PRECISE DETERMINATION OF THE ANGULAR DISTRIBUTION OF THE WINDING INDUCTANCE OF A SWITCHED RELUCTANCE MOTOR

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***Abstract* - The article describes a precise method to obtain the angular profile of the winding inductance of a switched reluctance motor. The introduction emphasises the importance of research carried out in the context of the development of fault-tolerant control of the motor drive. The basis of the analysis presented here is the study of the current waveform accompanied by a forcing voltage, thus revealing the finite dynamics of the circuit RL. The study considers the nonlinear approximation function modeling the current waveform against other simplified methods. Further data processing and the methodology used in the context of the proprietary hardware layer allow to obtain repeatable and reliable results.**

I. INTRODUCTION

The publication aims to present an automatic and precise method for determining the angular inductance distribution in a switched reluctance motor (SRM) phase winding. The inductance profile is a fundamental component of the SRM model based on the fundamental circuit equation [1-3]:

$$U_p = i_p R_p + \frac{d\Psi_p}{dt}, \tag{1}$$

where: p – phase number, U_p(V) – winding voltage, R_p(Ω) – resistance, Ψ_p(Wb) magnetic flux linkage, t(s) - time.

Assuming that the linked flux Ψ_p is dependent on the angle of the shaft position (θ_p) and winding current value (i_p) taking into account the parameter describing the dynamics of the magnetic field energy storage phenomenon in the circuit equation (winding inductance):

$$\Psi_p\left(\theta_p, i_p\right) = L_p\left(\theta_p, i_p\right) i_p \tag{2}$$

it becomes clear that the difficulty of modeling an SRM comes down to the description of its inductance variability (highly nonlinear). Even if consider some simplification of equation (2) aimed at reducing computational complexity for real-time processing [4] to the form:

$$\Psi_p\left(\theta_p, i_p\right) = F_1(\theta_p) F_2(i_p), \tag{3}$$

where: F_1 – inductance (and its derivative of the argument x $F_1'(x)$) angular profile (L_p), F_2 – simplified model of saturation (independent from rotor position), the fundamental motor equations, based on the expansion of the general circuit equation (1):

$$U_p = i_p R_p + \frac{F_1(\theta_p) F_2(i_p)}{\partial i_p} \frac{di_p}{dt} + \frac{F_1(\theta_p) F_2(i_p)}{\partial \theta_p} \frac{d\theta_p}{dt} \tag{4}$$

are:

$$\varepsilon = F_1'\left(\theta_p\right) F_2\left(i_p\right) \omega_r, \tag{5}$$

for back-electromagnetic force, and:

$$T_p\left(\theta_p, i_p\right) = F_1'\left(\theta_p\right) \int_{\nu=0}^{i_p} F_2(\tau) d\nu. \tag{6}$$

for electromagnetic torque generation.

Considering the above, two 1D nonlinear relations of inductance profile (F_1) and magnetic circuit saturation modeling function (F_2) are required.

The well-determined motor model is the basis for the development of complex and precise algorithms in particular sensorless and fault tolerant control (FTC).

II. LABORATORY TEST BENCH

For the presented study, a dedicated laboratory stand was constructed. The stand structure and its view are shown in Fig. 1 and Fig. 2, respectively.

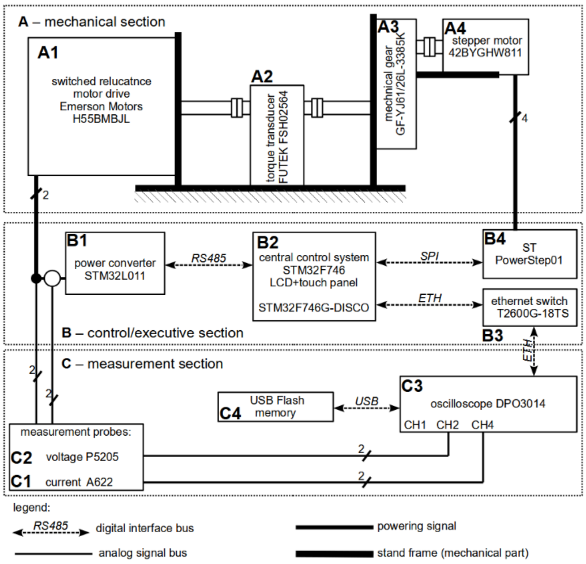

Fig. 1. Structure of the laboratory stand

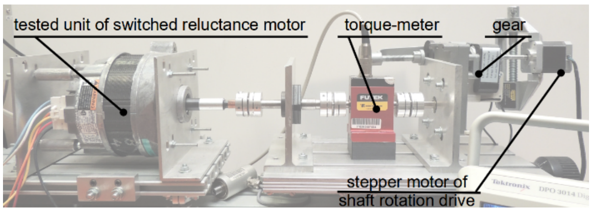

Fig. 2. The mechanical part of the laboratory setup (kinematic chain)

The fully automated, proprietary laboratory test bench has many interesting solutions for data acquisition with very high precision of position angle setting, i.e. 72,5x10^{-9} *rad*.

