Measuring the Hysteresis Loop of the Toroidal Core Using LabVIEW to Optimize the Design of PMSM

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Abstrakt

Při průchodu proudu vodičem vzniká v okolí tohoto vodiče magnetické pole B. Toto magnetické pole může být zesíleno při použití feromagnetických materiálů, čehož se využívá například v elektromotorech. Tato práce se zabývá měřením hysterezní smyčky (B-H křivky) toroidního jádra, aby bylo možné stanovit její charakteristiku a celkové ztráty představující výkon spotřebovaný magnetickým materiálem při jeho střídavém magnetování. Výsledky budou sloužit pro konstrukci synchronního motoru s permanentními magnety, kde bude zvolený materiál jádra použit v jeho statorové části pro zesílení elektromagnetického pole v okolí vinutí cívek, a pro optimalizaci návrhu tohoto motoru. Pro automatizaci měření je využit software LabVIEW, který usnadňuje práci se získáním a uložením naměřených dat.

Keywords

Hysteresis loop, Toroidal core, LabVIEW

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 magnetic flux density $B(t)$. Its dimensions and shape widely influence stator core losses of the PMSM which are not negligible [1, 6]. Using software such as FEMM (Finite Element Method Magnetics) 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. Also if possible, we would like to find an influence of the core's operating temperature to our results. This all has to be made by using low cost amplifier and other devices, because professional equipment used in the industry is expensive [4].

2. Design of the hysteresis measurement

Measuring procedure 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

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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 [2]:

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

where N_1 is the number of turns in the primary winding, i_1 *(t)* is the current in the same winding and *r* is the middle radius of the toroidal shape core (value of denominator is the equivalent to the magnetic length of the material).

Result of the magnetic field intensity *H (t)* is the creation of the magnetic flux ϕ *(t)* inside the core. Then, the magnetic flux density *B (t)* can be measured and calculated based on the induced voltage u_2 *(t)* as [2]:

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

where N_2 is the number of turns in the secondary winding, u_2 *(t)* is the induced voltage of the secondary coil, *S* is the cross section of the toroidal shape core and B_0 is an offset.

The integration is a time consuming method and with increasing frequency the noise is expected to increase. Based on the [2] 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 [2]) 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 [2]:

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

where v_2 *(t)* is the measured voltage on capacitor, *R* is the value of used resistor, and *C* is the value of used capacitor in the integrator circuit. After acquiring data from measured voltage, induced voltage can be then easily calculated and substituted into equation (2) without offset B_0.

In the end, all the data from measurements are saved in PC and ready for further analysis.

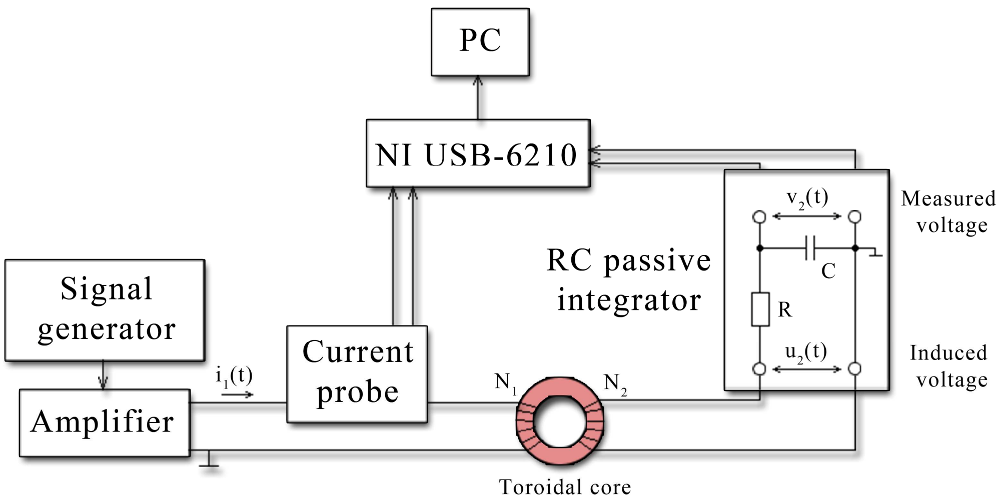

***Fig. 1** Measuring procedure*

2.1 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. GUI is shown in *Fig. 2* and program block diagram can be found in *Fig. 3*. 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.

