Asian Journal of Information Technology 6 (3): 369-374, 2007

Criteria of the APM Stator Winding and Lifespan Evaluation Using Accelerated Tests

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Abstract: This research is devoted to the study of the two layer winding permeances with round conductors placed in the stator by Asymmetrical Placement Method (APM) without double flexion. An application criterion of these winding types is proposed. Theoretical and experimental analyses are centred on the performances of the proposed new method of two layer winding placement-Symmetrical Placement Method (SPM) starting from the polynomial model based on the multifactorial experiment in order to replace the generally utilised methods: "lifted" and asymmetrical methods. The obtained results made it possible to highlight a lifespan variation law according to the temperature in an interval of humidity values.

Key words: Lifespan, winding technology, induction machines, accelerated tests, planning experiment

INTRODUCTION

Most firms continue to use the traditional lifted double flexion placement method of the two layers winding. A designed winding using round insulated conductor is depicted in Fig. 1. Coils, which number is equal to the winding pitch, are lifted then placed into the slots according to the required technological process, i.e. double flexion. The remaining coils are automatically placed one side on the top, the other on the bottom of the slots. The principal advantage of such method is the possibility to obtain a perfectly symmetric winding where each coil has a beam places in top and the other in bottom of the slot. This propriety allows realising 2p parallel branches.

However, Theoretical and experimental analyses show the negative influence of the double-flexion technological operation with the round conductors, which creates mechanical stress on the beams at the end of the slots during coils placement reducing the lifespan of the machine by 6 to 8% owing to the involved microscopic cracks (Abdessemad *et al*., 2002). This value varies with the conductor insulator quality. In addition to the process difficulty and the time necessary to its execution, this method cannot be used in the machines having small diameters.

That's Why many APM have been proposed. The principal disadvantage of these methods is the non uniform distribution of the beams in top and in bottom of the slots what makes difficult the formation of the parallel branches. Generally these methods are used in the factories only for the reparation of the electric machines by changing the failure windings.

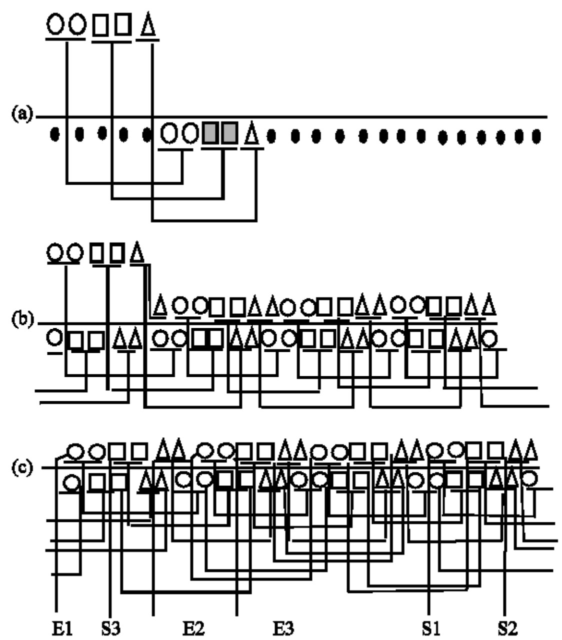

Fig. 1: Lifted Placement Method (LPM) of two-layer three-phase winding

The existing asymmetrical methods involve a difference of current values between phases and parallel branches due to the leakage flux which increases with the reduction of the shorter pitch. The study of performance criterion of the APM, and the lifespan of proposed SPM are the subject of the study.

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Permeance formulation (Voldek, 1978; Schisky, 1968): The reactance of slot permeances of the winding with a parallel branches:

$$X_s = 4\pi\mu_0 f \frac{\omega^2}{pq} l_\delta \lambda_s \qquad (1)$$

where I_δ-the stator length.

