

The study of the current form influence on measurement of the weber-ampere characteristics

A M Lankin and M V Lankin

Department of information and measuring systems and technologies, Federal State Educational Institution of Higher Professional Education 'M I Platov South Russian State Technical University (NPI)', 132, Prosveshcheniya st., Novocherkassk, 346428, Russia

E-mail: lankinjohn@rambler.ru

Abstract. The article describes the study of the effect of measurement error of the current form on determination of weber-ampere characteristics of electric cutting machines. During experimental studies we have developed a method for determining the weber-ampere characteristics of the electric machine tools. However, there is an error in the measurement of the harmonic content of the current, which requires additional studies of the current form effect on weber-ampere characteristics.

1. Introduction

A method for determination of the weber-ampere characteristics of the electric machine tools is based on the methods of harmonic balance and a field-test model [3-8]. The authors have determined weber-ampere characteristics for measuring the form of the supply voltage and current consumption.

2. Materials and methods

Weber-ampere characteristics obtained during the flow of alternating current for operating the electric winding machine tool will have a hysteresis. In the measurement two things must be taken into account: the distortion of the curve, and the phase shift between magnetic flux F and current I in the coil. The relationship between F and I is determined by the shape of the dynamic loop.

The lag phase of a curve flow of the current curve is due to the influence of eddy currents and magnetic viscosity. The angle of lag δ is called the angle of losses.

To consider the effects of the distortion curve shape and the presence of the phase shift dependence, $F = f(I)$, when magnetizing an alternating field, it was suggested that the real dynamic loop is equivalent to ellipse, which satisfies the equation in coordinates F and I :

$$\begin{aligned} i(t) &= I_{\max} \sin(\omega t); \\ F(t) &= F_{\max} \sin(\omega t - \delta). \end{aligned}$$

If we introduce a component stream, $F_{\max 1} = F_{\max} \cos \delta$, which is in the phase with direction I , component $F_{\max 2} = F_{\max} \sin \delta$ lags by 90° from I , when $F_{\max 1}$ is associated with reversible processes of energy transformation during magnetization reversal, and $F_{\max 2}$ – with irreversible magnetization. Expression (2) takes the following form:

$$F(t) = F_{\max 1} \sin(\omega t) - F_{\max 2} \cos(\omega t).$$



We propose a method of determining loop $F = f(I) + F_{\max 2} \cos(\omega t)$, which takes into account its hysteresis. In order to realize this, we will implement the solution of the inverse problem of the harmonic balance [1, 3-5, 9] method of natural-model tests [2, 6-8, 10], the unifying dimension of the physical object and modeling of the object. The method allows determining the shape of loop $F = f(I) + F_{\max 2} \cos(\omega t)$, the well-known current flowing through the coil, set in a Fourier series:

$$i(t) = \sum_{m=1}^n I_{(2m-1)} \sin((2m-1)\omega t),$$

Where $I_{(2m-1)}$ – amplitude $(2m-1)$ of harmonic current and the known shape, and amplitude U_a of the voltage applied to the coil :

$$u(t) = U_a \sin(\omega t).$$

For the reversible component of the hysteresis of the weber-ampere characteristics of electrical products, we set an approximating expression:

$$F(i) = \sum_{m=1}^n k_{(2m-1)} i^{2m-1},$$

Where F – value of the magnetic flux, $k_{(2m-1)}$ – coefficients of the approximate expression of the weber-ampere characteristics, $m = \overline{1, n}$, n – the number of terms in the approximate expression, i – the current flowing through the coil.

The problem is formulated as follows. There is an electric machine tool with unknown hysteresis, known laws of variation of the voltage applied to the non-linear inductance and current flowing through it. It is required to determine coefficients $k_{(2m-1)}$ of expressions approximating the hysteresis of the weber-ampere characteristics and the amplitude of irreversible flow component $F_{\max 2}$.

The equation of the circuit of the electrical device is

$$u(t) = Ri + \frac{dF}{dt}.$$

Let us rewrite it taking into account the known laws of current change (4) and voltage (5):

$$U_a \sin \omega t = R \left(\sum_{m=1}^n I_{(2m-1)} \sin((2m-1)\omega t) \right) + \frac{d \sum_{m=1}^n k_{(2m-1)} \sum_{m=1}^n (I_{(2m-1)})^{2m-1} \sin((2m-1)\omega t)}{dt} + F_{\max 2} \sin(\omega t)$$

The experiments are used as a method for the determination of the hysteresis of the weber-ampere characteristics of the algorithm used in natural-model tests.