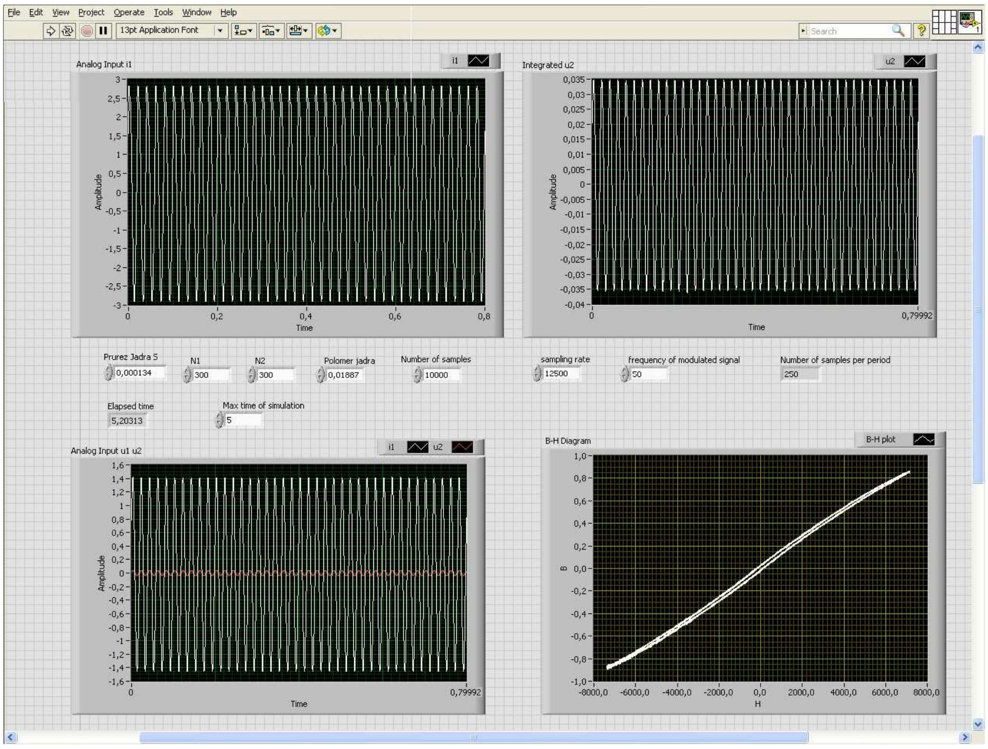

Fig. 2 *GUI from LabVIEW*

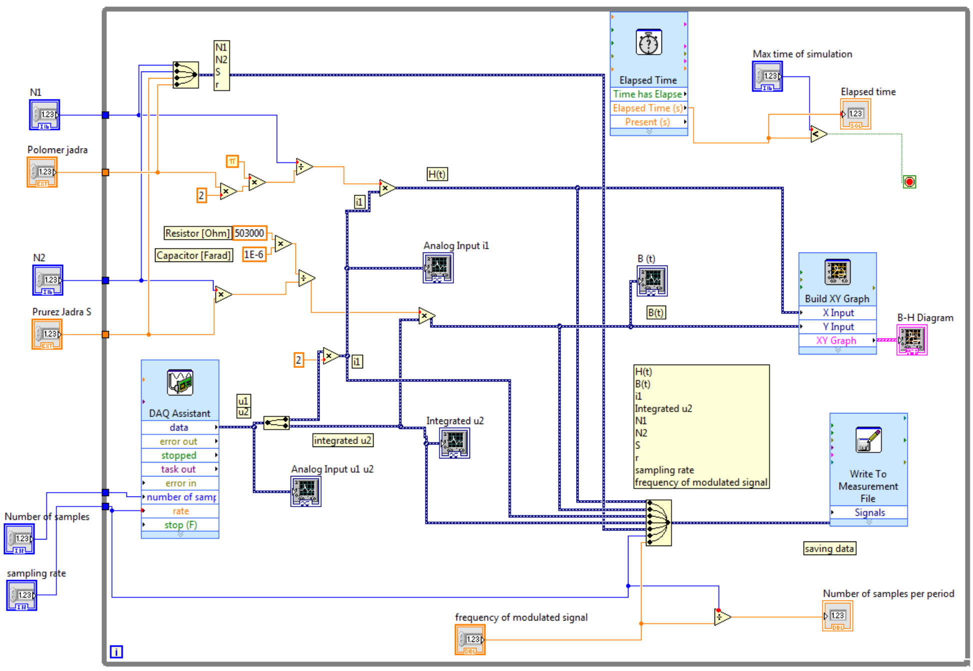

Fig. 3 *Program block diagram*

3. Analyzing acquired data

Parameters of tested toroidal shape core together with supplementary parameters can be found in *Tab. 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), it give us around 62500 data for one chosen current and frequency. These data can be now analyzed.

There is more than one way how to do it. First - the easier one - is to choose only a part of measured