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Power Indexes of Induction Motors and Electromagnetic Efficiency their Windings

J. Bukšnaitis
Department of Agroenergetics, Lithuanian University of Agriculture,
Akademija, LT – 53361 Kaunas distr., Lithuania, phone: +370 7 397529, e-mail: juozas.buksnaitis@lzuu.lt

Introduction

Large part of electrical energy used is transformed into mechanical energy in the electric drives of various machines and devices. Three-phase cage rotor induction motors are used to transform the energy in these drives since their construction is simple, they are most reliable during exploitation, have the least relative weight and are least expensive. Three-phase stator winding is one of the most important construction parts of these engines. Main energy interchange processes take place in this winding therefore it essentially determined the operation of the motor.

When electric currents forming the symmetric three-phase system of the currents flow through the three-phase winding of induction motor they create non-sinusoidal magnetic fields which move in space and periodically change their shape in the course of time. Usually only odd space harmonics except for the multiples of three exist in the harmonic spectrum of these non-sinusoidal magnetic fields.

There are many different constructions of the three-phase windings of induction motors and each of them have distinctive parameters [1, 2]. Therefore harmonic spectrum of the magnetic fields created by these windings and at the same time the electromagnetic properties differ and they in turn determine the power indexes and operation quality of induction motors [3]. Electromagnetic efficiency factor is used to evaluate electromagnetic properties of three-phase windings [4].

The aim of this paper is to perform a theoretical analysis of electromagnetic efficiencies of two types of three-phase windings and to relate them theoretically and experimentally to the power indexes of particular induction motors.

Object of research

Standard dimensioned 1,5 kW three-phase induction motor with single-layer former winding and the same motor with stator winding replaced with sinusoidal winding is investigated in this work. Common parameters of stator for both motors are the following: number of phases $m = 3$; number of stator magnetic circuit slots $Z = 24$; number of poles $2p = 2$; number of pole and phase slots $q = Z/(2p\,m) = 24/(2 \cdot 3) = 4$; pole pitch $\tau = Z/2p = 24/2 = 12$; slot span expressed in electrical degrees $\alpha = 360^\circ p/Z = 360^\circ \cdot 1/24 = 15^\circ$. The relative magnitude of number of turns of any coil for the single-layer former winding sections with four coils is $N_1^* = 1/q = 1/4 = 0{,}25$. Relative magnitudes of number of turns of any section in sinusoidal winding calculated according corresponding formulas [4] are obtained: $N_{21}^* = 0{,}114$; $N_{22}^* = 0{,}1862$; $N_{23}^* = 0{,}13165$; $N_{24}^* = 0{,}06815$.

Distribution of elements of the analyzed windings is given in Tables 1 and 2.

Table 1. Distribution of elements of single-layer former three-phase winding

Phase alteration	U1	W2	V1	U2	W1	V2
Number of coils in a section	4	4	4	4	4	4
Slot No.	1; 2; 3; 4	5; 6; 7; 8	9; 10; 11; 12	13; 14; 15; 16	17; 18; 19; 20	21; 22 23; 24

Table 2. Distribution of elements of sinusoidal three-phase winding

Phase alteration		U1	W2	V1	U2	W1	V2
Number of coils in a section		4	4	4	4	4	4
Slot No.	Z	1; 2; 3; 4	5; 6; 7; 8	9; 10; 11; 12	13; 14 15; 16	17; 18 19; 20	21; 22 23; 24
	Z'	10; 11 12; 13	14; 15 16; 17	18; 19 20; 21	22; 23 24; 1	2; 3; 4; 5	6; 7; 8; 9

Relative magnitudes of the instantaneous values of electric currents in both windings in time moment $t = 0$ are $i_U^* = \sin 0^\circ = 0$; $i_V^* = \sin 120^\circ = 0{,}866$; $i_W^* = \sin 240^\circ = -0{,}866$. Conditional magnetomotive force changes $\Delta F = i^* N^*$ in the slots of magnetic circuit of the stator in time moment $t = 0$ (Tables 3 and 4) are calculated according to the determined number of coil turns and relative magnitudes of electric currents by using the layouts of electric circuits of the analyzed windings.