Since the measurement range of the current error occurs, we investigated the effect of measurement error on the current harmonics error in determining the weber-ampere characteristics. These studies were conducted by means of the theory of planning a multi-factor experiment. Zero values of the factors are taken as measurement results of the first five odd harmonics of current $I_1 - I_9$. The upper and lower values of each factor are obtained by adding or subtracting a predetermined value of the absolute error of measurement.

The weber-ampere characteristic obtained in the center of the plan, i.e. the measured values of the current harmonics are taken as exemplary characteristics.

Central composite design experiments are built in the shape of an orthogon, one of which is a nucleus from fractional factorial experiment 2^{5-2} . A variation interval for each factor was set so that its values correspond to absolute current harmonics measurement error – 3 %, provided that the size of the stellar arm maximum change was current harmonics ± 4.4 %.

Table 1 shows the scheduling matrix of the experiment. The accuracy was determined by two methods of obtaining the weber-ampere characteristics: natural-model tests (NMT) and a numerical solution of the inverse problem of the harmonic balance (HB).

There is a dependence of additional error methods on the values of the first five odd harmonics of current.

Table 1. The matrix of the experimental design.

№	I_1		I_3		I_5		I_7		I_9		Accuracy	
	Code	Physic	Code	Physic	Code	Physic	Code	Physic	Code	Physic	NMT	HB
		A		A		A		A		A	%	%
1	-1	4.199	-1	0.928	-1	0.496	1	0.264	1	0.148	0.26	0.78
2	1	4.459	-1	0.928	-1	0.496	-1	0.248	1	0.148	0.44	0.91
3	-1	4.199	1	0.986	-1	0.496	-1	0.248	-1	0.140	0.33	0.83
4	1	4.459	1	0.986	-1	0.496	1	0.264	-1	0.134	0.41	0.57
5	-1	4.199	-1	0.928	1	0.526	1	0.264	-1	0.134	0.31	0.77
6	1	4.459	-1	0.928	1	0.526	-1	0.248	-1	0.140	0.41	0.69
7	-1	4.199	1	0.986	1	0.526	-1	0.248	1	0.148	0.33	0.98
8	1	4.459	1	0.986	1	0.526	1	0.264	1	0.148	0.58	0.81
9	1.47	4.52	0	0.957	0	0.511	0	0.256	0	0.144	0.31	0.53
10	-1.47	4.138	0	0.957	0	0.511	0	0.256	0	0.144	0.41	0.41
11	0	4.329	1.47	0.999	0	0.511	0	0.256	0	0.144	0.18	0.27
12	0	4.329	-1.47	0.915	0	0.511	0	0.256	0	0.144	0.35	0.63
13	0	4.329	0	0.957	1.47	0.534	0	0.256	0	0.144	0.33	0.44
14	0	4.329	0	0.957	-1.47	0.488	0	0.256	0	0.144	0.44	0.21
15	0	4.329	0	0.957	0	0.511	1.47	0.267	0	0.144	0.28	0.68
16	0	4.329	0	0.957	0	0.511	-1.47	0.245	0	0.144	0.07	0.37
17	0	4.329	0	0.957	0	0.511	0	0.256	1.47	0.150	0.31	0.53
18	0	4.329	0	0.957	0	0.511	0	0.256	-1.47	0.138	0.14	0.17
19	0	4.329	0	0.957	0	0.511	0	0.256	0	0.144	0	0

3. Results

For the method based on natural-model tests:
physical values of factors are

$$\delta = 281,52 - 44,37I_1 + 5,16I_1^2 + 52,92I_3^2 + 429,52I_5^2 - 8,09I_7 - 351,59I_9 + 1247,54I_9^2;$$

in the coded values of factors there is

$$Y = 0,148 + 0,038X_1 + 0,087X_1^2 + 0,044X_3^2 + 0,1X_5^2 + 0,029X_7 + 0,033X_9 + 0,023X_9^2.$$

For the method based on the inversion harmonic balance:
physical values of factors are

$$\begin{aligned} \delta = & 774,36 - 82,81I_1 + 9,55I_1^2 - 353,95I_3 + \\ & + 184,21I_3^2 - 406,44I_5 + 400,27I_5^2 + 3161,88I_7^2 - 1608,36I_9 + 5659,55I_9^2; \end{aligned}$$

in the coded values of factors there is

$$\begin{aligned} Y = & 0,103 - 0,017X_1 + 0,161X_1^2 - 0,04X_3 + 0,152X_3^2 + \\ & + 0,04X_5 + 0,094X_5^2 + 0,186X_7^2 + 0,093X_9 + 0,106X_9^2. \end{aligned}$$