In the general case, the slot permeances of the two-layer windings are defined by:

$$\lambda_s = \frac{\lambda_l + \lambda_h + 2g.\lambda_g}{4} \qquad (2)$$

The permeances of the coil low and high sides are defined by (Fig.2):

$$\lambda_l = \lambda_h = \frac{4h_1^{'}}{3b} + \frac{h^{'} + h_2^{'}}{b} + \frac{h_3}{a_3} + \frac{h_4}{a_4} \qquad (3)$$

Permeances due to mutual inductance when the currents are in phase:

$$\lambda_g = \frac{h_1^{'}}{2b} + \frac{h_2}{b} + \frac{h_3}{b} + \frac{h_3}{a_3} + \frac{h_4}{a_4} \qquad (4)$$

where g-coefficient taking account of no phase between the currents in top in bottom of the slots (Schuisky, 1968): $g = \frac{3\beta + 1}{4}$ where β- the relative pitch of the winding. The expression of the average permeance of the slot of a two-layer winding:

$$\lambda_s = \frac{1}{4}\left[\frac{23 + 9\beta}{12}.\frac{h_1^{'}}{b} + \frac{h^{'}}{b} + \frac{3\beta + 5}{2}\left(\frac{h_2}{b} + \frac{h_3}{a_3} + \frac{h_4}{a_4}\right)\right] \qquad (5)$$

This expression does not take account of the winding placement and supposes that this one is perfectly symmetric (case of LPM). If the winding is realised with LPM, the beam number in bottom and top of the slots in each parallel branch is the same one and is equal to 2pq/a.

In asymmetrical winding with two layers, the number of beams in top of the slots in one of the parallel branches of the B phase is always higher than the number of beams located in bottom. What means that in top one has (2pq/a) + d and in bottom (2pq/a)−d.

Where d-the number of beams in a branch parallel superior to the average value.

To be able to take account of the no uniform distribution of the beams in the slots, let us write the expression of the permeances in the form:

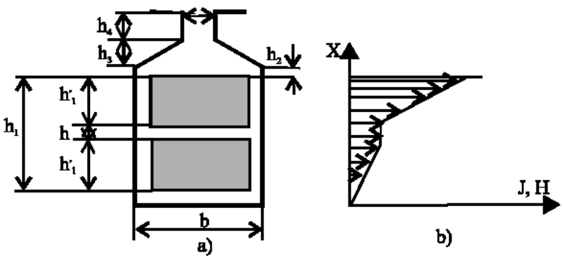

Fig. 2: Slot of the stator a) and current distribution relative to the slot height b)

$$\lambda_S = \left[\Sigma\lambda_l + \Sigma\lambda_h + \frac{pq}{a}2g\lambda_g\right]\frac{a}{4.2pq} \qquad (6)$$

With the introduction of the beam number in top and in bottom of the B phase, the average permeances become:

$$\lambda_s = \left[\frac{2pq}{a}\left(\lambda_l + \lambda_h + 2g\lambda_g\right) + d\left(\lambda_l + \lambda_h\right)\right]\frac{a}{8pq} \qquad (7)$$

By introducing the slot dimensions (Fig.2):

$$\lambda_s = \frac{1}{4}\left[\frac{23 + 9\beta}{12}.\frac{h_1^{'}}{b} + \frac{h^{'}}{b} + \frac{3\beta + 5}{2}\left(\frac{h_2}{b} + \frac{h_3}{a_3} + \frac{h_4}{a_4}\right)\right] - \frac{da}{8pq}\left(\frac{h_1^{'}}{b} + \frac{h^{'}}{b}\right) \qquad (8)$$

If the winding is symmetric:

$$\lambda_{so} = \frac{1}{4}\left[\frac{23 + 9\beta}{12}.\frac{h_1^{'}}{b} + \frac{h^{'}}{b} + \frac{3\beta + 5}{2}\left(\frac{h_2}{b} + \frac{h_3}{a_3} + \frac{h_4}{a_4}\right)\right] \qquad (9)$$

If the winding has one layer (β = 1):

$$\lambda_{s1} = \frac{32}{48}.\frac{h_1^{'}}{b} + \frac{12h^{'}}{48b} + \frac{h_2}{b} + \frac{h_3}{a_3} + \frac{h_4}{a_4} \qquad (10)$$

Knowing that $h_1 = 2h_1 + h$:

$$\lambda_{s1} = \frac{h_1^{'}}{3b} - \frac{h^{'}}{12b} + \left(\frac{h_2}{b} + \frac{h_3}{a_3} + \frac{h_4}{a_4}\right) \qquad (11)$$

From (Schuisky, 1968) the winding permeances of a one layer have as an expression:

$$\lambda_{s1*} = \frac{h_1^{'}}{3b} + \frac{h_2}{b} + \frac{h_3}{a_3} + \frac{h_4}{a_4} \qquad (12)$$

then : $\lambda_{s1} = \lambda_{s1}^{*} - \frac{h'}{12b}$.