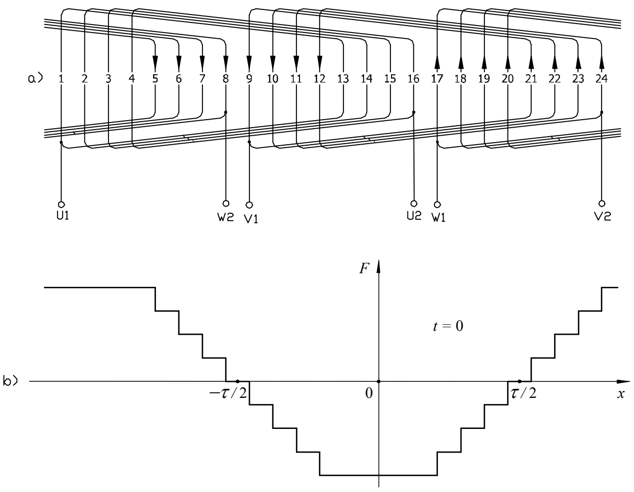

Fig. 1. Electrical circuit layout of single-layer former three-phase winding, with q = 4, (a) and the distribution of their rotating magnetomotive force in time moment t = 0 (b)

Electric circuit layout of the sinusoidal three-phase winding is formed according to the data presented in Table 2 (Fig. 2, a).

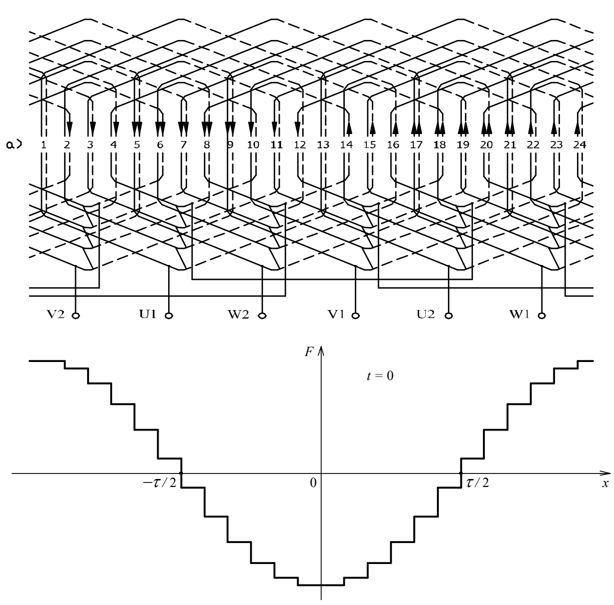

Fig. 2. Electrical circuit layout of sinusoidal three-phase winding, with q = 4, (a) and the distribution of their rotating magnetomotive force in time moment t = 0 (b)

Table 3. Conditional changes of magnetomotive force in slots of single-layer former three-phase winding in time moment t = 0

Slot No.	1	2	3	4	5
ΔF	0	0	0	0	–0,216

Table 3 (continued)

6	7	8	9	10	11	12
–0,216	–0,216	–0,216	–0,216	–0,216	–0,216	–0,216

Table 4. Conditional changes of magnetomotive force in slots of sinusoidal three-phase winding in time moment t = 0

Slot No.	1	2	3	4	5	6
ΔF	0	–0,059	–0,114	–0,1613	–0,1975	–0,220

Table 4 (continued)

7	8	9	10	11	12
–0,228	–0,220	–0,1975	–0,1613	–0,1140	–0,0590

Space distributions of rotating magnetomotive force in the defined moment of time are determined according to the results from Tables 3 and 4 (Fig. 1., b and Fig. 2, b).