The analysis of regression equations shows that the relationship between variations of harmonic currents and mostly square errors and one of the harmonics are not the dominant influence on the error.

Processing of the results of the experiment was carried out using the software 'Statistica 10' (Figures 1 and 2).

Factor	SS	df	MS	F	p
(1)Var1 (L)	0,052435	1	0,052435	174,2897	0,000000
Var1 (Q)	0,212656	1	0,212656	706,8455	0,000000
(2)Var2 (L)	0,000220	1	0,000220	0,7297	0,398327
Var2 (Q)	0,053454	1	0,053454	177,6740	0,000000
(3)Var3 (L)	0,000071	1	0,000071	0,2365	0,629523
Var3 (Q)	0,286296	1	0,286296	951,6164	0,000000
(4)Var4 (L)	0,031920	1	0,031920	106,0974	0,000000
Var4 (Q)	0,000053	1	0,000053	0,1759	0,677253
(5)Var5 (L)	0,040951	1	0,040951	136,1154	0,000000
Var5 (Q)	0,015230	1	0,015230	50,6246	0,000000
Lack of Fit	0,372211	8	0,046526	154,6489	0,000000
Pure Error	0,011432	38	0,030085		
Total SS	1,077131	56			

Factor	Effect	Std.Err. Pure Err	t(38)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	Coeff.	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	0,147799	0,005273	28,03106	0,000000	0,137125	0,158473	0,147799	0,005273	0,137125	0,158473
(1)Var1 (L)	0,075308	0,005704	13,20188	0,000000	0,063760	0,086856	0,037654	0,002852	0,031880	0,043428
Var1 (Q)	0,173994	0,006544	26,58657	0,000000	0,160745	0,187242	0,086997	0,003272	0,080373	0,093621
(2)Var2 (L)	-0,004873	0,005704	-0,85424	0,398327	-0,016421	0,006675	-0,002436	0,002852	-0,008210	0,003337
Var2 (Q)	0,087233	0,006544	13,32944	0,000000	0,073985	0,100482	0,043617	0,003272	0,036992	0,050241
(3)Var3 (L)	0,002774	0,005704	0,48633	0,629523	-0,008774	0,014322	0,001387	0,002852	-0,004387	0,007161
Var3 (Q)	0,201884	0,006544	30,84828	0,000000	0,188636	0,215132	0,100942	0,003272	0,094318	0,107566
(4)Var4 (L)	0,058757	0,005704	10,30036	0,000000	0,047209	0,070305	0,029378	0,002852	0,023604	0,035152
Var4 (Q)	0,002745	0,006544	0,41945	0,677253	-0,010503	0,015994	0,001373	0,003272	-0,005252	0,007997
(5)Var5 (L)	0,066552	0,005704	11,66685	0,000000	0,055004	0,078099	0,033276	0,002852	0,027502	0,039050
Var5 (Q)	0,046564	0,006544	7,11509	0,000000	0,033316	0,059813	0,023282	0,003272	0,016658	0,029906

Figure 1. Listing of the program 'Statistica 10' (NMT).

Factor	SS	df	MS	F	p
(1)Var1 (L)	0,010076	1	0,010076	29,538	0,000003
Var1 (Q)	0,729024	1	0,729024	2137,154	0,000000
(2)Var2 (L)	0,058325	1	0,058325	170,980	0,000000
Var2 (Q)	0,647760	1	0,647760	1898,926	0,000000
(3)Var3 (L)	0,060433	1	0,060433	177,161	0,000000
Var3 (Q)	0,248627	1	0,248627	728,856	0,000000
(4)Var4 (L)	0,000140	1	0,000140	0,411	0,525522
Var4 (Q)	0,977254	1	0,977254	2864,848	0,000000
(5)Var5 (L)	0,321590	1	0,321590	942,752	0,000000
Var5 (Q)	0,313451	1	0,313451	918,890	0,000000
Lack of Fit	0,561635	8	0,070204	205,806	0,000000
Pure Error	0,129625	38	0,034112		
Total SS	3,942994	56			

