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Building working characteristics testing tool of BLDC engine using cylinder from space on the excell software platform

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Abstract: *In this article, the author focuses on building and modeling 3-phase BLDC permanent magnet motor that attaches the surface at a stable working state based on the Maxwell equation, the law of conservation of energy correlation between mechanical - electrical - magnetic. The method of analyzing circuits from space is used to calculate the electrical characteristics of the motor including: the magnetic field distributed at the air gap, the magnetic field in the teeth / gong stator, the magnetic field distributed in the permanent magnet as in Rotor. Thereby calculating the basic coefficients of the motor such as: values of axial inductance and horizontal axis inductance, motor magnetic coefficients, ferromagnetic loss, copper loss ... Results of the analysis process is the input basis for the construction of an equivalent circuit model in the motor, calculation of power, starting torque, breaking moment and the input for the design of dynamic control engine, as well as the optimization of engine structure in the next sections. The entire process of analysis and calculation is packaged into a tool on Excell software platform to help users easily use and quickly test. The calculation tool results are compared with Maxwell's electromagnetic simulation software to compare the accuracy as well as the speed and convenience of the tool..*

Keywords: *BLDC working characteristics, magnetic circuit space; BLDC motor modeling; surface gluing on Maxwell's equations system.*

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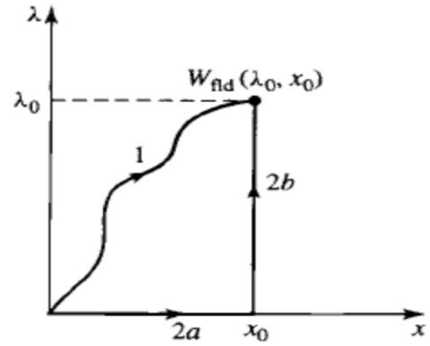
I. Theory basis

- Suppose the magnetic circuit is linear in x:



Graph of internal performance in x

- We have the internal potential at x_0 defined by the formula

$$W_{fld(\Psi_0,x_0)} = \frac{1}{2}\frac{1}{L(x_0)}\Psi_0^2$$

- Relationship between electromagnetic forces and kinetic energy

$$dW_{fld} = id\Psi - Fdx$$

- Consider $W_{fld} = W_{fld}(i,x)$, we have:

$$dW_{fld} = \frac{\partial W_{fld}}{\partial \Psi} d\Psi + \frac{\partial W_{fld}}{\partial x} dx$$

=>

$$\begin{cases} i = \dfrac{\partial W_{fld}}{\partial \Psi} \\ F = -\dfrac{\partial W_{fld}}{\partial x} \end{cases}$$

- Define the concept of "**co-energy**" $W^{'}_{fld}$ according to amperage I and position x:

$$W^{'}_{fld} = i\Psi - W_{fld}(\Psi, i)$$

- Derivative two sides of the equation we get:

$$\begin{cases} \Psi = \dfrac{\partial W^{'}_{fld}(i,x)}{\partial i} \\ \begin{bmatrix} f_{fld} = \dfrac{\partial W^{'}_{fld}(i,x)}{\partial x} \\ t_e = \dfrac{\partial W^{'}_{fld}(i,\theta)}{\partial \theta} \end{bmatrix} \end{cases}$$

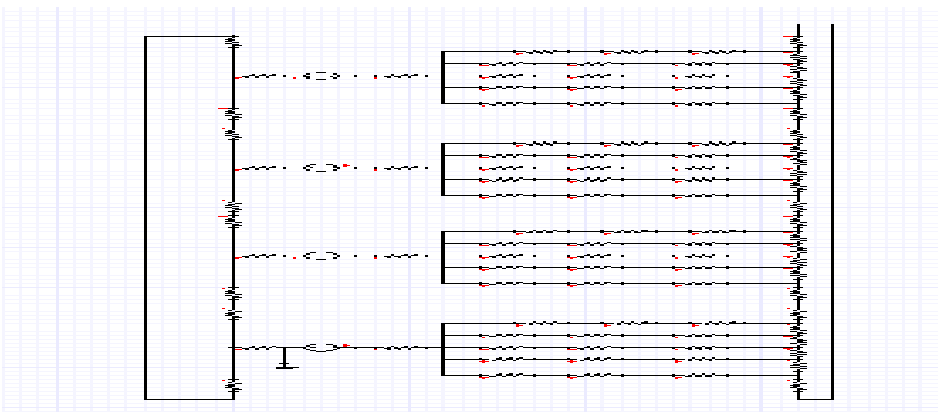
- The energy co-linear system can be calculated by

