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Performance and Efficiency of Redesign Induction Motor Using Asymmetric Windings

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Abstract: This paper investigates the performance and efficiency of redesigning squirrel-cage induction motors using fractional-slot asymmetric windings, particularly when the number of slots per pole per phase results in a fraction whose denominator is a multiple of the number of phases. Under such circumstances, conventional methods for calculating winding factors become ineffective due to the high degree of asymmetry and complex harmonic distribution. To address this challenge, three different winding configurations were proposed and systematically analyzed in terms of harmonic content, winding factors, and magneto motive force symmetry. Electromagnetic simulations were performed using the FLINT software to evaluate and compare their operational performance under rated conditions. The results demonstrated that a partially symmetrized asymmetric winding (Option III) could achieve acceptable thermal, magnetic, and electromagnetic performance, with a predicted decrease in rated power of approximately 12.5% compared to the standard symmetric winding. These findings support the feasibility and potential advantages of using asymmetric windings in motor repair, redesign, and performance optimization for machines up to around 3.5 kW.

Keywords: Asymmetry, Balancing, The denominator of the fraction, Induction motor, Electrical and mechanical characteristic

Introduction

In the practice of repairing asynchronous machines (Lercel et al., 2024), there are situations where performing the rewinding of the stator winding of the motor with a number of poles p, which is a multiple of the number of phases m, is only possible when using asymmetric windings. In this case, it is necessary to determine the changes in the technical parameters of the repaired motor compared to the serial analogy (Bishop, 2022; Anthony et al., 2024). This can be achieved through electromagnetic calculations. The generally accepted approach to performing these calculations, which is based on the traditional representation of winding factors, is not applicable in this case. The formal definition of these factors for each phase (Bukšnaitis, 2009; Dorrell, 2014; Bishop, 2022) does not provide any useful information and does not allow for the correct determination of the winding data of the motor (Jannati et al., 2015).

The main objective of this research is to develop a redesigned induction motor with a different speed and pole number from the original machine by rewinding or replacing its faulty windings. This approach aims not only to restore the motor's operability but also to create a modified machine with new operational characteristics. Special attention is given to evaluating the electromagnetic properties of the redesigned motor and analyzing how the change in pole number influences the harmonic content and its overall performance.

Method

It is known that, under the condition of the fraction denominator **d** being a multiple of the number of phases **m**, it is impossible to create a symmetrical multi-phase winding for the motor. Such asymmetric windings have not found application in serial production of electrical machines (Stock et al., 2023) due to the sharp deterioration of technical parameters such as rated power, winding overheating values, and efficiency. When using such asymmetric windings, the harmonic composition of the magneto motive forces (MMF) of the winding deteriorates sharply, resulting in both forward and reverse rotating harmonics, creating elliptical magnetic fields in the working air gap. The manifestation of these harmonics is especially dangerous with respect to the operating harmonic. As a result, additional losses increase, torque curve dips appear, the non-sinusoidal nature of the electromotive forces (EMF) at the generator terminals increases, and energy and vibro-acoustic indicators decrease, leading to a reduction in power compared to serial machines.

The Proposed Asymmetrical Machine

The study suggests the possibility of applying asymmetric fractional windings in repair production conditions and comparing the extent of their use with serial analogs. To solve this task, it is necessary not only to design a winding with the minimum level of asymmetry, manufacture and place it in the slots of the asynchronous motor, but also to determine its operating properties.

For denominators of the fraction **d** that are multiples of the number of phases **m**, the windings are characterized by an unacceptably high level of asymmetry, primarily concerning the operating harmonic **ν**. To reduce this level, it is necessary to redistribute the active coil sides (ACS) in such a way as to reduce or completely eliminate the asymmetry, at least in the operating harmonic (Esam et al., 2024) This transformation, which involves either transforming the numerical series of the winding (Demir & Aydin, 2016) or changing the number of turns in the coils (Tak et al., 2022), is referred to as symmetrization. The first stage of solving the set task involves designing windings with the minimum possible level of asymmetry. This stage was carried out using the symmetrization method (Marfoli, 2020).

