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Research on the Combination of IE3-IE5 Series Energy-Efficient Three-Phase Induction Motor

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ABSTRACT: Motor energy efficiency has gradually become a research hotspot. In this paper, the optimization analysis of motor energy efficiency is carried out for the widely used three-phase induction motors. Based on keeping the stator and rotor structure parameters unchanged, a reasonable combination of motor steel material, winding type, and bar conductor material can realize the change in motor energy efficiency class. Firstly, the influence of stator and rotor steel materials on iron consumption is analyzed using the triple equation of iron consumption. And the loss distribution and efficiency of DW540, DW470, DW360, DW310, DW270, 1J22, and amorphous alloy materials are discussed. Secondly, the effect of different winding types on the no-load reverse electromotive force is analyzed and discussed, and its simulation model is constructed. The corresponding motor efficiency is summarized. Then, the impact of cast copper and aluminum rotors on energy efficiency is compared and analyzed. Finally, the steel material combinations, winding type, and bar conductor material are classified according to the IE3, IE4, and IE5 energy-efficiency classes. The results show that by choosing the right combination, the motor's energy efficiency can be increased by up to 95.3%.

1. INTRODUCTION

The pursuit of carbon neutrality and the peak of carbon emissions have made the study of energy-efficient motors an increasingly hot topic [1–3]. Induction motors, known for their low cost, high reliability, ease of maintenance, good starting performance, and wide range of speed regulation, are the most commonly used AC motors in the industry. Thus, research on improving the energy efficiency of three-phase induction motor series is of significant practical importance.

In 2008, the International Electrotechnical Commission (IEC) introduced the standard for the "Energy efficiency classification of single-speed, three-phase cage induction motors," establishing a unified benchmark for global motor efficiency. In 2016, the IEC published IEC 60034-30-2 [4], which for the first time defined the IE5 efficiency class values. The international standardization of IE5 class values has spurred companies worldwide to research motors of IE4 and IE5 energy efficiency grades. Siemens, a German company, has designed a series of motors that meet the IE4 energy efficiency class [5]. The Shanghai Engineering and Technology Research Center for Energy Conservation in Electrical Systems Co. Ltd. and several enterprises in China's small and medium-sized motor industry have jointly developed a series of ultra-high efficiency motors with IE4 energy efficiency class [6]. GREE, a famous Chinese electrical appliance company, has developed permanent magnet-assisted synchronous reluctance motors with IE4 and IE5 energy efficiency classes [7].

China's release of the Energy Efficiency Limits and Energy Efficiency Grades for Electric Motors (GB 18613-2020), which specifies the energy efficiency grades for three-phase induction motors [8] and was implemented in June 2021, has been a significant step. Since the implementation date of the standard, China has clearly stated that IE3 efficiency will become the lowest energy efficiency limit for three-phase induction motors. Meanwhile, motors below the IE3 energy efficiency limit will not be produced and sold. The restriction of inefficient motors has further promoted the research on the energy efficiency of induction motors. For the 4 kW 4-pole induction motor used in this paper, the energy efficiency limit value of the IE3 motor is 88.6%; that of the IE4 motor is 91.1%; and that of the IE5 motor is 92.8%. The domestic motor energy efficiency classes correspond to the international classes IE3, IE4, and IE5. The motors that reach the corresponding energy efficiency classes can be called high-efficiency motors, super high-efficiency motors, and ultra-super high-efficiency motors. Improving motor energy efficiency can be achieved by changing the motor pole-slot fit, slot type, winding type, and silicon steel sheet to reduce motor losses and improve motor efficiency [9]. Some researchers [10] have indicated that utilizing high-quality silicon steel for stator cores can significantly decrease iron consumption in stators. Furthermore, by employing the Taguchi method to optimize the stator slot configuration, the efficiency of remanufactured motors was enhanced to IE3. Additionally, other scholars [11] investigated the feasibility of converting low-efficiency three-phase induction motors into permanent magnet motors, achieving IE4 energy-efficiency classification for remanufactured units. However, only a few scholars have re-

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searched improving motor efficiency without altering the structural parameters.