If $\frac{h'}{12b}$ is very small (what is always the case), then

$\lambda_{s1} = \lambda_{s1}^{*}$

When $\beta \neq 1$ the comparison between (5) and (8) in the case of an asymmetrical winding, one notices that the permeances decrease by a value of:

$$\frac{da}{8pq}\left(\frac{h_1'}{b} + \frac{h'}{b}\right) \quad (13)$$

In the particular case of the winding obtained by Asymmetrical Successive Placement Method (ASPM - the more utilised asymmetrical method) (Fig.3) consisting in the placement of the coil groups successively in the same direction until obtaining the winding, the expression (13) becomes:

$$\frac{3a}{8p}\left(\frac{h_1'}{b} + \frac{h'}{b}\right)(\beta - 1) \quad (14)$$

what means that the application of the generally presented expressions to the asymmetrical windings of two and one-two layers permeances involves an overvaluation of this coefficient. It is noticed, from (13) and (14) that the asymmetry depends primarily on β, a and p.

Consequently, for an effective use of asymmetrical windings, it is necessary to introduce a criterion binding the winding parameters and the acceptable value of the asymmetry. Let us choose the criterion based on the variation of the currents:

$$\overset{*}{\Delta I} = \frac{I_h - I_m}{I_m} \leq \delta_{cr} \quad (15)$$

where I_h-the greatest value of the current in a parallel branch; I_m- the average current of a parallel branch. Knowing that $\lambda_s = \lambda_1 + \lambda_h + \lambda_o$, where the frontal permeances, D the number of beams in top of a parallel branch and the number of beams of a branch; then (4pq/a)-D-the number of beams in bottom. The permeance coefficient of the parallel branch:

$$\lambda_s = D\lambda_h - \left(\frac{4pq}{a} - D\right)\lambda_1 + \frac{2pq}{a}\lambda_o \quad (16)$$

The average permeances are obtained when D = (4pq/a); or D = 2pq/a; then,

$$\lambda_{s.m} = \frac{2pq}{a}(\lambda_1 + \lambda_h + \lambda)_o$$

The variation of the current in a parallel branch (or phase) compared to the average current is:

$$\overset{*}{\Delta I} \approx \frac{1/X_{min} - 1/X_{moy}}{1/X_{moy}} = \frac{X_{moy} - X_{min}}{X_{min}} = \frac{\lambda_{moy} - \lambda_{min}}{\lambda_{min}} \quad (17)$$

where X_{min}, X_{moy} minimal and average short circuit reactances.

From the electrotechnical standards, the current variation must be lower than 0.03 While taking account of the rotor effect, it can be carried to 0.06; in this case:

$$\overset{*}{\Delta I} \approx \frac{\lambda_{moy} - \lambda_{min}}{\lambda_{min}} \leq 0,06 \quad (18)$$

λ_{min} corresponds to the branch where the number of beams in top is larger than that of bottom

$$\lambda_{min\,//} = D\lambda_h - \left(D - \frac{4pq}{a}\right)\lambda_1 + \frac{2pq}{a}\lambda_o \quad (19)$$

knowing that 2pqm = Z , the current variation becomes:

$$\overset{*}{\Delta I} \approx \frac{\left(\frac{Z}{3a} - D\right)\left(\frac{\lambda_h}{\lambda_h + \lambda_1} - \frac{\lambda_1}{\lambda_h + \lambda_1}\right)}{\frac{\lambda_h}{\lambda_h + \lambda_1}D - \left(D - \frac{2Z}{3a}\right)\frac{\lambda_1}{\lambda_h + \lambda_1} + \frac{Z}{3a}\frac{\lambda_o}{\lambda_h + \lambda_1}} \quad (20)$$

From the design practice of the electric machines (Domborvsky and Kouteresky, 1974)

$$\frac{\lambda_h}{\lambda_h + \lambda_1} \approx 0,2\ ;\ \frac{\lambda_1}{\lambda_h + \lambda_1} \approx 0,8$$

$$\frac{\lambda_o}{\lambda_h + \lambda_1} \approx 0,4 \text{ for } 2p = 2$$

$$\frac{\lambda_o}{\lambda_h + \lambda_1} \approx \frac{13}{5} \text{ for } 2p = 4;\ 6$$

and $\frac{\lambda_o}{\lambda_h + \lambda_1} \approx 2 \text{ for } 2p = 8;\ 10$

Then:

$$\overset{*}{\Delta I} \approx \frac{D - \frac{Z}{3a}}{\frac{28Z}{9a} - D} \leq 0,06 \quad \text{for} \quad 2p = 2$$

$$\overset{*}{\Delta I} \approx \frac{D - \frac{Z}{3a}}{\frac{7Z}{3a} - D} \leq 0{,}06 \text{ for } 2p = 4;\, 6$$

$$\overset{*}{\Delta I} \approx \frac{D - \frac{Z}{3a}}{\frac{2Z}{a} - D} \leq 0{,}06 \text{ for } 2p = 8;\, 10 \qquad (21)$$

These expressions represent the winding symmetry criterion of the two and 1-2 layers AC machines until 100 kW.