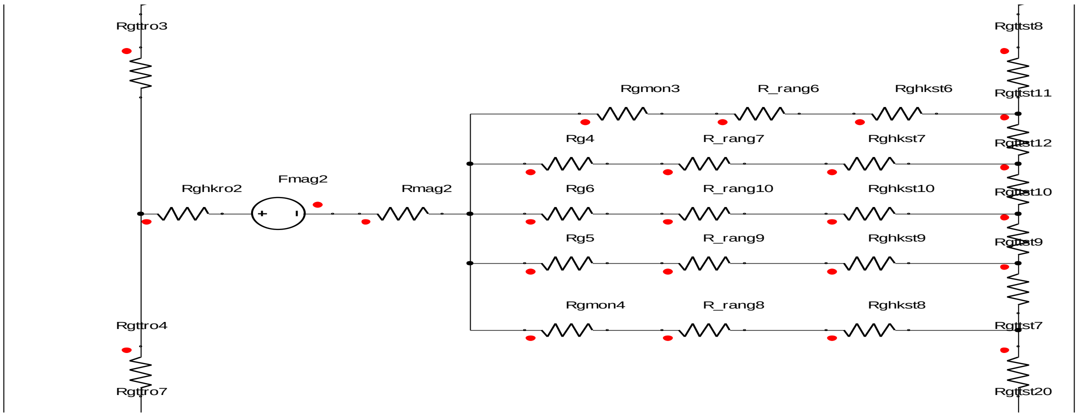
$$W^{'}_{fld}(i_0, x_0) = \frac{1}{2} L(x_0) i_0^2$$

Hay $W^{'}_{fld}(i,x) = \frac{1}{2} L(x) i^2$

II. Construction model

Equivalent main magnetic circuit model





III. The results of motor characteristics analysis

1. Induction from horizontal and vertical axis

- Induction values from horizontal and vertical are given by the formula

$$\begin{cases} L_d = k_{qd}\dfrac{N^2}{R_d} = 0.025138 \\ L_q = k_{qd}\dfrac{N^2}{R_q} = 0.021560 \end{cases}$$

- The induced electromotive force generated by the magnet poles is:

$$\begin{bmatrix} e_a \\ e_b \end{bmatrix} = \begin{bmatrix} e_{\max} * \cos(\omega_{dien} t) \\ e_{\max} * \cos(\omega_{dien} t + \pi / 2) \end{bmatrix}$$

- Suppose the input voltage is modulated in the form of a sine wave:

$$\begin{bmatrix} v_a \\ v_b \end{bmatrix} = \begin{bmatrix} 220 * \cos(\omega_{dien} t) \\ 220 * \cos(\omega_{dien} t + \pi / 2) \end{bmatrix}$$

- The motor equation is written in dq coordinates:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} - \begin{bmatrix} e_d \\ e_q \end{bmatrix} = \begin{bmatrix} R_1 & L_q\omega_e \\ -L_d\omega_e & R_1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

- We have:

+ Conversion matrix of coordinate axis C

$$C = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

$$C^t = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

+ The transformation of the coordinate axis dq

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = C^t \begin{bmatrix} v_a \\ v_b \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_a \\ v_b \end{bmatrix} = \begin{bmatrix} v_a\cos\theta + v_b\sin\theta \\ v_a\sin\theta + v_b\cos\theta \end{bmatrix}$$

$$\begin{bmatrix} e_d \\ e_q \end{bmatrix} = C^t \begin{bmatrix} e_a \\ e_b \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_a \\ v_b \end{bmatrix} = \begin{bmatrix} e_a \cos\theta + e_b \sin\theta \\ e_a \sin\theta + e_b \cos\theta \end{bmatrix}$$

+ R1 is the resistance of the copper wire determined by the expression

$$R_1 = \frac{\rho l_{day}}{s_d} = 0.6$$

+ Where l is the length of the 1-pole wire

$$l_{day} = \left(2l_{moto} * 1.15 + 2 * \frac{C_4 * \mathrm{p}_{wind}}{n_{t-sta}} \right) * n_{day} * \frac{n_{t-sta}}{2p} = 36$$