signal, for example 4 periods. Then the hysteresis loop can be plotted only from these 4 periods and the result is shown in *Fig.4*.

Table 1 *Parameters of tested toroidal core with supplementary parameters*

Name of used toroidal core	**0078090A7 (Magnetics)**
N_1 [ ]	300
N_2 [ ]	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
L_1 [H]	0,008592
L_1 [H]	0,008867
R_1 [Ω]	7,2
R_2 [Ω]	7,3

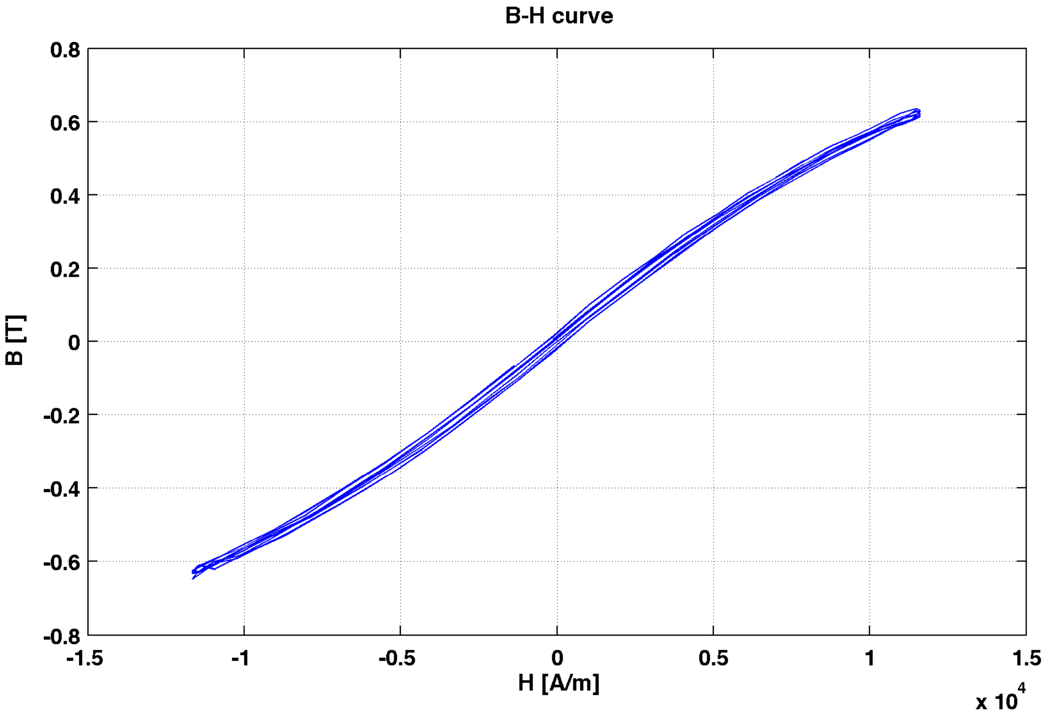

Fig. 4 *Hysteresis loop of the toroidal shape core; applied current 3 A, applied frequency 250 Hz*