In the particular case of an ASPM, the criterion is:

$$\chi = \frac{Z}{aq|(1-\beta)|} \qquad (22)$$

$\chi \geq 19$ pour 2p = 2 ; $\chi \geq 26.5$ pour 2p = 4; 6 et $\chi \geq 32$ pour 2p = 8; 10.

Among the research results in this direction, a new placement method of two layer winding is proposed allowing the replacement of the two generally more utilised methods: LPM and ASPM.

Description of no lifted symmetrical winding: The proposed Symmetrical Placement Method (SPM) consists in following steps:

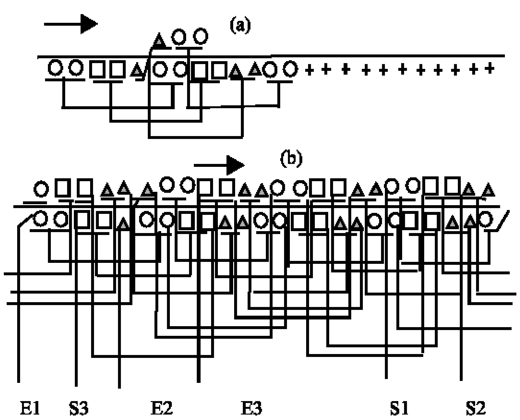

Fig. 3: Asymmetrical successive placement method (ASPM) of two-layer winding

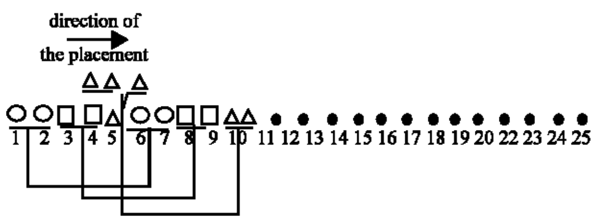

Fig. 4: First step of placement

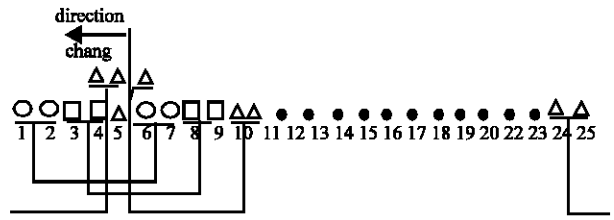

Fig. 5: Second step of the placement

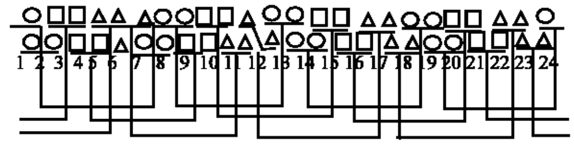

Fig. 6: The obtained two layer winding

- The first three groups of coils are placed in slots from left to right (Fig. 4).
- The remaining groups are placed successively in the opposite direction, starting from the slot which number corresponds to the winding pitch (Fig.5).

Figure 6 shows the obtained two layer winding. The experimental results of the proposed method show that it ensures an equality of the currents thanks to an identical distribution of the coil sides in top and bottom of the slots in the parallel branches of all phases without lifting.

However, if the LPM can ensure $\alpha_{max} = 2p$, the maximum number of parallel branches that can be obtained by the new method is $\alpha_{max} = p$.

The technological and classical experimental studies of this method on the important number of machines differing by the slot and the pole numbers show that this one can really replace the LPM method for the electrical machines having round conductor winding with $a \leq p$.

Modelling and experimentation: For the development of a accelerated testing method for the three phase asynchronous squirrel cage motor, a multifactorial experiment was taken for the lifespan evaluation of the proposed method according to the following factors: the temperature of winding, rest period of the motor X_2, the vibrations X_3 and humidity X_4.

