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MEASURING HYSTERESIS LOOP AND OPTIMIZATION OF THE STATOR TOOTH WIDTH
IN THE PERMANENT MAGNET SYNCHRONOUS MACHINE

MĚŘENÍ HYSTEREZNÍ SMYČKY A OPTIMALIZACE ŠÍŘKY PÓLOVÉHO NÁSTAVCE
SYNCHRONNÍHO STROJE S PERMANENTNÍMI MAGNETY

Abstract

The first part of this paper deals with the measuring of hysteresis loop of the toroidal shape core. LabVIEW software is used to automate this process. The results are compared with the data from the manufacturer and used in the FEMM software for setting parameters of the stator core of Permanent magnet synchronous motor (PMSM). Then, in the second part of this paper, the Lua scripting engine in FEMM software is used to optimize stator tooth width. Program code is written in the Matlab environment and after starting the run process, Matlab uses inter-process communication via ActiveX to connect with FEMM. In this process program tries several options for the stator tooth width. Based on the results, user can evaluate all the data about the overall progress and choose the optimal stator tooth width.

Abstrakt

První část této práce se zabývá měřením hysterezní smyčky toroidního jádra. Prostředí Labview je použito k automatizaci tohoto procesu. Výsledky jsou porovnány s daty od výrobce a použity v programu FEMM pro nastavení parametrů jádra statoru synchronního motoru s permanentními magnety (PMSM). Ve druhé části je poté použit skriptovací prvek Lua v programu FEMM k optimalizaci šířky pólového nástavce. Kód programu je sepsán v prostředí Matlab a po jeho spuštění proběhne navázání komunikace Matlabu s FEMM pomocí Activex. V tomto procesu program vyzkouší několik možností pro nastavení šířky pólového nástavce. V závislosti na těchto výsledcích pak uživatel může vyhodnotit všechna data ohledně celkového průběhu výsledků a rozhodnout se pro optimální šířku pólového nástavce.

1 INTRODUCTION

Knowledge of the hysteresis loop for the material of stator core in the permanent magnet synchronous motor (PMSM) is a very important part of the motor's design. The hysteresis characteristics itself consists of the dependence between the magnetic field intensity $H(t)$ and the

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magnetic flux density *B(t)*. Its dimensions and shape widely influence stator core losses of the PMSM which are not negligible [1], [5]. Using software such as FEMM (Finite Element Method Magnetics) [8] it is possible to implement data of the known B-H curve in the process of the motor's design and improve its properties, so the core power losses can be decreased.

Measurement of the hysteresis loop of the toroidal shape core is made by using LabVIEW. Similar papers and literature about this topic have been already published [2], [3]. One of our goals is to check the dependence between the frequency of the generated signal and the shape – and therefore losses – of the hysteresis loop for our stator material. This all has to be made by using low cost amplifier and other devices, because professional equipment used in the industry is expensive [4].

Also to find optimal proportions for any technical equipment or device can become quite time consuming problem. Usually there are more possible ways, how the final design of a device can look like. Even if we find e.g. 5 possibilities of these designs and all of them will be functional- in the term that the device does what it should do- there will be probably only one design, which will fulfill the given criteria such as weight, power consumption, energy production, final dimensions, etc. To find the optimal point, where all requirements are met and it is done in a relatively short time, can be done using e.g. some algorithm. In this algorithm, all possibilities of a design for the final product are simulated and results are available for the consideration.

Such an approach may be used to find optimal proportions of the stator tooth width in a PMSM. Also, this tooth doesn't have to be considered only as some iron material. In the case of using air core, we will have to use different settings in the simulation, but still the principle of a program is the same as for the iron material. Other dimensions, such as stator and rotor diameter, are given by their manufacturers (together with their properties), and they will remain throughout the simulation constant.

There are several software products available for solving the magnetic problems. The top ones, which are used in the engineering practice, are quite expensive. Therefore using some free software is inevitable. One of the free products is the FEMM (Finite Element Method Magnetics) [8] and it offers solving given 2D planar problems using FEM.

This paper is divided into two parts – chapter 2 deals with the measurement of hysteresis loop and chapter 3 is about using FEMM software for optimization of the stator tooth width in the PMSM.

2 MEASUREMENT OF HYSTERESIS LOOP

2.1 Design of the hysteresis measurement

Measuring procedure is based on [3] and is shown in figure Fig. 1. Signal generator is a frequency generator with a given frequency and amplitude of a generated sinusoidal signal. This signal is then amplified by the 400W amplifier and the current $i_1(t)$ is measured by the current probe.