This paper takes a 4 kW 4-pole, three-phase induction motor as an example. Based on keeping the parameters of the stator and rotor steel structure, the changes of stator and rotor steel material, winding type, and bar conductor material are discussed so that the motor can achieve the energy efficiency classes of high efficiency, super efficiency, and ultra-super efficiency. Finally, some plausible combinations that fulfill the IE3, IE4, and IE5 energy efficiency classes are given.

2. INTRODUCTION OF MOTOR STRUCTURE

Some parameters of the three-phase induction motor used in the simulation are shown in Table 1. The schematic diagram of the motor cross-sectional area and specific stator and rotor structure parameters are given in Fig. 1.

TABLE 1. Motor performance and structural parameters.

Parameter	Value	Parameter	Value
Rated power (kW)	4	Length of rotor (mm)	160
Number of poles (2p)	4	Stator outer diameter (mm)	175
Rated slip	0.03	Stator inner diameter (mm)	110
Motor winding	Wye	Rotor outer diameter (mm)	109.3
Stator/Rotor slots	36/28	Rotor inner diameter (mm)	38

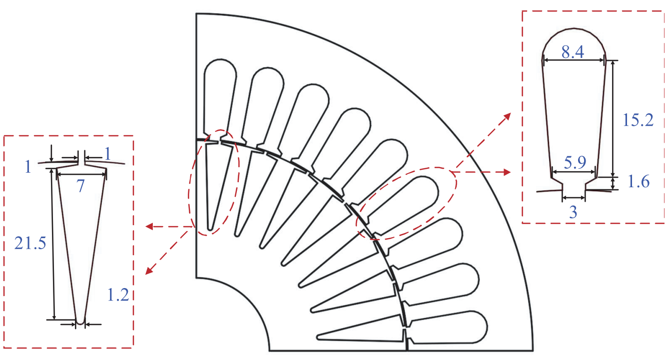

FIGURE 1. Motor cross-section.

To improve motor efficiency, based on the absence of changing the structural parameters of the motor, a standard induction motor model is selected for comparative analysis of different stator and rotor steel materials, winding types, and bar conductor materials.

3. ANALYSIS OF THE INFLUENCE OF STATOR AND ROTOR STEEL MATERIALS ON MOTOR ENERGY EFFICIENCY

During the energy conversion process inside the motor, the energy loss consists of two main components, namely, mechanical and electromagnetic losses [12]. Among them, the mechanical losses are caused by the rotation of the motor rotor and, thus, friction with the air and the motor shaft. The electromagnetic losses are divided into winding copper consumption and iron losses. Iron loss is a critical factor that affects motor efficiency when only the stator and rotor steel material are changed. Various iron loss calculation models have been proposed in a large amount of literature. The more common three-term model for iron consumption is [13, 14]

$$\begin{cases} P_h = k_h f B^2 \\ P_c = k_c (fB)^2 \\ P_e = k_e (fB)^{1.5} \\ P_{Fe} = P_h + P_c + P_e \end{cases} \tag{1}$$

where P_h, P_c, P_e, and P_{Fe} are hysteresis loss, eddy current loss, stray loss, and total iron consumption, respectively; f is the motor frequency; B is the flux density amplitude; k_h, k_c, k_e are hysteresis loss parameter, eddy current loss parameter, and stray loss parameter, respectively, which can be obtained by fitting the loss curve.

Seven materials were selected for the comparative analysis of the stator and rotor steel, including DW540, DW470, DW360, DW310, and DW270 silicon steel materials commonly used in the market, as well as 1J22 and amorphous alloy materials. DW540, DW470, DW360, DW310, and DW270 are cold-rolled non-oriented silicon steel. At a peak magnetic susceptibility of 1.5 T with a frequency of 50 Hz and a sinusoidal waveform, their iron losses are 5.4 W/kg, 4.7 W/kg, 3.6 W/kg, 3.1 W/kg, and 2.7 W/kg, respectively. 1J22 is a high saturation magnetic induction intensity iron-cobalt-vanadium soft magnetic alloy, which has the highest saturation magnetic induction intensity of the existing soft magnetic materials. When making motors of the same power, using a 1J22 stator and rotor silicon steel sheet material can significantly reduce the size. The high Curie point of the material allows the alloy to operate at higher temperatures where other soft magnetic materials have been demagnetized and maintain good magnetic stability. Compared to conventional silicon steel, amorphous alloys have higher resistivity and thinner strip thickness. Therefore, it is much smaller than the thickness of silicon steel sheet materials [15]. Meanwhile, the high resistance suppresses eddy current motion, which reduces the core's current losses so that losses can be reduced [16, 17].