III. RAW DATA SOURCE

Input data for the analysis and determination of the inductance profile are series: the excitation voltage and the resulting motor phase current (Fig. 3). Data comes from remote controlled oscilloscope measurements in setup that allows to obtain best results e.g. coverage of the measurement range (in an automated process).

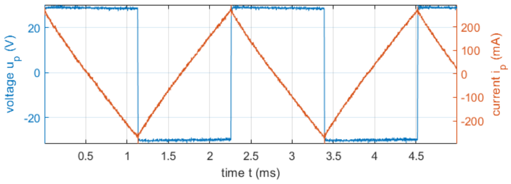

Fig. 3. Waveforms of the excitation voltage and the resulting winding current

IV. APPROXIMATION MODELS

For comparison, two classes of models of the phenomenon describing the dynamics of motor current waveform were used. A simplified - linear and a more accurate nonlinear one. Three methods were used to determine the inductance L_p at a given shaft position θ_p : "*LinA*" called (with no resistance component), "*LinB*" and "*EXP*" (taking into account the time constant of the RL circuit). In linear model, the directional coefficient of regression (a_l) was calculated, what gives the final formula for (*LinA*) and (*LinB*) approach:

$$\text{(A) } L_{p-LinA} = \frac{\overline{U}_p}{a_l} \qquad \text{(B) } L_{p-LinB} = \frac{\overline{U}_p - \overline{i}_p R_p}{a_l}. \tag{7}$$

where $\overline{U}_p$, $\overline{i}_p$ – average values in registered data series.

The resulting inductance for the *EXP* method is based on the time constant value τ :

$$L_{p-EXP} = \tau R_p , \tag{8}$$

that results from approximation formula, where parameter β models an non-zero initial value of measured signal (Figure 3):

$$f(\tau, \beta) = \left(\frac{\overline{U}_p}{R_p} - \beta\right)\left(1 - e^{-t/\tau}\right) + \beta \tag{9}$$

V. RESULTS

Figure 4 presents a plot of inductance profiles obtained by different approximation formulas of motor winding current waveforms. When comparing, relative differences are not large, but it highly depends on measurement conditions (as on relative current peak-to-peak value). Results complies with parametric relations shown in Figure 5 and 6 obtained from accurate simulation of the experimental process. One of the most important is the peak value of current winding (i_m) as the result of PWM voltage excitation. The controlled peak current value during data acquisition for results shown in Figure 4 was 250 mA – quite small in relation to steady state value $i_A = U_p / R_p$ i.e.: 0,07 (see Figure 6 for that value).

The further studies focused only on analysis of obtained inductance profiles from best quality *EXP* approximation. The repeatability was checked for different source data series. The compensation methods of used probes measurement error (linearity, offset) and mechanical imperfections (e.g. gear clearances) were introduced. All efforts provide final, symmetric and ready to use in mathematical model reference inductance angular profile and its derivative (see equations (5) and (6)).

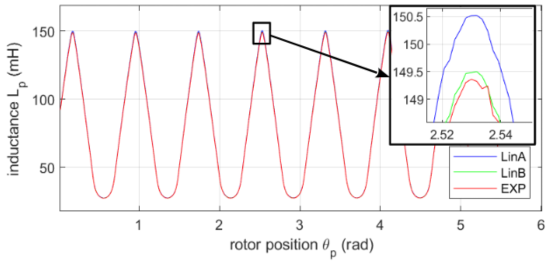

Fig. 4.The plot of selected inductance profiles determined based on calculation of different forms of approximation formulas.

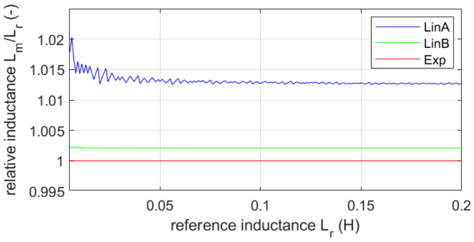

Fig. 5. Computation results of relative inductance (L_m/L_r) from the reference value (L_r) for different approximation formulas used

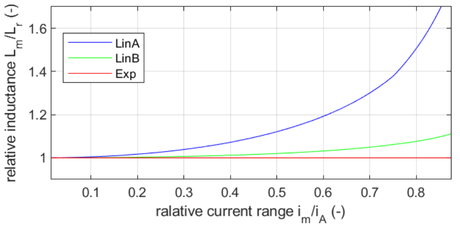

Fig. 6. Calculated relative inductance value L_m/L_r in dependence of relative winding current peak value (i_m / i_A) as process parameter

VI. SUMMARY

The paper discusses a method leading to the precise determination of the angular distribution of the switched reluctance motor winding inductance based on measurements realized on a proprietary automated test bench. Finally obtained results serve as the basis for developing fault-tolerant control algorithms using nonlinear reference model calculated in real-time regime.

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