Output from the current probe is a voltage and it is measured by the NI USB-6210 (National Instruments data acquisition device with USB PC connection). Due to the current flow in the primary winding of the toroidal shape core, the magnetic field intensity *H(t)* is created. Its magnitude can be calculated based on Ampere's law as [3]:

$$H(t) = \frac{N_1 i_1(t)}{2r\pi} \tag{1}$$

where:

$H(t)$ – magnetic field intensity $\left[A \cdot m^{-1}\right]$,

N_1 – number of turns in the primary winding $[\ ]$,

$i_1(t)$ – current in the same winding $[A]$,

r – middle radius of the toroidal shape core $[m]$.
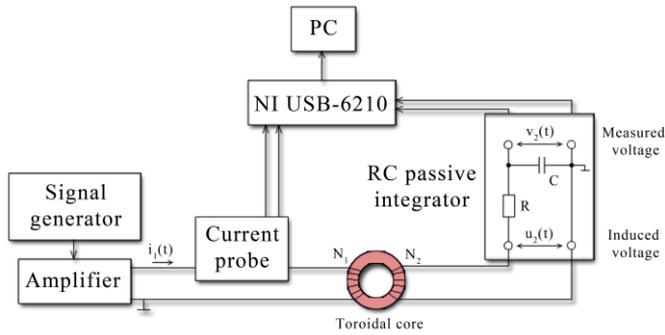
Fig. 1 Measuring procedure

Result of the magnetic field intensity *H(t)* is the creation of the magnetic flux inside the core. Then, the magnetic flux density *B (t)* can be measured and calculated based on the induced voltage $u_2(t)$ as [3]:

$$B(t) = B_0 + \frac{1}{SN_2} \int_0^t u_2(\tau)d\tau \qquad (2)$$

where:

B (t) – magnetic field intensity $[T]$,

N_2 – number of turns in the secondary winding $[\ ]$,

S – cross section of the toroidal shape core $[m^2]$,

$u_2 (t)$ – induced voltage in the secondary coil $[V]$,

B_0 – offset $[T]$.

The integration is a time consuming method and with increasing frequency the noise is expected to increase. Based on the [3] direct voltage measurement can be applied only up to 200 Hz and some filters has to be used to cut the added noise. Therefore using analog RC passive integrator seems to be a good way how to increase possible applied frequency (up to 1 kHz [3]) and even not to use any further signal processing algorithms, because it is working as a low-pass filter. Measured voltage is then given by [3]:

$$v_2(t) = -\frac{1}{RC} \int_0^t u_2(\xi)d\xi \qquad (3)$$

where:

$v_2 (t)$ – measured voltage on capacitor $[V]$,

R – value of used resistor $[\Omega]$,

C – value of used capacitor in the integrator circuit $[F]$.

2.2 Using LabVIEW for data acquisition

For the purposes of our measurements, adjustable graphical user interface (GUI) was created. Because in the future we would like to measure different materials of toroidal shape cores, variables such as N_1, N_2, frequency of modulated signal, number of data samples/s, *S*, *r* can be changed without having to interfere with values in the program block diagram. All acquired data together with input variables are saved in a data file, from where they can be used for further analysis in the future.

2.3 Analyzing acquired data

Parameters of tested toroidal shape core together with supplementary parameters can be found in Table 1. During measurement, current value was set as constant while the frequency was changing. With increasing frequency the current is dropping so to keep its value constant, amplitude of a generated signal has to be increased. The sampling rate per channel was 12500 samples per second. If the testing time was set as 5 seconds (to be able to cut possible disturbances from the beginning of the measurement), this gives us around 62500 data for one chosen current and frequency. These data can be now analyzed.

Tab. 1 Parameters of tested toroidal core with supplementary parameters

Name of used toroidal core	0078090A7 (Magnetics)
N1 [ ]	300
N2 [ ]	300
S [m^2]	0,000134
r [m]	0,0188775
Applied frequencies [Hz] / Applied current [A]	30~700 / 1 30~400 / 2 30~250 / 3
L1 [H]	0,008592
L1 [H]	0,008867
R1 [Ω]	7,2
R2 [Ω]	7,3

If we choose only a part of measured signal, for example 4 periods, then the hysteresis loop can be plotted from only these 4 periods and the result is shown in Fig.2. It is visible, that hysteresis curve is not very wide, if we consider it as a loop. If we plot other B-H curves with the same value of the current, but for different (lower) frequencies, we would obtain almost same progress as shown in Fig. 2. If we use a lower current, it will only lower magnitude of *B*. This is due to the parameters of the used coil. Its length due to the number of turns is high (for this measurement) and therefore its resistance is also high. Commonly used coils in high speed PMSM have their resistance less than 1 Ω [6], [7].
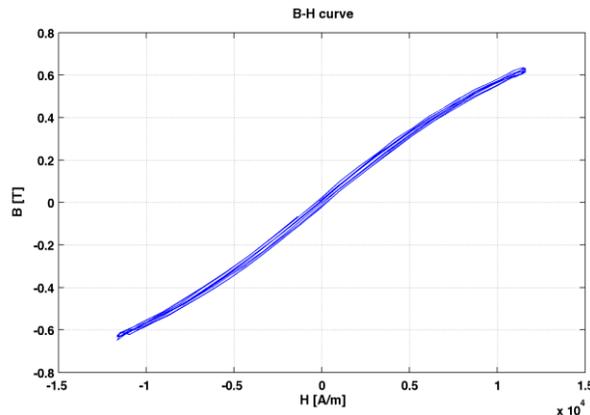