In Table 2, The core losses, total losses, and efficiencies of 7 stator and rotor steel sheet materials are compared by simulation when the winding wiring is a single-layer cross type with pitch 8/7, 2 parallel branches, and the bar conductor material is aluminum. Comparing the results, the highest efficiency of 94.79% is achieved when amorphous alloy material is used for the stator and rotor steels. Its iron loss is significantly smaller than other materials, about 9.92% of the core loss of different materials.

4. ANALYSIS OF THE INFLUENCE OF WINDING TYPE ON MOTOR ENERGY EFFICIENCY

A three-phase alternating current is passed into the stator winding to generate an induced electromotive force whose direction is opposite to the direction of the applied voltage in the winding. The different winding types will affect the motor's efficiency by changing the size of the no-load back potential. Therefore, the

TABLE 2. Loss distribution and efficiency of steel materials.

Steel	k_h	k_c	k_e	Iron loss (W)	Total loss (W)	η (%)
DW540	268	0.82	0	158.01	553.13	87.85
DW470	190	0.82	0	158.62	497.43	88.94
DW360	168	0.82	0	106.76	559.66	87.72
DW310	179	0.40	0	102.17	504.03	88.81
DW270	169	0.10	0	87.01	332.26	92.33
1J22	244	0.18	0	134.15	334.84	92.28
Amorphous alloy	13	0	1.8	12.34	220.12	94.79

stator winding generated back electromotive force is analyzed. The total resultant no-load back electromotive force (EMF) of each phase winding is [18]:

$$E = 4.44 K_{dp} N f \Phi_m \tag{2}$$

where K_{dp} is the winding coefficient; N is the number of series turns per phase; Φ_m is the total flux of a magnetic pole.

The winding coefficient K_{dp} can be expressed as [18]:

$$K_{dp} = K_d K_p \tag{3}$$

$$\begin{cases} K_d = \frac{\sin\left(q\frac{\alpha}{2}\right)}{q\sin\left(\frac{\alpha}{2}\right)} \\ K_p = \sin\left(\frac{\pi}{2}\times\frac{y}{\tau}\right) \end{cases} \tag{4}$$

where K_d is the winding distribution coefficient; K_p is the winding short-distance coefficient; q is the number of slots per pole per phase; α is the electrical angle between two adjacent slots; y is the average coil pitch of the winding; τ is the motor pole distance. In formula (3), K_{dp} is only related to the average coil pitch y of the motor windings when the motor structure parameters do not change.

The expression for N is [18]:

$$N = \frac{\lambda p q N_c}{a} \tag{5}$$

where λ represents the number of winding layers, $\lambda = 1$ for single-layer winding, $\lambda = 2$ for double-layer winding; p is the number of motor poles; N_c is the number of turns per coil; and a is the number of parallel branches.

From the analysis of the above formula, it can be seen that the average coil pitch y, the number of winding layers λ, and the number of parallel branches a will directly affect the no-load back EMF E generated by the stator windings when the motor structure parameters remain, and only the winding mode of the motor is changed. Under constant power operation, the greater the no-load back EMF is, the greater the motor loss is, and the lower the motor efficiency η is. The specific influences are as follows:

a) When $y = \tau$, the value of E is the largest, but η is the smallest.

b) As λ increases, the value of E increases, but η decreases.

c) As a increases, the value of E decreases, but η increases.

From the above analysis, changing the winding type will affect the motor's energy efficiency. On the one hand, a reasonable value of average coil pitch y can weaken the no-load back EMF E. Therefore, the winding type of stator winding is analyzed from three aspects: average coil pitch y, winding layer λ, and parallel branch a.