For example, the redesign of the serial asynchronous motor 4A112MV8U3 is considered, which has 48 slots with 2p = 8 poles on the same stator, compared to 2p = 6 poles when p is the number of pole pairs (Demir & Aydin, 2016). In this case, the number of slots per pole and phase in the repaired motor will be: $q = Z / (2\,pm) = 8/3$, where m = 3.

Under these conditions, the possibility arises to design windings with identical numbers of turns in the coils, which are characterized by the following options for the repeating part of the winding's numerical series:

I – 3, 3, 2, 3, 3, 2, 3, 3, 2;
II – 3, 3, 2, 2, 3, 3, 3, 3, 2;
III – 3, 3, 2, 3, 2, 3, 2, 3, 3.

Each of these options corresponds to windings with a possible distribution of phase zones of one layer over half of the winding space from 24 slots (Pyrhonen et al., 2013; Staszak , 2023) (Fig. 1).

Option I
|1| |3| |5| |7| |9| |11| |13| |15| |17| |19| |21| |23| | *№№ Slots*
| *A* | *z* | *B* | *x* | *C* | *y* | *A* | *z* | *B* | *Phase zones*

Option II
|1| |3| |5| |7| |9| |11| |13| |15| |17| |19| |21| |23| | *№№ Slots*
| *A* | *z* | *B* | *x* | *C* | *y* | *A* | *z* | *B* | *Phase zones*

Option III
|1| |3| |5| |7| |9| |11| |13| |15| |17| |19| |21| |23| | *№№ Slots*
| *A* | *z* | *B* | *x* | *C* | *y* | *A* | *z* | *B* | *Phase zones*

Figure 1. Distribution of phase zones 1/2 of the winding with the number of poles 2p = 6 and the number of slots Z = 48 for I, II and III options

The windings distribution map for III option with the phase zones is shown in Fig 2. It is easy to see that the winding in option I is characterized by maximum asymmetry, which is sharply manifested already in relation to the number of active coil sides (ACS) — the phase zones A and C each contain 18 ACS, while phase B contains 12 ACS. In option II, phase zones A and B each contain 15 ACS, while phase C contains 18 ACS. Option III is fully symmetrical in this regard (Joksimović, 2011; Vukosavic, 2012; Hagedorn et al., 2018).

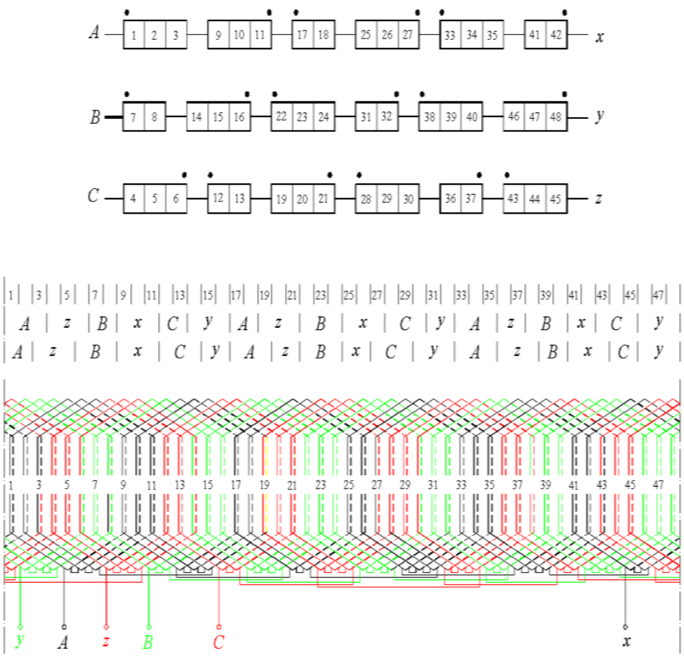

Figure 2. The map for windings distribution with the number of poles 2p = 6 and the number of slots being, Z = 48 for III option.

