dry-type submersible motor as an example. The results demonstrate that this optimization approach can achieve a 21% reduction in motor additional losses while essentially maintaining other performance characteristics. The method' s advantage lies in its ability to clearly identify the influence of individual slot dimension variables on additional losses and rapidly determine optimal slot dimensions. Its limitation is the lack of universal applicability—the fitting functions cannot be directly determined from motor parameters alone, requiring simulation analysis for different motor models.

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