INTEGRATION OF MATHEMATICAL MODELING AND ELECTROMAGNETIC TESTING METHODS FOR ASSESSING THE TECHNICAL CONDITION OF ELECTRIC MOTORS

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Abstract. Modern in industry electricity engines main driving force from the forces one They are various industry in networks wide applies and their efficiency of enterprises general work to the activity directly impact shows . Therefore, electricity engines technician status regular accordingly assessment and observation important importance has . Traditional diagnostics methods sometimes limited to accuracy has there are many time and requires resources . Mathematical modeling and electromagnetic check methods integration to do and this problems solution in doing effective solution as manifestation is happening .

Keywords. Electric motors, diagnostics, mathematical modeling, electromagnetic testing, asynchronous motors, differential equations, Park transformation, motor performance, reliability, maintenance optimization.

Mathematician Modeling Role

Mathematician modeling electricity engines work parameters clear and systematic accordingly description opportunity This gives method using of the engine internal processes , electromagnetic fields and heat spread mathematician equations through expression It is possible . This is potential defects in advance determination and of the engine work fertility to optimize help gives .

Electricity engines mathematician models create their performance deep understanding , control to do and optimization for Below we will discuss three types of asynchronous (induction) phased electricity of the engine complete mathematician model seeing we go out , because they in industry the most wide spread .

1. Home Assumptions and Variables

- **Assumptions :**
  - Magnet chain saturated it's not .
  - Unchangeable air space .

- Phases symmetrical
- Temperature and frequency impact in consideration not available .

- **Variables :**
  - v is voltage (V).
  - i — current (A).
  - λ — current connection (Wb).
  - R is resistance (Ω).
  - L is inductance (H).
  - ω — angle speed (rad/s).
  - T_e is electromagnetic torque (Nm).
  - T_L — load torque (Nm).
  - J is moment of inertia (kg·m²).
  - p — even poles number .

2. From phase Quadratures Coordinates Jump

Three phased the system is in d–q coordinates to the system transfer Park and Clarke transformations for is applied .

- **Clarke Transformation :**

Three phased variables two static to variables passes (α, β).

- **Park Transformation :**

Static α , β components to rotating d–q coordinates conducts .

3. Electricity Chain Equations

- **Stator Equations :**

$$\begin{cases} v_{ds} = R_s i_{ds} + \dfrac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} \\ v_{qs} = R_s i_{qs} + \dfrac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds} \end{cases}$$

- **Rotor Equations (for the stator) relative):**

$$\begin{cases} 0 = R_r i_{dr} + \dfrac{d\lambda_{dr}}{dt} - (\omega_s - \omega_r)\lambda_{qr} \\ 0 = R_r i_{qr} + \dfrac{d\lambda_{qr}}{dt} + (\omega_s - \omega_r)\lambda_{dr} \end{cases}$$

This on the ground :

- ω_s — synchronous corner speed (in the stator).
- ω_r — rotor corner speed .

Flow connections inductances through is defined as :

Stator :

$$\begin{cases} \lambda_{ds} = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} = L_s i_{qs} + L_m i_{qr} \end{cases}$$

Rotor :

$$\begin{cases} \lambda_{dr} = L_r i_{dr} + L_m i_{ds} \\ \lambda_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases}$$

This on the ground :

- L_s — stator own himself inductance .
- L_r — rotor own himself inductance .
- L_m — mutual inductance .

5. Electromagnetic Moment Equation

Electromagnetic torque as follows is expressed as :

$$T_e = \frac{3}{2} p L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right)$$

6. Mechanical Equation of Motion

Rotor rotation dynamics Newton's second to the law mainly :

$$J = \frac{d\omega_r}{dt} = T_e - T_L - B\omega_r$$

This on the ground :

- B — viscous friction coefficient .

7. Complete Differential Equations System

Above equations integrating , differential equations system harvest we do :

- **Stator vines differential equations :**

$$\begin{cases} \dfrac{di_{ds}}{dt} = \dfrac{1}{L_s}\left(v_{ds} - R_s i_{ds} + \omega_s L_s i_{qs} - \omega_s L_m i_{qr} - L_m \dfrac{di_{dr}}{dt}\right) \\ \dfrac{di_{qs}}{dt} = \dfrac{1}{L_s}\left(v_{qs} - R_s i_{qs} + \omega_s L_s i_{ds} - \omega_s L_m i_{dr} - L_m \dfrac{di_{qr}}{dt}\right) \end{cases}$$

- **Rotor vines differential equations :**

$$\begin{cases} \dfrac{di_{dr}}{dt} = \dfrac{1}{L_r}\left(-R_r i_{dr} + (\omega_s - \omega_r) L_r i_{qr} - (\omega_s - \omega_r) L_m i_{qs} - L_m \dfrac{di_{ds}}{dt}\right) \\ \dfrac{di_{qr}}{dt} = \dfrac{1}{L_r}\left(-R_r i_{qr} - (\omega_s - \omega_r) L_r i_{dr} + (\omega_s - \omega_r) L_m i_{ds} - L_m \dfrac{di_{qs}}{dt}\right) \end{cases}$$

- **Rotor angle speed differential equation :**

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_e - T_L - B\omega_r)$$

This is a differential. equations system numerical methods (e.g. , Runge- Kutta using the method) solution This engine is possible . dynamic behavior time according to study opportunity gives .