Fig. 2 Hysteresis loop of the toroidal shape core; applied current 3 A, applied frequency 250 Hz

Summary, to achieve more adequate hysteresis curve for our material, it is necessary to decrease number of turns of our coil, which will lead to a smaller resistance of the primary and secondary winding, and therefore possibility to use higher frequencies and current.

3 OPTIMIZATION OF THE STATOR TOOTH WIDTH

3.1 FEMM Software and Lua Scripting Engine

When using FEMM, there are basically two approaches available for the user how to describe 2D planar magnetic problems which should be solved. The first one can be expressed with the following steps:

1. *Problem description:* First of all, user has to define type of a problem (planar, axisymmetric), length units, depth, solver precision, etc.

2. *Drawing the model (cross-section model):* User has to draw the problem, in our case it is a cross section model of a PMSM. This is one of the most time consuming part, because it is required to draw nodes with using their coordinates and connect them as a lines or arc segments. Hopefully, it is possible to import DXF file from the higher software for technical drawing, such as AutoCAD.

3. *Setting properties:* All used materials has to be descirbed and placed in the drawing to corresponding positions. If there are any electrical circuits, they have to be described only with the applied current. FEM requires defining boundaries which also have to be placed.

4. *Analysis and results:* After setting all parameters, FEMM can now create a mesh for FEM and solve the problem. The user can view all the results and apply different tools for acquiring required data from the result output.

This approach can be used if the user already knows final dimensions for his product. But for the optimization process, where the chosen parameter is changing from e.g. 1 to 500, it is not a good choice. The user in this case would have to repeat steps b) and d) 499 times before being able to see the result of complete analysis.

To avoid this, it is possible to choose the second choice which offers using the Lua scripting engine. Lua is an open-source scripting language and more information about it can be found in [9]. This language has been used to add scripting possibilities for FEMM. There are several command sets which user can use for writing the script. Because every operation mentioned in the first kind of approach can be written with these commands, whole process of solving the problem can be automated. If the user chooses appropriate nodes and attach them into groups, after finishing the analysis and obtaining results, he can erase all of them with one command and replace them for iteration. This will greatly save his time required to find optimal solution of the problem.

To be able to further use obtained data from FEMM analysis, it is also possible to write a script in Matlab. Here, the Lua script commands are written as functions. After running a script, the interface for inter-process communication is then established via ActiveX.

3.2 Results of the Analysis

The optimization script has been created for 3 stator cores with a different dimensions and different tooth material. Parameters of the first one, which analysis results will be shown in figures, are given in the Table 2. Material properties of the toroidal shape stator can be obtained using method mentioned in the chapter 2 or found on the website of the manufacturer. For the proper demonstration of optimization process, manufacturer data were used.

A PMSM design is shown in Figure 3. We can see there are small black dots around some points, which are representing changes in the tooth width (iterations).

Tab. 2 Toroidal stator parameters

Parameter	Value
Type of stator	0078337A7 (Magnetics company)
Outer diameter [mm]	134
Inner diameter [mm]	77
Permeability [ ]	26
Motor length [mm]	50

The overall results from the optimization process are shown in Figure 4. Because we always read a value of flux density *B* at one location in the tooth, it can create a slightly jagged waveform at some location in the output characteristics, which is only a cosmetic problem that can be removed by changing location of reading flux density or using some approximation functions to fit the curve. Because with changing the stator tooth width the space available for the coil is decreasing, so the maximum number of turns has to also decrease. The only energized coil is the one where we measure the value of flux density (denoted as circuit B).
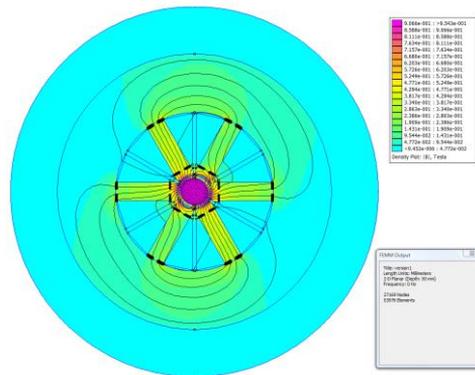