Research method

On the base of Fig. 1, b and Fig. 2, b, the amplitude value of rotating magnetomotive force of the υ-th harmonic $F_{m\nu}$ is calculated using this analytical expression [4]:

$$F_{m\nu} = \frac{4}{\pi\,\nu}\sum_{i=1}^{k} F_{is}\,\sin(\nu\,\beta_i/2); \qquad (1)$$

here k – number of rectangles forming the half-period of rotating magnetomotive force; F_{is} – height of the i-th rectangle of the stair-shaped magnetomotive force; β_i – width of the i-th rectangle of the stair-shaped magnetomotive force expressed in electrical degrees of the fundamental space harmonic; υ – number of harmonic.

Then relative magnitudes of harmonics of rotating magnetomotive force are calculated on the base of results of harmonic analysis of rotating magnetomotive force functions (Fig. 1, b and Fig. 2, b) [4]:

$$f_\nu = F_{m\nu} / F_{m1}\ ; \qquad (2)$$

here F_{m1} – amplitude value of the first (fundamental) harmonic of rotating magnetomotive force.

Electromagnetic efficiency factors of the considered three-phase windings are calculated according to this expression [4]:

$$k_{\text{ef}} = 1 - \sqrt{\sum_{\nu=1}^{\infty} f_\nu^2 - 1}\ . \qquad (3)$$

All power indexes of the standard dimensioned induction motor with single-layer former winding and motor with stator winding replaced with sinusoidal three-phase winding are calculated after completing their no-load and load tests of the motor by using the segregated-losses method. Respective power indexes of asynchronous motors are compared under the indicated load.

Research results

According to the expression (1) and determined parameters of rotating magnetomotive force half-period (k = 4; $F_{1s} = -0{,}2165$; $F_{2s} = -0{,}2165$; $F_{3s} = -0{,}2165$; $F_{4s} = -0{,}2165$; $\beta_1 = 165^\circ$; $\beta_2 = 135^\circ$; $\beta_3 = 105^\circ$; $\beta_4 = 75^\circ$) the harmonic analysis of instantaneous rotating magnetomotive force function (Fig. 1, b) of single-layer former three-phase winding (Fig. 1, a) was completed and relative magnitudes of its space harmonics were calculated (Table 5).

Table 5. Results of harmonic analysis of the instantaneous rotating magnetomotive force function of the single-layer former three-phase winding with q = 4 and relative magnitudes of its space harmonics

υ	1	5	7	11
$F_{m\upsilon}$	–0,914	0,0390	0,0210	–0,0110
f_υ	1	0,0429	0,0235	0,01197

Table 5 (continued)

13	17	19	23	25
–0,0090	0,0090	0,0100	–0,0400	0,0370
0,01013	0,00968	0,01129	0,0435	0,0400

According to expression (1) and determined parameters of rotating magnetomotive force half-period ($k = 6$; $F_{1s} = -0{,}1140$; $F_{2s} = -0{,}2203$; $F_{3s} = -0{,}1975$; $F_{4s} = -0{,}1613$; $F_{5s} = -0{,}1140$; $F_{6s} = -0{,}0590$; $\beta_1 = 180^\circ$; $\beta_2 = 150^\circ$; $\beta_3 = 120^\circ$; $\beta_4 = 90^\circ$; $\beta_5 = 60^\circ$; $\beta_6 = 30^\circ$) the harmonic analysis of the instantaneous rotating magnetomotive force function (Fig. 2, b) of the sinusoidal three-phase winding (Fig. 2, a) was performed and relative magnitudes of its space harmonics were calculated (Table 6).

Table 6. Results of harmonic analysis of the instantaneous rotating magnetomotive force function of the sinusoidal three-phase winding with q = 4 and relative magnitudes of its space harmonics

υ	1	5	7	11	13	17	19	23	25
$F_{m\upsilon}$	–0,871	0	0	0	0	0	0	0,0380	–0,035
f_υ	1	0	0	0	0	0	0	0,0436	0,0402

According to expression (3) the respective electromagnetic efficiency factors k_{ef} of the single layer former and sinusoidal three-phase windings with q = 4 are calculated: k_{ef1} = 0,9139; k_{ef2} = = 0,9335. Electromagnetic efficiency factor of the sinusoidal three-phase winding is obtained by 2,14 % higher than in case of single-layer former winding.