Factor	Effect	Std.Err. Pure Err	t(38)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	Coeff.	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	0,103251	0,005614	18,3901	0,000000	0,091885	0,114617	0,103251	0,005614	0,091885	0,114617
(1)Var1 (L)	-0,033012	0,006074	-5,4349	0,000003	-0,045308	-0,020716	-0,016506	0,003037	-0,022654	-0,010358
Var1 (Q)	0,322155	0,006969	46,2294	0,000000	0,308048	0,336263	0,161078	0,003484	0,154024	0,168131
(2)Var2 (L)	-0,079425	0,006074	-13,0759	0,000000	-0,091721	-0,067128	-0,039712	0,003037	-0,045860	-0,033564
Var2 (Q)	0,303670	0,006969	43,5767	0,000000	0,289562	0,317777	0,151835	0,003484	0,144781	0,158888
(3)Var3 (L)	0,080847	0,006074	13,3102	0,000000	0,068551	0,093144	0,040424	0,003037	0,034275	0,046572
Var3 (Q)	0,188134	0,006969	26,9973	0,000000	0,174027	0,202242	0,094067	0,003484	0,087014	0,101121
(4)Var4 (L)	-0,003892	0,006074	-0,6408	0,525522	-0,016188	0,008404	-0,001946	0,003037	-0,008094	0,004202
Var4 (Q)	0,372991	0,006969	53,5243	0,000000	0,358884	0,387098	0,186495	0,003484	0,179442	0,193549
(5)Var5 (L)	0,186501	0,006074	30,7043	0,000000	0,174204	0,198797	0,093250	0,003037	0,087102	0,099398
Var5 (Q)	0,211242	0,006969	30,3132	0,000000	0,197134	0,225349	0,105621	0,003484	0,098567	0,112674

Figure 2. Listing the program 'Statistica 10' (HB).

4. Conclusion

Table 1 and figure 1 show that by varying the values of the harmonic currents in the range of $\pm 4.4\%$, the obtained error of the weber-ampere characteristics does not exceed 1%. The error of the method based on natural-model tests did not exceed 0.6 %.

Acknowledgment

The research has been conducted with the support of project № 1.2690.2014 / K ‘Methods for solving inverse problems of diagnosis of complex systems (engineering and medicine) on the basis of the natural-model experiment’ performed in the framework of the project state task using the CCU equipment ‘Diagnosis and energy-efficient electrical equipment’ of South Russian State Technical University (NPI) after MI Platov.

References

- [1] Bakhvalov Y A, Gorbatenko N I, Grechikhin V V 2015 *Measurement Techniques* **58** 336–340
- [2] Borovoi V V, Gorbatenko N I, Grechikhin V V 2015 *Measurement Techniques* **56** 614–617
- [3] Gorbatenko N I, Lankin M V 2004 *Russian Electrical Engineering* **8** 63–66
- [4] Gorbatenko N I, Lankin M V 2004 *Elektrotehnika* **8** 19–26
- [5] Gorbatenko N, Lankin M, Shaykhutdinov D, Gazarov K, Kolomiets A 2011 *Proceedings of the 6th International Forum on Strategic Technology* (Harbin: Heilongjiang) pp 194–196
- [6] Gorbatenko N I, Lankin A M, Lankin M V, Shaykhutdinov D V 2015 *International Journal of Applied Engineering Research* **3** 6509–6519
- [7] Gorbatenko N I, Grechikhin V V, Shaikhutdinov D V 2015 *Measurement Techniques* **56** 609–613
- [8] Lankin A M, Lankin M V, Aleksanyan G K, Narakidze N D 2015 *International Journal of Applied Engineering Research* **3** 6489–6498
- [9] Shaykhutdinov D V, Gorbatenko N I, Akhmedov Sh V, Shaykhutdinova M V, Shirokov K M 2013 *Life Science Journal* **10** 2698–2702
- [10] Shaikhutdinov D V, Gorbatenko N I, Shirokov K M 2015 *Measurement Techniques* **56** 618–620