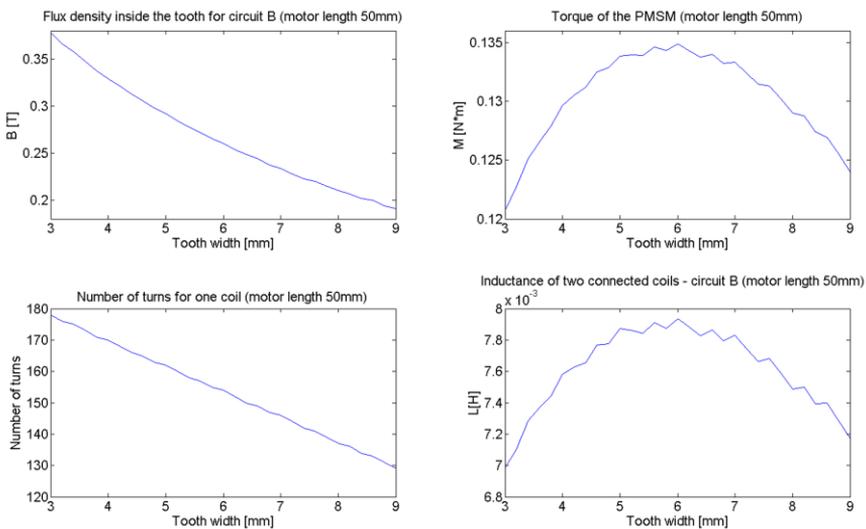**Fig. 3** Design of PMSM; tooth width is 9 mm, applied current in circuit B is 3A

Fig. 4 Results of the analysis; applied current 3A in the circuit B

4 CONCLUSIONS

Based on the measuring procedure, the measuring workplace was assembled and required data for the hysteresis characteristic of the toroidal shape core were measured. The B-H curve was plotted using acquired data and analyzed. Due to the high resistance of used coil, it is necessary to continue with another measurement and find optimal parameters for frequency and current in our PMSM, so the power losses in stator core will be kept at an acceptable level. A good plan for the future is also, if possible, finding an influence of the core's operating temperature to our results while measuring its hysteresis characteristics.

The optimization process has been applied to the PMSM design. Characteristics for a different tooth width have been acquired and they can be now used to design an ideal PMSM for our purposes. Other improvements in the script can be considered as well as a different type of materials used for the stator and tooth in the PMSM.

REFERENCES

[1]   KRISHNAN, R. *Permanent magnet synchronous and brushless DC motor drives*. Boca Raton: CRC Press/Taylor, 2010, 575 p. ISBN 08-247-5384-4.

[2]   TUMANSKI, S. *Handbook of magnetic measurements*. Boca Raton, FL: CRC Press. ISBN 978-143-9829-523.

[3]   POLIK, Z. a M. KUCZMANN. Measuring and control the hysteresis loop by using analog and digital integrators. In: *Journal of optoelectronics and advanced materials*. 2008, Vol. 10, No. 7, pages 5. ISSN 1454-4164.

[4]   ADLY, A.A., M.M. ABD-EL-AZIZ a H.H. ZEINELDIN. A low cost device for deducing B-H curves of magnetic materials. In: *2003 46th Midwest Symposium on Circuits and Systems*. IEEE, 2003, p. 886-888. DOI: 10.1109/MWSCAS.2003.1562428. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1562428

[5]   CHYSKÝ, J. - NOVÁK, J. - NOVÁK, M. - NOVÁK, Z.: Determination of Losses in Ferromagnetic Circuit of a Sinusoidal Filter Powered with Frequency Inverter. In: *Proceedings of 15th Mechatronika 2012*. Praha: Czech Technical University in Prague, 2012, p. 251-256. ISBN 978-80-01-04985-3.

[6]   NOVÁK, M. - NOVÁK, J. - CHYSKÝ, J.: Experimental Verification of High-Speed Permanent Magnet Synchronous Motor Model. In: *Proceedings of the XXth International Conference on Electrical Machines ICEM2012*. Marseille: IEEE, 2012, p. 2433-2438. ISBN 978-1-4673-0141-1.

[7]   PFISTER, PIERRE-DANIEL: Very high-speed slotless permanent-magnet motors: theory, design and validation. Lausanne: EPFL, 2009. Dissertation. École polytechnique fédérale de Lausanne EPFL. Advisor: Perriard, Yves.

[8]   D. Meeker, "Finite Element Method Magnetics: DavidMeeker" [online]. 24.06.2011 [Retrieved 2013-11-12]. Available at: http://www.femm.info/wiki/HomePage.

[9]   R. Lerusalimschy, W. Celes and L. Henrique de Figueiredo, "The Programming Language Lua "[online]. © 1994–2013 [Retrieved 2013-11-12]. Available at: http://www.lua.org/.