Experimental tests of the standard dimensioned asynchronous motor with the researched single-layer former winding and motor with stator winding replaced with sinusoidal three-phase winding (under no-load and load conditions) were performed and power indexes of analyzed motors were calculated according to received results using the segregated-losses method [5] (Tables 7 and 8).

Table 7. Experimental and calculation results of the standard dimensioned asynchronous motor with single-layer former winding

No.	I_1, A	P_1, W	n, min^{-1}	M, Nm	ΣP W	P_2, W	η %	cos φ
1	1,75	405	2983	0,586	315	90	22,2	0,351
2	2,03	840	2961	1,93	333	507	60,4	0,627
3	2,30	1110	2945	2,71	361	749	67,5	0,731
4	2,70	1410	2924	3,61	402	1008	71,5	0,791
5	3,13	1725	2899	4,50	457	1268	73,5	0,835
6	3,65	2100	2870	5,55	535	1565	74,5	0,872
7	4,13	2370	2851	6,23	610	1760	74,3	0,869
8	4,98	2805	2810	7,38	741	2064	73,6	0,853

Table 8. Experimental and calculation results of the asynchronous motor with stator winding replaced with sinusoidal three-phase winding

No.	I_1, A	P_1, W	n, min^{-1}	M, Nm	ΣP, W	P_2, W	η %	cos φ
1	1,80	385	2948	0,83	232	153	39,7	0,324
2	2,20	1215	2923	3,31	298	917	75,5	0,837
3	2,50	1440	2902	3,95	337	1103	76,6	0,873
4	2,87	1695	2882	4,65	387	1308	77,2	0,895
5	3,03	1800	2868	4,92	419	1381	76,7	0,900
6	3,35	1995	2847	5,45	472	1523	76,3	0,902
7	3,60	2145	2825	5,83	522	1623	75,7	0,903
8	3,95	2345	2798	6,33	596	1749	74,6	0,899
9	4,50	2655	2756	7,08	718	1937	73,0	0,894

In Tables 7 and 8 I_1 – phase current of stator winding; P_1 – consumed power; n – rotational speed of rotor; M – electromagnetic torque; ΣP – total power losses of motor; P_2 – useful power; η – efficiency; cos φ – power factor.

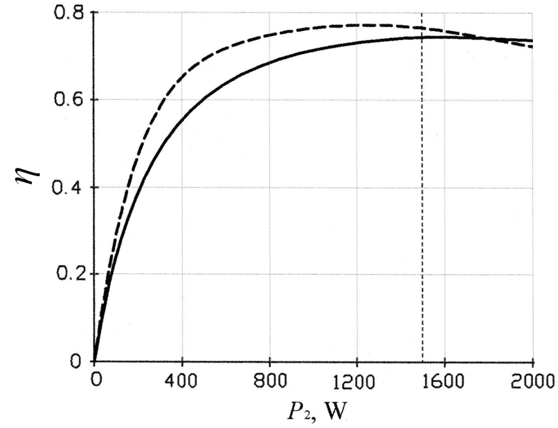

Fig. 3. Diagrams of function η = f(P_2) of the standard dimensioned motor (——) and motor with stator winding replaced (– – –)