The windings of three-phase induction motors are classified into various winding types: single-layer winding, double-layer winding, and single-double hybrid winding according to the number of layers of coil sides in the slot, stacked winding, chain winding, concentric winding, cross winding, and concentric cross winding according to the winding connection type. Fig. 2 is a winding wiring diagram. These lines represent the positions of the coils, and the three phases are distinguished by different colors.

To improve energy efficiency, reduce material cost, and lower temperature rise by reducing stray losses, many motors will use single-double hybrid windings in the manufacturing process of three-phase induction motors to improve the market competitiveness of their products [19]. Compared to single-layer and double-layer windings, single-double hybrid windings have the advantages of suitable magnetic field waveform and starting performance and low stray losses. Single-double hybrid winding is a special type of double-layer winding in which the upper and lower conductors of the same phase are replaced by single-layer winding. The upper and lower conductors not belonging to the agreed phase remain in the original double-layer winding.

The different winding types are compared when the steel material is an amorphous alloy, and the cast aluminum rotor is used. The data from the simulation analysis are shown in Table 3. Four classifications of the winding types, namely the number of winding layers, winding type, coil pitch, and the number of parallel branches, were used to obtain a total of 11 winding types.

Combined with the above formulas and the simulation data in Table 3, the average coil pitch, the number of parallel branches, and winding layers of type 2 and type 5 are similar. The final simulation results of the two types are also consistent, verifying that the motor energy efficiency is closely related to the winding type. Type 6 is also consistent with type 8. In addition, different combinations of the number of winding layers, winding connection types, coil pitch, and the number of parallel branches will affect the stator copper loss. The effect of winding type on the energy efficiency of motors is discussed in three separate areas based on different classifications of winding types:

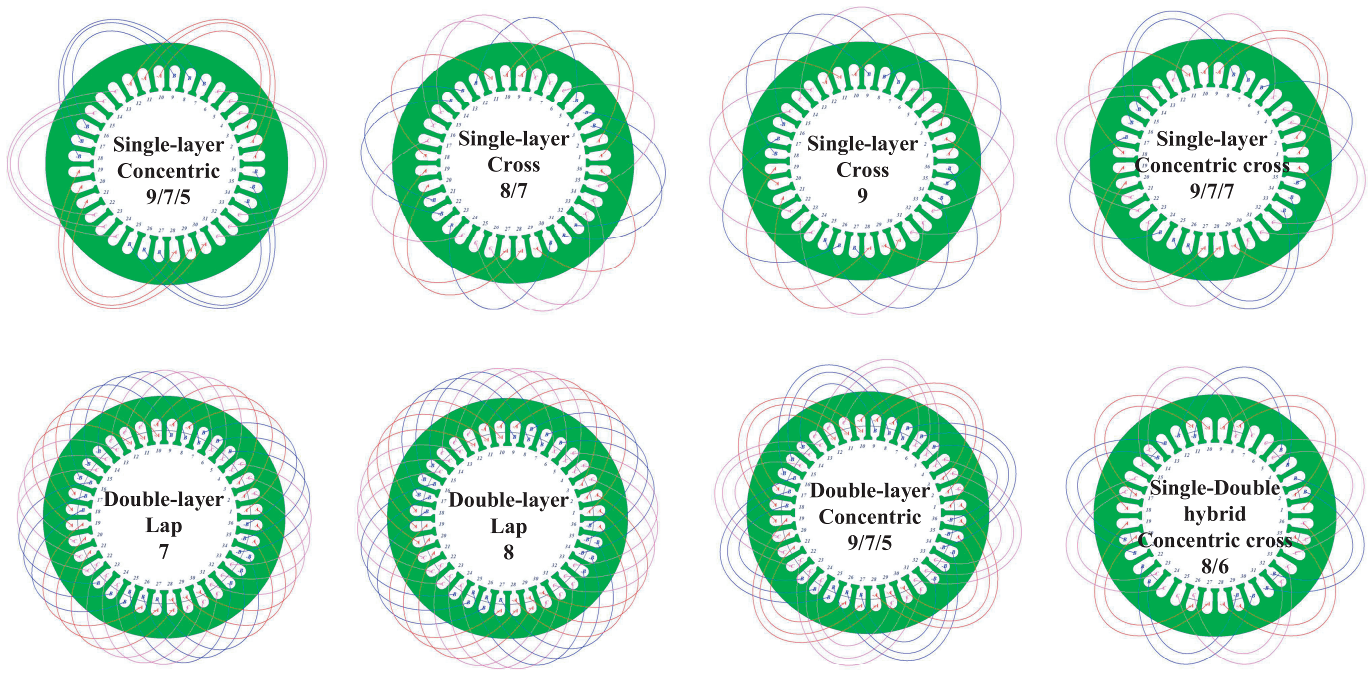

FIGURE 2. Winding diagrams.

TABLE 3. Different winding types of efficiency.

Type	Layer	Winding Connection	Coil Pitch	Parallel Branch	Stator copper loss (W)	η (%)
1	1	Concentric	9/7/5	1	574.74	79.51
2	1	Cross	8/7	1	509.29	82.03
3	1	Cross	8/7	2	108.01	94.79
4	1	Cross	9	1	574.58	79.51
5	1	Concentric cross	9/7/7	1	509.26	82.03
6	2	Lap	7	1	429.72	83.86
7	2	Lap	7	2	110.18	94.87
8	2	Lap	8	1	476.81	82.17
9	2	Lap	8	2	110.18	94.78
10	2	Concentric	9/7/5	1	429.72	83.86
11	2/1	Concentric cross	8/6	1	535.26	80.58

a) From the perspective of average coil pitch, the pole distance of the three-phase induction motor used in this paper is 9; when $y = \tau$, type 4, the motor efficiency is 79.51%, which does not reach the IE3 energy efficiency level. In order to improve the motor energy efficiency, it is necessary to meet $y \neq \tau$.

b) From the view of the number of winding layers, type 1 to type 5 are single-layer windings; type 6 to type 10 are double-layer windings; and type 11 is single-double layer hybrid winding. Compared with the simulation data, the efficiency of single-layer winding is generally higher.

c) Judging from the number of parallel branches, Type 3, type 7, and type 9 are the cases when the number of parallel branches is 2 for type 2, type 6, and type 8, respectively. Their respective comparisons show that the increase in the number of parallel branches is beneficial to reducing stator copper losses and improving the motor's efficiency.

The maximum efficiency of 94.87% was achieved when winding type 7 was selected (i.e., double stacked type with a pitch of 7 and parallel branches of 2).

5. ANALYSIS OF THE INFLUENCE OF BAR CONDUCTOR MATERIAL ON MOTOR ENERGY EFFICIENCY

The choice of bar conductor material for induction motors impacts the design of high-efficiency motors [20, 21]. The resistance of each bar conductor can be expressed as

$$R_b = \frac{K_b l_b \rho_b}{A_b} \tag{6}$$

where l_b is the length of the rotor bar conductors; A_b is the cross-sectional area of the rotor bar conductors; K_b is the coefficient of increase in the resistance of the bar conductors due

TABLE 4. Different bar conductor material efficiency.

Bar	Rotor copper loss (W)	Total loss (W)	η (%)
Al	51.73	216.10	94.87
Cu	33.59	197.34	95.30

TABLE 5. Efficiency-efficient portfolio.