A comparison of the options in terms of symmetry level with respect to the operating harmonic of the MMF **ν = p = 3** based on vector diagrams (Marfoli, 2020) leads to the following results. In option I, the amplitudes of the MMF are $\mathbf{F_A = F_C = 17.09}$, $\mathbf{F_B = 11.77}$, and their relative shifts are: $\boldsymbol{\varphi_{AB} = \varphi_{CB} = 123.75^o}$, $\boldsymbol{\varphi_{AC} = 112.5^o}$ (Krause et al., 2002; Tang & Brown, 2018)**.** Thus, the amplitude mismatch...

$$\Delta F_{\mathrm{I}} = \frac{F_A - F_B}{F_A} = \frac{17{,}08 - 11{,}76}{17{,}08} = 0{,}31 \qquad (1)$$

In option II, the amplitudes of the resulting MMF vectors are $\mathbf{F_A = F_B = 4.786}$, $\mathbf{F_C = 5.586}$, and their relative shifts are:

$\boldsymbol{\varphi_{AB} = 121.68°}$, $\boldsymbol{\varphi_{CB} = \varphi_{AC} = 119.16°}$. Thus, the amplitude mismatch...

$$\Delta F_{\mathrm{II}} = \frac{F_A - F_C}{F_A} = \frac{4{,}786 - 5{,}586}{4{,}786} = 0{,}16 \qquad (2) \qquad (2)$$

The angular mismatch of the MMF vectors is

$\boldsymbol{\Delta\varphi = 121.68° - 119.16° = 2.52}$

In option III, the amplitudes of the resulting MMF vectors are $\mathbf{F_A = F_C = 15.25}$, $\mathbf{F_B = 15.09}$, and their relative shifts are:

$\boldsymbol{\varphi_{AB} = \varphi_{CB} = 120.875°}$, $\boldsymbol{\varphi_{AC} = 118.25°}$. Thus, the amplitude mismatch...

$$\Delta F_{\mathrm{III}} = \frac{F_A - F_B}{F_A} = \frac{15{,}25 - 15{,}09}{15{,}25} = 0{,}01 \qquad (3) \qquad (3)$$

The angular mismatch of the MMF vectors is $\boldsymbol{\Delta\varphi = 120.875° - 118.25° = 2.62°}$.

Based on the comparison results of the options according to the number of coils in the phases and with respect to the operating harmonic **ν**, option I is immediately excluded. The comparison of options II and III was performed based on a detailed harmonic analysis, which relies on the representation of the symmetrical components of the winding factors **Kwdv**, **Kwrv** (Tak, 2022), using the corresponding program (Bukšnaitis, 2009) implemented in the MathCAD environment (Table 1), where:

v – harmonic order;
Kwdv – winding factors for the forward sequence of the **v**-th order harmonic;
Kwrv – winding factors for the reverse sequence of the **v**-th order harmonic;

$H_{(d.r)v} = \frac{K_{wv} \cdot P}{K_{wp} \cdot V}$– relative amplitude of the MMF for the forward and reverse sequence of the **v**-th order harmonic, respectively.

Table 1.Comparative harmonic analysis of II and III options of windings

N	kwdvII	kwrvII	HdvII	HrvII
Option II				
3	0.947	0.042	1.000	0.045
9	0.052	0.011	0.018	0.004
15	0.154	0.012	0.033	0.003
21	0.062	0.086	0.009	0.013
Option III				
1	0.0409	0.0134	0.1290	0.0423
3	0.9502	0.0051	1.0000	0.0053
5	0.0416	0.0231	0.0263	0.0146
7	0.0081	0.0313	0.0037	0.0141
9	0.0129	0.0205	0.0045	0.0072
11	0.0184	0.0231	0.0053	0.0066
13	0.0346	0.0374	0.0084	0.0091
15	0.0378	0.1677	0.0082	0.0353
17	0.0275	0.0409	0.0102	0.0102
19	0.0346	0.0027	0.0115	0.0009
21`	0.1045	0.0205	0.0157	0.0030
23	0.0395	0.0081	0.0108	0.0022

I will conduct a comparative analysis under the assumption that the specified windings are intended to be placed in the slots of the stator of a short-circuited asynchronous motor designed for long-term operation in the motor mode. In this case, for symmetrical windings, the greatest danger is posed by the forward-rotating higher harmonics, as they can cause dips in the motor torque curve **M** and deteriorate the starting and overload characteristics of the motor. A comparison of the data shows that, despite the higher number of such harmonics in option III, it is preferable to option II for the most significant higher harmonics (**Hd5 = 0.0263** and **Hd21 = 0.0157**), whereas the most significant harmonics in option II are **Hd15 = 0.033** and **Hd9 = 0.018**.