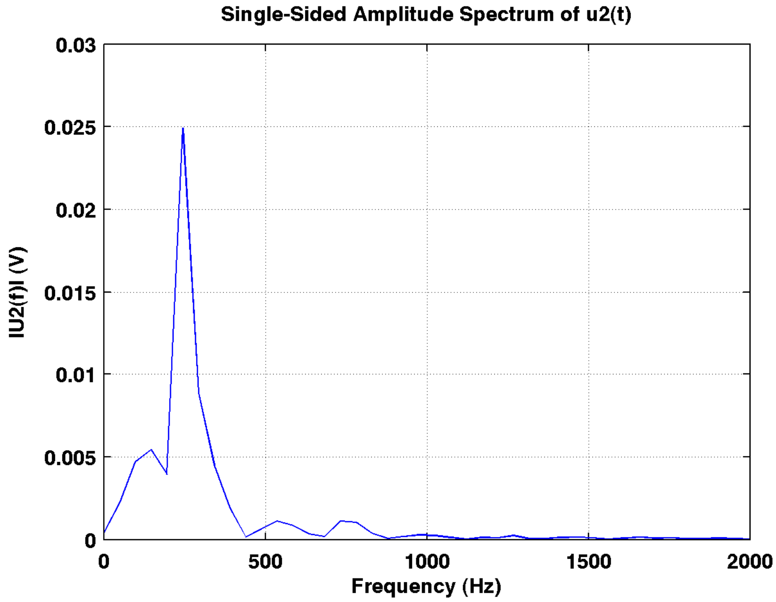

Fig. 5 *Single-sided amplitude spectrum of $u_2(t)$; applied current 3A, applied frequency 250 Hz*

The second choice is to use wider interval of acquired data (or again just 4 periods) and use some method for digital signal processing, such as Fast Fourier Transform (FFT). With FFT, it is possible to bring down complexity of acquired data [5] and then analyze only the simplified signal which one still has the key role in the measurement. Because we used RC passive integrator, calculated induced voltage should be already filtered from added noise of higher frequencies. But still, it is possible to check the induced voltage with FFT to find frequency components of a signal. The result can be seen in *Fig.5*. It is clearly visible that for generated signal of frequency 250 Hz the induced signal is composed with also different frequencies (mostly lower one). The next steps would be to limit these additional frequencies, reconstruction of original signal with inverse FFT and computing B-H curve again.

At this point, it is not necessary to make further analysis of achieved B-H curves. From the Fig. 4 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. 4. 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 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 [7, 8]. 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.

During the measurement, the toroidal shape core was located in the tank with mixing the water and the water temperature controller (set to 30°C). It was possible to keep toroidal core at nearly same temperature as surrounding water, but for higher currents and frequencies, there was a bigger temperature difference. Therefore, how to maintain same temperature of the core during the whole measurement needs further investigation.

3.1 Application of acquired data

Even when it wasn't possible to achieve B-H characteristic for the higher frequencies and current, it is already possible to use acquired data to check design of our PMSM. Implementing data of B-H curve into FEMM software is shown in *Fig. 6*.