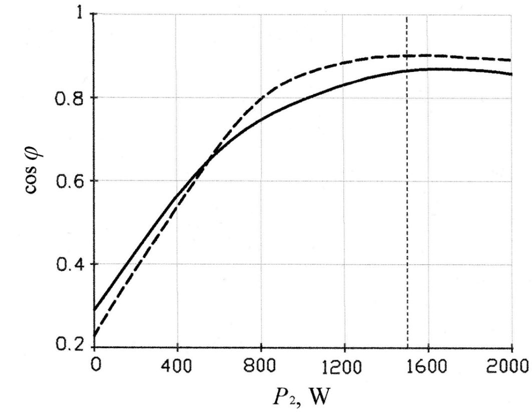

Fig. 4. Diagrams of function cos φ = f(P_2) of the standard dimensioned motor (——) and motor with stator winding replaced (– – –)

After comparing experimental and calculation results under indicated load from Tables 7 and 8 it is received that in case of asynchronous motor with stator winding replaced with sinusoidal three-phase winding the phase current of the stator winding decreased by 6,9 %, power taken from electric grid decreased by 5,0 %, power losses decreased by 11,7 %, efficiency factor increased by 2,4 % and power factor increased by 3,4 %.

Conclusions

- Electromagnetic properties of the three-phase windings can be evaluated by performing harmonic analysis of the rotating magnetomotive force created by them and by calculating electromagnetic efficiency factors based on the results of this analysis.

- It was determined theoretically that electromagnetic efficiency factor of the single-layer former three-phase winding k_{ef1} = 0,9139 and of sinusoidal three-phase winding – k_{ef2} = 0,9335, i.e. by 2,14 % higher than respective factor of the first winding.
- In case of induction motor with sinusoidal three-phase winding under the indicated load the phase current of the stator winding decreased by 6,9 %, power taken from electric grid decreased by 5,0 %, power losses decreased by 11,7 %, efficiency factor increased by 2,4 % and power factor increased by 3,4 % compare to the respective power indexes of the same motor with single-layer former winding obtained under the same load.
- Induction motors with the stator winding electromagnetic efficiency factors closer to one have better power indexes.

References

1. **Timar P. L.** Induction motor fiel analysis. In: Engelmann R. H., Middendorf W. H. (eds). Handbook of Electric Motors. Marcel Dekker, New York, 1995. – P. 228–273.
2. **Жерве Г. К.** Обмотки электрических машин. Ленинград: Энергоатомиздат, 1989. – 399 с.
3. **Gečys S., Smolskas P.** Copper-squirrel-cage Solid Rotor Teeth Zone Parameter Rational Choice for Induction Motor Operating under Geophysical Conditions // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 1(89). – P. 91-94.
4. **Bukšnaitis J.** Kintamosios srovės trifazių elektros mašinų apvijų elektromagnetinis efektyvumas: monografija. – Kaunas: Technologija, 2007. – 196 p.
5. **Kostrauskas P.** Asinchroninės elektros mašinos. – Kaunas: Technologija, 2000. –116 p.

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In the paper the standard dimensioned 1,5 kW three-phase induction motor with single-layer former winding and the same motor with stator winding replaced with sinusoidal winding was analyzed. Electromagnetic features of stator windings of the considered motors were evaluated on the base of harmonic analysis of rotating magnetomotive forces created by them and by calculating electromagnetic efficiency factors on the base of the analysis results. It was determined that the electromagnetic efficiency factor of the single-layer former three-phase winding k_{ef1} = 0,9139, and for sinusoidal three-phase winding – k_{ef2} = 0,9335, i. e. by 2,14 % higher than the factor of the first winding. All power indexes of standard dimensioned induction motor with single-layer winding and of motor with stator winding replaced with sinusoidal three-phase winding were calculated after completing no-load and load tests of the motor and by applying the segregated-losses method. It was found that the phase current of the induction motor with stator winding replaced with sinusoidal three phase winding under indicated load decreased by 6,9 % , power taken from electric grid decreased by 5,0 %, power losses decreased by 11,7 %, efficiency factor increased by 2,4 % and power factor increased by 3,4 % compare to the respective power indexes of the standard dimensioned induction motor under the same load. It was determined that induction motor with three-phase winding of higher electromagnetic efficiency factor also has better power indexes. Ill. 4, bibl. 5, tabl. 8 (in English; abstracts in English, Russian and Lithuanian).