Furthermore, the winding of option III is characterized by a slightly higher winding factor for the operating harmonic: **Kwd3 = 0.9504** compared to **Kwd3 = 0.947**, which should result in improved energy performance. The presence of a relatively significant lower harmonic with a relative amplitude of **Hd1 = 0.129** will slightly reduce this advantage but will contribute to some increase in the torque in the motor mode. However, the main drawback of the second option lies in the possibility of creating a fairly noticeable reverse-rotating magnetic field for the operating harmonic, with a relative amplitude of **4.5% (Hd1 = 0.045)** of the main harmonic.

The negative impact of higher harmonics on the starting characteristics of low-power asynchronous motors is minimal, but the asymmetry of the operating harmonic will cause a sharp deterioration in these characteristics regardless of the machine's size. As a result of the analysis, the winding of option III was selected for real use.

In the next stage, it is necessary to choose software that allows for an adequate determination of the operating properties of asynchronous motors with the windings of options II and III. The software should meet the following requirements:

- The subroutine for calculating winding factors must correspond to their interpretation outlined in (Tak et al., 2022), i.e., it should be based on the method of symmetrical components.

- It must be able to calculate the specified factors. The software that meets these requirements is the electromagnetic calculation program for short-circuited asynchronous motors, **FLINT** (Tak et al., 2022).

The correctness of selecting this program will be verified by testing two serial asynchronous motors: **4A112MV8** and **4A112MV6** (Table 2, where **P2н** is the rated power of the motor, **$I_{1Ф}$** is the phase current, **η** is the efficiency, **$n_н$** is the rated speed of the motor, **K_M** is the multiplicity of the maximum torque of the motor, and **$K_П$** is the multiplicity of the starting torque of the motor).

Table 2. (*a)* and (*b),* Comparative data of two serial asynchronous motors: 4A112MV8 and 4A112MV6

	P_{2N} kW	I_{1ph} A	η %	Cosφ
	Motor data4A112MB8			
Reference Serial (Kravchik et al., 2022)	3.0	7.72	79.5	0.74
Calculated	3.0	7.33	79.5	0.78
The relative discrepancy Δ%	0	5	0	5
	Motor data4A112MB6			
Reference Serial (Kravchik et al., 2022)	4.0	9.12	82	0.81
Calculated	4.0	8.99	82.4	0.817
The relative discrepancy Δ%	0	1	0.4	0.8

a

	N r.p.m	K_M	$K_п$
	Motor data4A112MB8		
Reference Serial (Kravchik et al., 2022)	707	2.2	1.90
Calculated	712	2.22	1.89
The relative discrepancy Δ%	0.7	1	0.1
	Motor data4A112MB6		
Reference Serial (Kravchik et al., 2022)	953	9.12	82
Calculated	951	8.99	82.4
The relative discrepancy Δ%	0.2	1	0.4

b

The relative discrepancies between the reference and calculated data do not exceed 5%, which is quite acceptable for engineering calculations and allows the use of the specified program for computational experiments. For this experiment, the motor **4A112MV8** was chosen as the base, where the replacement of the symmetrical serial winding with options II and III of asymmetric windings was considered. The nominal power **P2н = 3.5 kW** was selected based on the conditions for maintaining the multiplicities of the starting and maximum torques and the level of stator winding overheating.

In the first stage, the mechanical characteristics were calculated for the cases of applying the II and III winding options in the studied motor. The dependencies *MIII = f(s)* and *MII = f(s)* were calculated for applying option III and option II, where **s** is the slip of the asynchronous motor (Fig. 3). As can be seen from the comparison of these dependencies, the use of option II results in a sharp (11%) decrease in the maximum torque **M_{II}**, as was determined by the results of the analysis.

Therefore, in the subsequent calculations, option II for the winding was not considered, and the operating characteristics were determined only for the motor with the winding from option III, where **P_1** is the consumed power, **P_2** is the useful power at the shaft (Fig. 4). The main nominal data were obtained from the calculation results (Table 3).