To describe the process of insulator ageing, knowing that the relation of the winding lifespan and the temperature is a linear function, the polynomial form was selected as model (Ivibotenko *et al.*, Abdessemed *et al.*, 2003).

$$y = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1;\, j=1;\, i\neq j}^{k} b_{ij} x_i x_j \qquad (23)$$

Table 1: Experimentation matrix

	Factor level											
	X_1 Temperature (°C)			X_2 Eccentricity (N.m)			X_3 Rest period between inversions (s)			X_4 Humidity (%)		
N° of test	High. 200°C (+)	Low. 180°C (-)	Variat. Interval 10	High 0.095 (+)	Low 0.005 (-)	Variat. Interval 0.045	High 1.5 (+)	Low 0.5 (-)	Variat. Interval 0.5	High 100 (+)	Low 70 (-)	Variat. Interval 15
1		+			+			+			+	
2		-			+			+			+	
3		+			-			+			+	
4		-			-			+			+	
5		+			+			-			+	
6		-			+			-			+	
7		+			-			-			+	
8		-			-			-			+	
9		+			+			+			-	
10		-			+			+			-	
11		+			-			+			-	
12		-			-			+			-	
13		+			+			-			-	
14		-			+			-			-	
15		+			-			-			-	
16		-			-			-			-	

where y-the experiment response; k-the number of studied factors; x_i, x_j- test factors , ϕ_i ; -

$$x_i = \frac{(\phi_i - \bar{\phi}_i)}{I_i}$$

natural value of the i factor ϕ_i^h, ϕ_i^l ; - natural higher and lower values of the i factor $\bar{\phi}_i$; - natural value of principal level of the i factor $I_i = \phi_i^h - \bar{\phi}_i = \bar{\phi}_i - \phi_i^l$; - variation interval of i factor b_o, b_i, b_{ij}, b_{ii} ; - regression coefficient of the polynom .

The regression coefficients are defined by (Irtechsky and Bortnik, 1975;

$$b_{ui} = \frac{1}{n'} \sum_{j=1}^{n'} x_{uj} x_{ij} \bar{y}_j \qquad (24)$$

where u, I = 1, 2, 3, 4- factor numbers, u≠i; n' - number of test variants in the planning matrix ; j = 1, 2,...,16; - $\bar{y}_j$ planning matrix line number, ; - average value of the response in the line of the matrix (for a given experiment variant).

The study of the stator winding lifespan according to the action of the factors was made starting from the TPF (Total Plan Factor) , (Iribtenko *et al.*, 1975; Filippini *et al.*, 1993; IEEE, 1991; Vigier, 1988; Pllet, 1992).

The experimentation matrix is represented in the Table 1:

The winding insulation breakdown is considered as a failure criterion. The experiment was taken until the complete stop of all motors.

RESULTS AND DISCUSSION

After each failure, the insulator (between coil turns, phases and with the mass) is checked. The winding most sensitive element remains locating on the frontal part, on the connection side.

The obtained regression equation of the average lifespan resulted from the accelerated tests is:

$$Y = 1044{,}48 - 473{,}92X_1 - 14{,}85X_4 \qquad (25)$$

The adequacy of the expression with the experiment results is checked by comparing the experimental and theoretical values of Fisher criteria Kroug *et al.*, 1978.

For the extrapolation of the lifespan in the field of the operating conditions, the expression (25) can be written in the form (Vanyer, 1983; Kroun *et al.*, 1978:

$$\left.\begin{array}{l} \log Y_{100} = -6{,}95 + \frac{4585{,}20}{273+\theta} \\ \log Y_{70} = -6{,}48 + \frac{4467{,}5}{273+\theta} \end{array}\right\} \qquad (26)$$

what allows to evaluate the winding lifespan according to the temperature in an interval of 70 to 100% of humidity.

By comparing the obtained curve (Fig. 7) corresponding to the winding SPM with the one of two layer ASPM (Fig. 7), an improvement of the lifespan is observed. In the case of a manual placement, the study undertaken shows that it is suitable to use the SPM winding. However, for important power machines, when the winding is realised with the rectangular conductors, the lifted placement becomes necessary.