Ю. Букшнайтис. Энергетические показатели асинхронных двигателей и электромагнитная эффективность их обмоток // Электроника и электротехника. – Каунас: Технология, 2010. – № 4(100). – С. 11–14.

В работе рассмотрены заводской трёхфазный асинхронный двигатель 1,5 квт мощности с однослойной шаблонной и такой же перемотанный двигатель с синусоидальной статорной обмоткой. Электромагнитные свойства трёхфазных обмоток статора рассмотренных двигателей рассмотрены при исполнении гармонического анализа их созданной вращающейся магнитодвижущей силой и при вычислений по его результатам коэффициенты электромагнитной эффективности. Получено, что при однослойной шаблонной трёхфазной обмотке коэффициент электромагнитной эффективности является равным 0,9139, а при синусойдальной трёхфазной обмотке – 0,9335, т. е. на 2,14 % выше коэффициента первой обмотки. Все энергетические показатели заводского асинхронного и перемотанного двигателей рассчитаны при выполнении испытаний холостого хода и нагрузки, также при применении метод отдельных потерей мощности. Получено, что перемотанного асинхронного двигателя с синусоидальной трёхфазной обмоткой при номинальной нагрузки фазовый ток статорной обмотки уменьшился на 6,9 % , потребляемая мощность уменьшилась на 5 % , потери мощности уменьшились на 11,7 % , коэффициент полезного действия увеличился на 2,4 % , а коэффициент мощности увеличился на 3,4 % по сравнению с соответствующими энергетическими показателями заводского двигателя. Установлено, что асинхронные двигатели, имеющие трёхфазные обмотки с повышенными коэффициентами электромагнитной эффективности, имеют и лучшие энергетические показатели. Ил. 4, библ. 5, табл. 8 (на английском языке; рефераты на английском, русском и литовском яз.).

J. Bukšnaitis. Asinchroninių variklių energiniai rodikliai ir jų apvijų elektromagnetinis efektyvumas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 4(100). – P. 11–14.

Darbe išnagrinėtas gamyklinis trifazis asinchroninis 1,5 kW galios variklis su viensluoksne formine apvija ir toks pat pervyniotas variklis su sinusine statoriaus apvija. Nagrinėjamų variklių trifazių statoriaus apvijų elektromagnetinės savybės įvertintos atlikus jų kuriamų sukamųjų magnetovarų harmoninę analizę ir pagal jos rezultatus apskaičiavus elektromagnetinio efektyvumo koeficientus. Atlikus šių apvijų teorinius tyrimus, nustatyta, kad viensluoksnės forminės trifazės apvijos elektromagnetinio efektyvumo koeficientas k_{ef1} = = 0,9139, o sinusinės trifazės apvijos – k_{ef2} = 0,9335, t. y. 2,14 % didesnis už pirmosios apvijos šį koeficientą. Gamyklinio asinchroninio variklio su viensluoksne formine apvija ir pervynioto variklio su sinusine trifaze apvija visi energetiniai rodikliai apskaičiuoti atlikus jų tuščiosios veikos ir apkrovos bandymus bei panaudojus atskirų galios nuostolių metodą. Taip pat nustatyta, kad pervynioto asinchroninio variklio su sinusine trifaze apvija statoriaus apvijos fazinė srovė, esant nurodytajai apkrovai sumažėjo 6,9 % , imama iš tinklo galia sumažėjo 5,0 %, galios nuostoliai sumažėjo 11,7 %, naudingumo koeficientas padidėjo 2,4 % ir galios koeficientas padidėjo 3,4 % , palyginti su gamyklinio asinchroninio variklio atitinkamais energiniais rodikliais. Nustatyta, kad asinchroninio variklio, kurio trifazės apvijos elektromagnetinio efektyvumo koeficientas didesnis, geresni ir energiniai rodikliai. Il. 4, bibl. 5, lent. 8 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).