- The general motor equation is rewritten:

$$\begin{bmatrix} (v_a - e_a)\cos\theta + (v_b - e_b)\sin\theta \\ (v_a - e_a)\sin\theta + (v_b - e_b)\cos\theta \end{bmatrix} = \begin{bmatrix} R_1 & L_q\omega_e \\ -L_d\omega_e & R_1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} R_1 & L_q\omega_e \\ -L_d\omega_e & R_1 \end{bmatrix}^{-1} \begin{bmatrix} (v_a - e_a)\cos\theta + (v_b - e_b)\sin\theta \\ (v_a - e_a)\sin\theta + (v_b - e_b)\cos\theta \end{bmatrix}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \dfrac{R_1}{R_1^2 + L_d L_q \omega_e^2} & \dfrac{-L_q\omega_e}{R_1^2 + L_d L_q \omega_e^2} \\ \dfrac{L_d\omega_e}{R_1^2 + L_d L_q \omega_e^2} & \dfrac{R_1}{R_1^2 + L_d L_q \omega_e^2} \end{bmatrix} \begin{bmatrix} (v_a - e_a)\cos\theta + (v_b - e_b)\sin\theta \\ (v_a - e_a)\sin\theta + (v_b - e_b)\cos\theta \end{bmatrix}$$

$$\begin{cases} i_d = \dfrac{R_1\left((v_a - e_a)\cos\theta + (v_b - e_b)\sin\theta\right)}{R_1^2 + L_d L_q \omega_e^2} + \dfrac{-L_q\omega_e\left((v_a - e_a)\sin\theta + (v_b - e_b)\cos\theta\right)}{R_1^2 + L_d L_q \omega_e^2} \\ i_q = \dfrac{L_d\omega_e\left((v_a - e_a)\cos\theta + (v_b - e_b)\sin\theta\right)}{R_1^2 + L_d L_q \omega_e^2} + \dfrac{R_1\left((v_a - e_a)\sin\theta + (v_b - e_b)\cos\theta\right)}{R_1^2 + L_d L_q \omega_e^2} \end{cases}$$

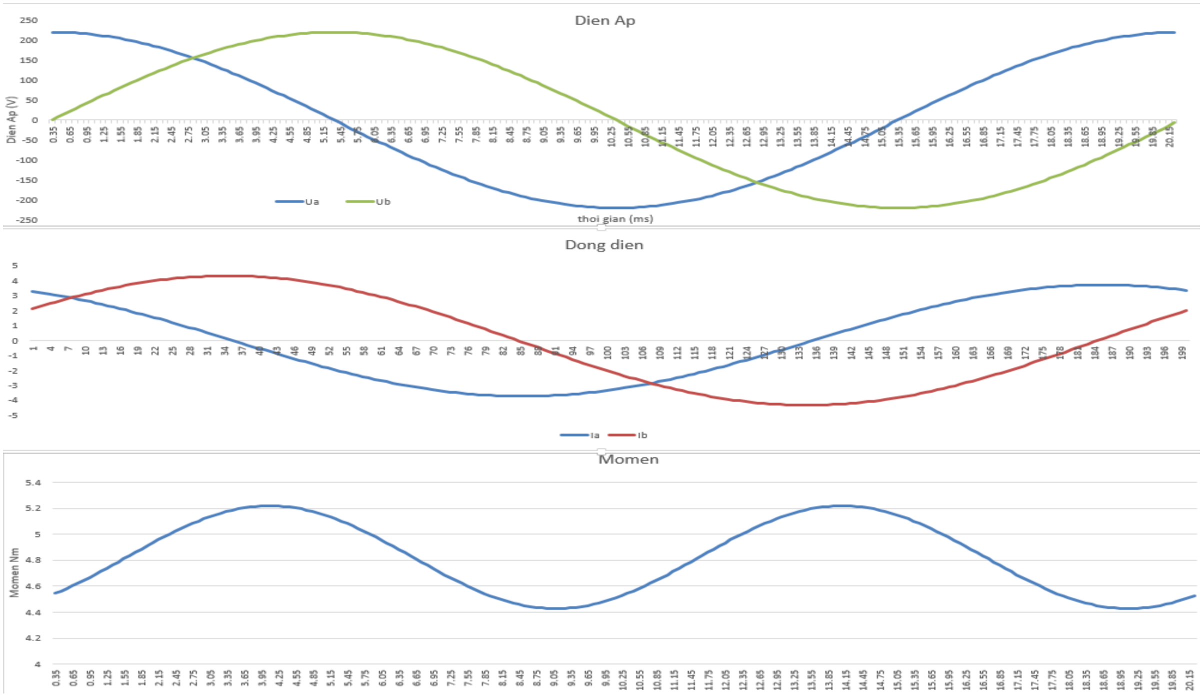
- The motor torque equation is determined by the formula:

$$T_e = \frac{(i_a e_a + i_b e_b)}{\mathrm{w}_{co}}$$

2. The simulation results

- Replace the numbers and we get the motor torque in the form as:

+ Adjust input voltage to have sinusoidal form:



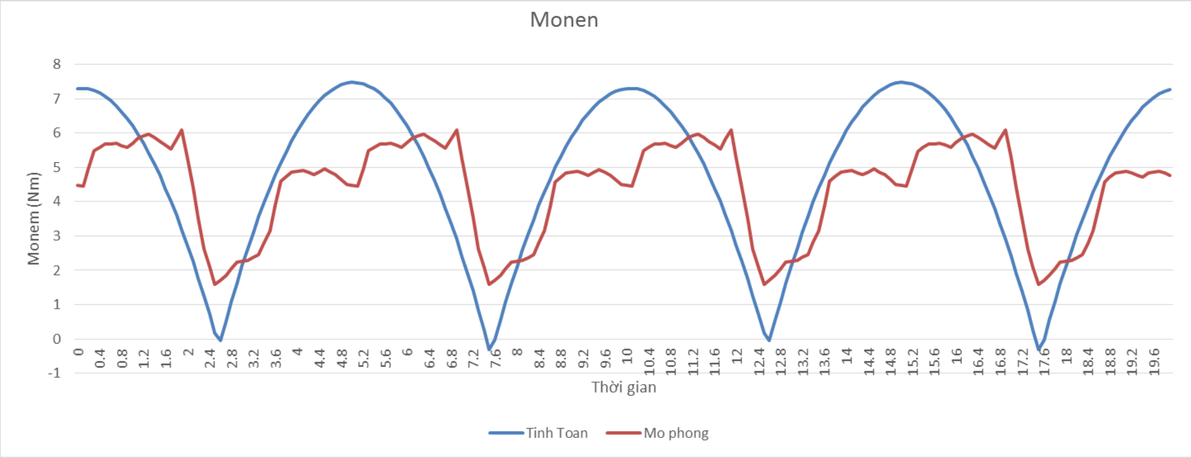
+ Maximum torque of 5.2Nm; minimum torque is 4.5Nm, average value is 4.85 Nm

+ Adjust input voltage to have square pulse

+ Maximum torque of 7.5 Nm; minimum torque reaches 0 Nm, average value reaches 4.7Nm

3.3 Compare results with calculus

Timetable torque



Torque

	Simulation	Calculation
Average torque value	4.4 Nm	4.7Nm
Maximum value	6.2 Nm	7.5Nm
Minimum value	1.5 Nm	0 Nm

Inductive:

	Simulation	Calculation
On the permanent magnet	0.789T	0.81T
Maximum induced electromotive force	213V	211V
The magnetic flux loops through each maximum phase	0.57Wb	0.65Wb

IV. Ratings and recommendations

- The analytical results show that there are certain differences between calculus and simulation.
- The basic parameters of magnetic field distribution, electromotive force are slightly different, but the torque value is much more different.
- To calculate the resistance of the circuit must be through the approximate formula and only calculated at a few relative motion points of the Rotor and Stator.
- Therefore, the calculated values can be approximations only. Meanwhile, the 3D simulation can calculate the exact value on each point and find out the instantaneous values.
- In addition, geometric non-linear elements and materials in analytical methods have been omitted to simplify the problem. While 3D simulation can mention the influence of these factors.

In order to improve the torque characteristics, we can optimize the shape of the rotor teeth, change the structure of the magnet pole surface to get a more evenly distributed or slotted teeth stator to create a uniform gap distribution or use the inclined magnet structure.

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