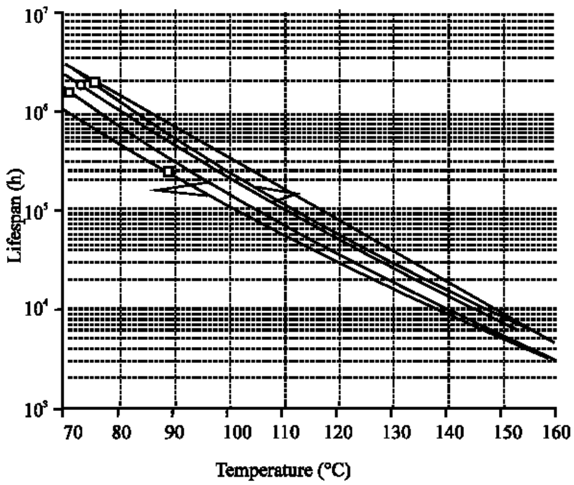

Fig. 7: Lifespans of the motor winding insulation with Symmetrical two layer winding; 2-ASPM two layer winding;- 70% and -100% of humidity

CONCLUSION

The results of elaborated work highlighted the lifespan variation rule according to the operating conditions (mainly the temperature). Under normal operating conditions, an improvement of the lifespan of the two layer winding Placed by Symmetrical Method (SPM) is observed comparing to the two layer winding with asymmetrical successive placement method. This improvement is justified by an equality of the currents thanks to an identical distribution of the small coil sides in top and bottom of the slots in the parallel branches of all phases.

Also, theoretical and experimental analyses of LPM (Abdessemed *et al*., 2002) show the negative influence of the double-flexion technological operation “lifting” with the round conductors, which creates mechanical stress on the beams at the end of the slots during coils placement reducing the lifespan of the machine. in addition, this method cannot be used in the machines with small diameters. Consequently, the use of the proposed SPM can really replace the LPM and APM in the electrical machines until 100 kW having round conductor winding with $a \leq p$.

Machine data: Nominal power p = 4kW; pole number 2p = 4; Number of coil turns W = (33+33);

Current $(\Delta/Y)(A)I = 14.2/8.2$; Diameter of the conductor d=1.08; Power factor φ = 0.88; Winding pitch y = 5; Speed n = 1447rpm; Resistance r =1.10Ω; Protection IP44; B class isolation.

Experimental cycles (Vaneye, 1983; Ostovskaya *et al*., 1975): The warming of the stator winding in inversion on no load mode; the inversion frequency for all motors 240 h^{-1}; a 16 h time warming for the high level and 48 h for the lower level; humidity time 24 h; 80° drying temperature for 4 h duration and 120°C for 8 h.

REFERENCES

Abdessemed, R., V.F. Tomachevitch and K.N. Vakoulenko, 2002. Influence of Coils Double Flexion on the Reliability of Two-Layer Winding AC Machines. Electrical Power Components and systems, Taylor and Francis, Vol. 30.

Abdessemed, R., V.F. Tomachevitch and L.I. Grinetch, 2003. Modeling of the Hybrid Stator Winding Lifespan of Induction Motors. Electrical Power Components and systems, Taylor and Francis, 31: 9.

Dombrovsky, V.V. and G.M. Khouteresky, 1974. The design bases of the AC electric machines. L. Energuya.

Filippini, J., P. Souvay and et T. Hans, 1993. Control adjustment by experimental designs, *Revue l'automaticien*.

Ivibotenko, B.A., N.F. Ilinsky and I.P. Kopilov, 1975. Planning of the experiment in electromechanics: M., Energuya.

Irtechsky, E.B., Bortnik G.M., 1975. Use of the planning experiment for the determination of the accelerated test coefficients of the asynchronous motor winding reliability, Tr. VNIIEM, T.43.

IEEE Gold Book, 1991. IEEE Recommended Practice for Design of reliable Industrial and Commercial Power Systems: IEEE. Press.

Kroug, G.A., Y.A. Sosoulin and V.A. Fatiev, 1978. Planning of the experiment in the identification and extrapolation problems: M., Naouka.

Ostrovskaya, E.L., A.B. Poyberg and E.A. Tigai, 1975. Kit for tests of the asynchronous motors winding asynchronous motors. Tech. Elec. Prod., pp: 11.

Pillet, M., 1992. Introduction to the experimental designs by the Taguchi method: Les éditions d'organisation.

Schuisky, V.P., 1968. Calculation of electrical machines. L. Energuya.

Voldek, A.I. and L. Electrical machines, 1978. Energuya.

Vigier, M.G., 1988. Practical of the experimental designs. Taguchi Methodologyie: Les Editions d'Organisation.

Vaneyev, B.N. *et al*., 1983. Reliability of asynchronous electromotors: K. Technika.