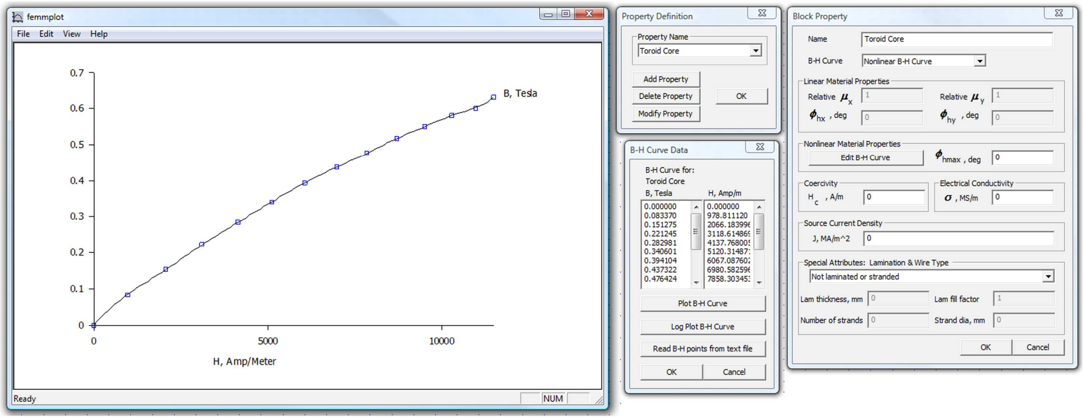

Fig. 6 *Inserting data of B-H curve into FEMM software*

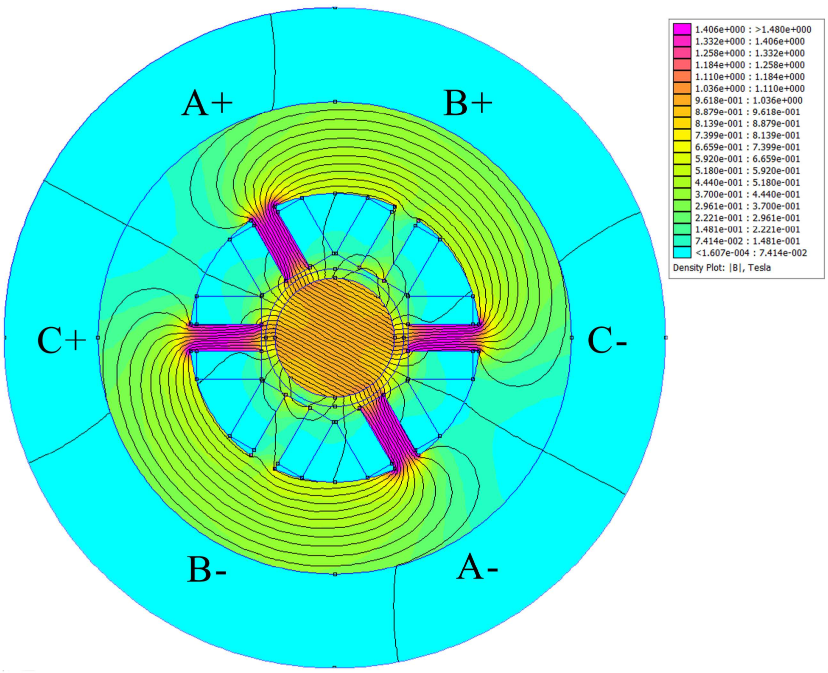

Fig. 7 *Result of FEM analysis with one active pole pair B+ and B-; current 3A*

Results of FEM analysis with current 3A in only one active pole pair B+ and B- is in *Fig. 7*. Used permanent magnet is type N42.

With using a built in computing functions, it is now possible to analyze hysteresis losses per cycle and compare them with analytical method solutions [6, 9]. Also, because our prototype of PMSM is already built, we can use obtained data from FEMM for a comparison with the real losses. Other functions such as computing the torque can be used.

4. Conclusion

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.

Obtained B-H characteristic was implemented into FEMM software and generated results from its computational core will be compared with data from real PMSM, so the design of PMSM can be improved in the future. Also, with the new measurement for different frequencies and current, the B-H characteristic will be updated. Based on these results, other materials for the toroidal shape core can be considered.

Nomenclature

$H\,(t)$	magnetic field intensity	$(\mathrm{A \cdot m^{-1}})$
$B\,(t)$	magnetic flux density	(T)
N_1	number of turns in the primary coil	( )
N_2	number of turns in the secondary coil	( )
S	cross section of the toroidal shape core	$(\mathrm{m^2})$
r	middle radius of the toroidal shape core	(m)
B_0	offset	(T)
$\phi\,(t)$	magnetic flux inside the core	(Wb)
$i_1\,(t)$	current of the primary coil	(A)
$u_2\,(t)$	induced voltage on the secondary coil	(V)
$v_2\,(t)$	measured voltage on the capacitor in the RC integrator circuit	(V)
R	value of the resistor in the RC integrator circuit	(Ω)
C	value of the capacitor in the RC integrator circuit	(F)
L_1	inductance of the primary coil	(H)
L_2	inductance of the secondary coil	(H)
R_1	resistance of the primary coil	(Ω)
R_2	resistance of the secondary coil	(Ω)
$U_2\,(f)$	discrete Fourier transform (DFT) of vector $u_2\,(t)$	(V)

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