Steel	Bar	Winding Type										
		1	2	3	4	5	6	7	8	9	10	11
DW540	Al	89.05	89.31	87.85	89.05	89.31	81.55	81.09	77.77	86.02	81.55	89.22
DW540	Cu	88.14	88.51	88.37	88.14	88.51	84.76	81.79	82.75	86.57	84.76	88.38
DW470	Al	89.06	89.32	88.94	89.06	89.32	81.37	85.00	76.97	87.53	81.37	89.23
DW470	Cu	88.14	88.51	89.22	88.14	88.51	84.65	85.41	82.52	88.02	84.65	88.38
DW360	Al	89.58	89.84	87.72	89.58	89.84	81.77	79.38	77.84	85.37	81.77	89.75
DW360	Cu	88.50	88.87	88.24	88.50	88.87	85.01	80.36	82.94	86.06	85.01	88.74
DW310	Al	89.63	91.10	88.81	89.63	91.10	81.74	82.04	77.62	86.82	81.74	89.80
DW310	Cu	88.54	88.91	89.07	88.54	88.91	85.01	81.49	82.88	87.42	85.01	88.77
DW270	Al	90.71	90.97	92.33	90.70	90.97	82.11	84.15	77.52	89.03	82.11	90.87
DW270	Cu	89.27	89.64	92.83	89.27	89.64	85.47	84.25	83.19	89.60	85.47	89.50
1J22	Al	89.35	89.62	92.28	89.35	89.62	81.54	91.93	77.31	92.16	81.54	89.52
1J22	Cu	88.34	88.71	92.81	88.34	88.71	84.82	92.33	82.70	92.60	84.82	88.58
Amorphous alloy	Al	79.51	82.03	94.79	79.51	82.03	83.86	94.87	82.17	94.78	83.86	80.58
Amorphous alloy	Cu	83.36	84.47	95.28	83.36	84.47	86.43	95.30	85.23	95.25	86.43	83.08

to the decrease in the effective area of the rotor slots caused by the misalignment of the rotor laminations, which is $K_b = 1.04$ for the cast aluminum rotor, and $K_b = 1$ for the copper bar rotor; and ρ_b is the resistance coefficient of the bar conductor material. Therefore, the choice of bar conductor material will affect the motor's energy efficiency.

Based on the stator and rotor steel materials and winding types discussion, different bar conductor materials were selected using amorphous alloy steel and winding type 7. In Table 4, the analysis compares the effect of cast copper rotor and cast aluminum rotor on the motor's efficiency. The cast copper rotor has 35% less copper loss and 0.43% higher efficiency than the cast aluminum rotor.

6. MOTOR ENERGY EFFICIENCY CLASS PORTFOLIO

Many simulations were conducted, considering the possible interaction between stator and rotor steel materials, winding types, and bar conductor materials. Different combinations were tested to achieve energy efficiency levels, and the data were summarized and classified.

Table 5 shows the energy efficiency combinations for single-layer, double-layer, and single-double hybrid winding, including the efficiency of all combinations of 7 steel materials, 11 winding types, and 2 bar conductor materials. The winding types in the table are abbreviated in Table 3. The efficiency by the energy efficiency level is marked by the bottom color, with green, yellow, and red corresponding to IE3, IE4, and IE5, respectively.

The efficiencies of winding type 2 and type 5 are the same. The stator and rotor steel material for DW540, DW470, and DW360 is the use of type 2 or type 5 and cast aluminum rotor combination of the maximum efficiency, respectively, 89.31%, 89.32%, and 89.84%, and all of them meet IE3 energy-efficiency classes. The DW310 motor, combined with type 2 or type 5 and cast aluminum rotor, has the best efficiency of 91.10%, which is in the IE4 energy-efficiency class, and DW270 and 1J22 motors, with type 3 and copper bar conductors, can achieve the maximum efficiency of the engine, respectively, 92.83% and 92.81%, and both meet the IE5 energy-efficiency class. 95.3%, and IE5 efficiency is achieved with type 7 and a cast copper rotor for amorphous alloys. The combinations of IE3, IE4, and IE5 energy efficiency levels in Table 5 are counted to obtain the distribution of energy efficiency levels for steel material, bar conductor material, and winding type, respectively, as shown in Fig. 3. The distribution of energy efficiency levels can be analyzed from the following three aspects.

From the perspective of steel materials, the better the materials are used, the higher the efficiency is. DW310 appears to meet the combination of IE4 energy efficiency levels. DW270 can achieve IE5 energy efficiency when selecting the right winding type and cage material. Only the combination of amorphous alloy meets the IE5 energy efficiency level, which reflects that the sensible choice of winding type and bar conductor material dramatically influences the steel of amorphous alloy material.

TABLE 6. IE3 energy efficiency class portfolio.