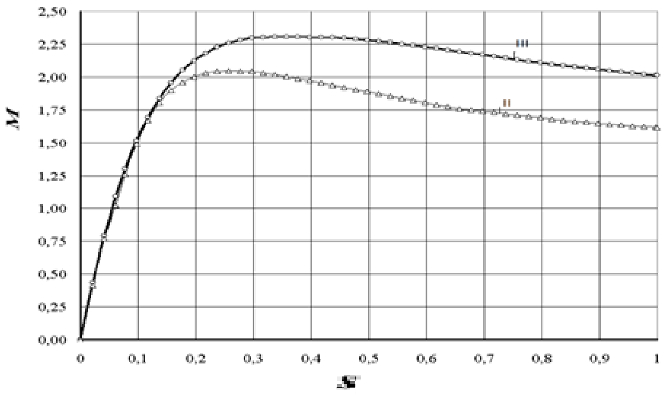

Figure 3. Starting characteristic M = f(s) of the motor with windings of options II and III.

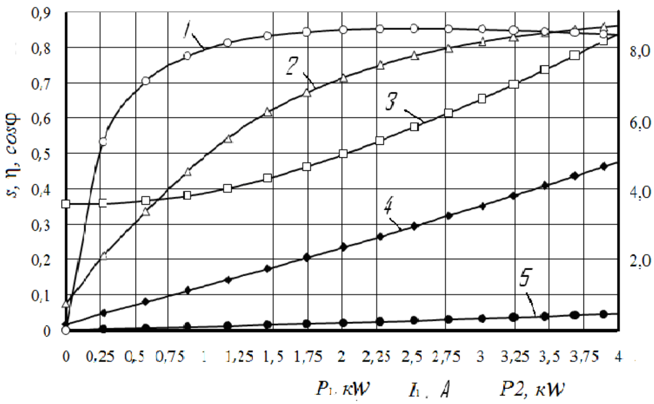

Figure 4. Operating characteristics of the motor 4A112MB6: η(1), cosφ(2), I1Φ(3), P2(4), S(5)..

The overheating of the symmetrized stator winding in option III was 60°C, while the corresponding values in the serial motors 4A112MB6 and 4A112MB8 were 75°C and 70°C, respectively.

Table 3. (a) and (b) Comparative data of the nominal parameters of the compared motors.

	P2N kW	I1ph A	η %	Cosφ
Motor data4A112MB6				
Reference Serial (Kravchik et al., 2022)	4.0	9.12	82	0.81
Estimated Serial	4.0	8.99	82.4	0.817
Estimated selected	3.5	7.4	84.0	0.85

a

	N r.p.m	KM	Kп
Motor data4A112MB6			
Reference Serial (Kravchik et al., 2022)	953	2.5	2.0
Estimated Serial	951	2.49	2.0
Estimated selected	949	2.4	2.0

b

Results and Conclusion

This study explored the performance and efficiency of a redesigned squirrel-cage induction motor using asymmetric windings as a rewinding technique. The results demonstrated that by selectively increasing the number of turns in one of the stator coil sides, it is possible to alter the magnetic field distribution and improve certain aspects of motor behaviour. Experimental tests showed that the redesigned motor retained acceptable torque and efficiency levels while potentially offering cost-effective and resource-saving benefits during the rewinding process. The method also opens the door for simplified control of motor speed and direction in specific applications.

However, this study is subject to several limitations. The proposed asymmetric winding configuration was tested only on a three-phase, small-capacity squirrel-cage induction motor (up to 3.5 kW), which may limit the generalizability of the results to higher-power machines. In this case, the expected decrease in nominal power will be approximately 12.5%. Additionally, the analysis primarily focused on steady-state performance and did not extensively cover dynamic behavior under varying loads or starting conditions. Thermal effects and long-term reliability aspects of the rewound motor were not examined in detail. Finally, the study did not account for cost-benefit analysis or manufacturing constraints, which may influence the practical adoption of the proposed rewinding technique in industrial settings.

Future research can address these limitations by expanding testing to a broader range of motor types and power ratings, analyzing dynamic and thermal performance, and conducting durability assessments under industrial load conditions. Furthermore, integration with modern control systems or power electronics may reveal additional benefits or applications of the asymmetric winding concept.

Scientific Ethics Declaration

* The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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