Steel	Layer	Winding Type	Coil Pitch	Parallel Branch	Bar	η (%)
DW540	1	Concentric	9/7/5	1	Al	89.05
	1	Cross	8/7	1	Al	89.31
	1	Cross	9	1	Al	89.05
	1	Concentric cross	9/7/7	1	Al	89.31
	2/1	Concentric cross	8/6	1	Al	89.22
DW470	1	Concentric	9/7/5	1	Al	89.06
	1	Cross	8/7	1	Al	89.32
	1	Cross	8/7	2	Al	88.94
	1	Cross	8/7	2	Cu	89.22
	1	Cross	9	1	Al	89.06
	1	Concentric cross	9/7/7	1	Al	89.32
	2/1	Concentric cross	8/6	1	Al	89.23
DW360	1	Concentric	9/7/5	1	Al	89.58
	1	Cross	8/7	1	Al	89.84
	1	Cross	8/7	1	Cu	88.87
	1	Cross	9	1	Al	89.58
	1	Concentric cross	9/7/7	1	Al	89.84
	1	Concentric cross	9/7/7	1	Cu	88.87
	2/1	Concentric cross	8/6	1	Al	89.75
	2/1	Concentric cross	8/6	1	Cu	88.74
DW310	1	Concentric	9/7/5	1	Al	89.63
	1	Cross	8/7	1	Cu	88.91
	1	Cross	8/7	2	Al	88.81
	1	Cross	8/8	3	Cu	89.07
	1	Cross	9	1	Al	89.63
	1	Concentric cross	9/7/7	1	Cu	88.91
DW270	1	Concentric	9/7/5	1	Al	90.71
	1	Concentric	9/7/5	1	Cu	89.27
	1	Cross	8/7	1	Al	90.97
	1	Cross	8/7	1	Cu	89.64
	1	Cross	9	1	Al	90.70
	1	Cross	9	1	Cu	89.27
	1	Concentric cross	9/7/7	1	Al	90.97
	1	Concentric cross	9/7/7	1	Cu	89.64
	2	Lap	8	2	Al	89.03
	2	Lap	8	2	Cu	89.60
	2/1	Concentric cross	8/6	1	Al	90.87
	2/1	Concentric cross	8/6	1	Cu	89.50
1J22	1	Concentric	9/7/5	1	Al	89.35
	1	Cross	8/7	1	Al	89.62
	1	Cross	8/7	1	Cu	88.71
	1	Cross	9	1	Al	89.35
	1	Concentric cross	9/7/7	1	Al	89.62
	1	Concentric cross	9/7/7	1	Cu	88.71
	2/1	Concentric cross	8/6	1	Al	89.52

TABLE 7. IE4 energy efficiency class portfolio.

Steel	Layer	Winding Type	Coil Pitch	Parallel Branch	Bar	η (%)
DW310	1	Cross	8/7	1	Al	91.10
	1	Concentric cross	9/7/7	1	Al	91.10
DW270	1	Cross	8/7	2	Al	92.33
1J22	1	Cross	8/7	2	Al	92.28
	2	Lap	7	2	Al	91.93
	2	Lap	7	2	Cu	92.33
	2	Lap	8	2	Al	92.16
	2	Lap	8	2	Cu	92.80

TABLE 8. IE5 energy efficiency class portfolio.

Steel	Layer	Winding Type	Coil Pitch	Parallel Branch	Bar	η (%)
DW270	1	Cross	8/7	2	Cu	92.83
1J22	1	Cross	8/7	2	Cu	92.81
Amorph-ous alloy	1	Cross	8/7	2	Al	94.79
	1	Cross	8/7	2	Cu	95.28
	2	Lap	7	2	Al	94.87
	2	Lap	7	2	Cu	95.30
	2	Lap	8	2	Al	94.78
	2	Lap	8	2	Cu	95.25

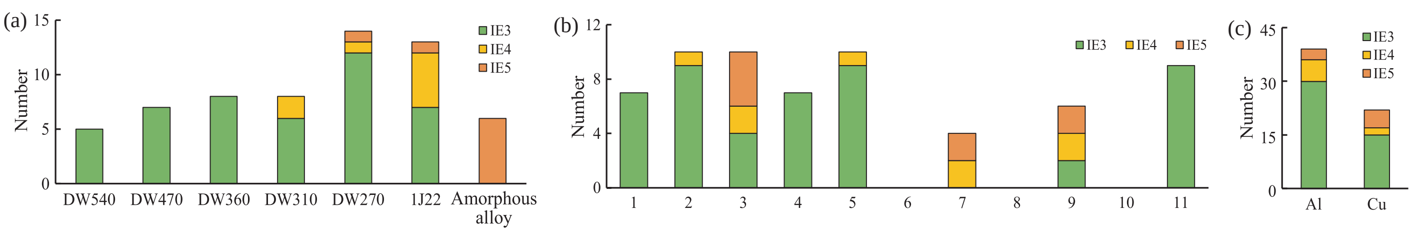

FIGURE 3. Energy-efficiency class distribution map. (a) Steel material. (b) Winding type. (c) Bar conductor type.

Then, regarding winding types, the total number of single-layer windings reaching energy efficiency level is significantly more than double-layer windings. The motor energy efficiency is better when the average coil pitch is not equal to the pole distance. Those that reach IE5 energy efficiency levels are type 3, type 7, and type 9, all of which have a parallel branch number of 2. Therefore, increasing the number of parallel branches helps improve motor efficiency. Among them, type 3 has the most significant number of combinations to achieve IE5 energy efficiency. Therefore, when improving motor efficiency, priority can be given to the single-layer cross type, with a pitch of 8/7 and a winding type with two parallel branches.

To sum up, regarding bar conductor material, the cast aluminum rotor is larger than the cast copper rotor in terms of the total number. However, the cast copper rotor is more significant in the combinations that achieve IE5 energy efficiency levels.

To more clearly summarize the combinations of steel materials, winding types, and bar conductor materials that meet various energy-efficiency classes, the combinations of IE3, IE4, and IE5 energy-efficiency classes are compiled in Table 6, Table 7, and Table 8, respectively.

Comparing Table 6, Table 7, and Table 8, the choice of stator and rotor steel material significantly impacts motor efficiency. For example, for the cast copper rotor motor with 1J22, the winding type is 8/7 coil pitch crossed single-layer winding, and the motor efficiency is 88.71% when the number of parallel branches is 1 to reach the IE3 energy efficiency level and 92.81% when the number of parallel branches is 2 to meet IE5 energy efficiency level. The bar conductor material is more evenly distributed in the above table. Although the cast copper rotor can reduce the rotor copper loss, it has little effect on improving the energy efficiency level of the motor.

To sum up, the motor efficiency is improved by reasonably selecting stator and rotor steel material, winding type, and bar conductor material without changing the stator and rotor structure parameters.

7. CONCLUSION

This paper takes a three-phase induction motor as an example. Under the condition that the stator and rotor structure parameters remain unchanged, the effects of different motor stator and rotor steel materials, winding types, and bar conductor materials on motor energy efficiency are compared. Moreover, the distributions of motor energy efficiency classes for steel materials, winding types, and bar conductor materials are summarized. The analysis shows that there are forty-five combinations to reach IE3, eight combinations to reach IE4, and eight combinations to reach IE5. The reasonable selection of steel material, winding type, and bar conductor material combination can improve the motor's energy efficiency. The final result is the highest efficiency combination: an amorphous alloy cast copper rotor induction motor, 7 coil pitch lapped double-layer winding with 2 parallel branches, is 95.3% efficient and complies with IE5 energy efficiency class.

1) The stator and rotor steel material significantly impact the motor's energy efficiency. The maximum efficiency of DW310 can meet the IE4 energy-efficiency level. The maximum efficiency of DW270 can meet the IE5 energy-efficiency level. Amorphous alloy is the best material, and the core loss is about 9.92% of that of other materials.

2) The winding type has a more significant impact on the motor's energy efficiency. The methods that can be used to improve the motor energy efficiency through the motor winding connection are as follows: select the average coil pitch that is not equal to the pole distance, use single-layer winding, and the number of parallel branches is 2. The 8/7 pitch single-layer cross winding with 2 parallel branches accounts for motors' largest share of energy efficiency.

3) Bar conductor material does not affect the three-phase induction motor's efficiency.

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