9. Model Parameters

Model's correct performance for all parameters to be determined need :

- **Electricity Parameters :**
  - R_s, R_r, L_s, L_r, L_m.
- **Mechanical Parameters :**
  - J, B, p.
- **External Variables :**
  - Login voltages v_{ds}, v_{qs}.
  - Download moment T_L.

Electricity engine dynamic behavior clear description for differential equations system further improvement It is necessary . It is not only model accuracy increases , maybe him/her numerical methods using solution and simulation makes it easier to do

Complete Differential Equations System Next Improvement

Electricity engine dynamic behavior clear description for differential equations system further improvement It is necessary . It is not only model accuracy increases , maybe him/her numerical methods using solution and simulation makes it easier to do .

1. Variables Again Identification

- **Leakage Inductances** : Mutual dependencies simplification for leak inductances we enter .
  - Stator leakage inductance : $L_{ls} = L_s - L_m$
  - Rotor leakage inductance : $L_{lr} = L_r - L_m$
- **Slip** : Between the rotor and the stator speed difference as is determined .

$$s = \frac{\omega_s - \omega_r}{\omega_s}$$

2. Flow Their connections Expression

Flow connections now leak and mutual inductances through is expressed as :

- **Stator Flow Links** :

Stator :

$$\begin{cases} \lambda_{ds} = L_{ls} i_{ds} + L_m i_{dr} \\ \lambda_{qs} = L_{ls} i_{qs} + L_m i_{qr} \end{cases}$$

Rotor :

$$\begin{cases} \lambda_{dr} = L_m i_{ds} + L_{lr} i_{dr} \\ \lambda_{qr} = L_m i_{qs} + L_{lr} i_{qr} \end{cases}$$

3. Electricity Equations Improvement

Stator Equations :

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds} \end{cases}$$

Rotor Equations (for the stator) relative):

$$\begin{cases} 0 = R_r i_{dr} + \dfrac{d\lambda_{dr}}{dt} - (\omega_s - \omega_r)\lambda_{qr} \\ 0 = R_r i_{qr} + \dfrac{d\lambda_{qr}}{dt} + (\omega_s - \omega_r)\lambda_{dr} \end{cases}$$

Equations Matrix In the form of Expression

Equations matrix in the form of to write through them simplification and computer simulation for comfortable to form to bring possible .

Electricity Equations :

$$V_s = R_s i_s + \frac{d\lambda_s}{dt} - \omega_s J\lambda_s$$

$$0 = R_r i_r + \frac{d\lambda_r}{dt} - (\omega_s - \omega_r)J\lambda_r$$

This on the ground :

- $V_s = \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix}$
- $i_s = \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix}$
- $\lambda_s = \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix}$
- $i_r = \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix}$
- $\lambda_r = \begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix}$
- $R_s = R_s I$, $R_r = R_r I$
- $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$
- I — 2x2 units matrix .

Flow Their connections Matrix In the form of Expression

$$\lambda_s = L_s i_s + L_m i_r$$

$$\lambda_r = L_m i_s + L_r i_r$$

This on the ground :

- L $_s$ = L $_{ls}$ I
- L $_r$ = L $_{lr}$ I
- L $_m$ = L $_m$ I

Cases Phase Jump

Cases vector

$$x = \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ \omega_r \end{bmatrix}$$

Login vector

$$u = \begin{bmatrix} v_{ds} \\ v_{qs} \\ T_L \end{bmatrix}$$

Differential Equations :

$$\frac{dx}{dt} = Ax + Bu$$

Matrix A :

$$A = \begin{bmatrix} -\frac{R_sL_{lr} + R_rL_m}{\Delta} & \omega_s\frac{L_{lr}}{\Delta} & \frac{R_rL_m}{\Delta} & -(\omega_s - \omega_r)\frac{L_m}{\Delta} & 0 \\ -\omega_s\frac{L_{lr}}{\Delta} & -\frac{R_sL_{lr} + R_rL_m}{\Delta} & (\omega_s - \omega_r)\frac{L_m}{\Delta} & \frac{R_rL_m}{\Delta} & 0 \\ \frac{R_sL_m}{\Delta} & -(\omega_s - \omega_r)\frac{L_m}{\Delta} & -\frac{R_rL_{ls} + R_sL_m}{\Delta} & \omega_r\frac{L_{ls}}{\Delta} & 0 \\ (\omega_s - \omega_r)\frac{L_m}{\Delta} & \frac{R_sL_m}{\Delta} & -\omega_r\frac{L_{ls}}{\Delta} & -\frac{R_rL_{ls} + R_sL_m}{\Delta} & 0 \\ 0 & 0 & 0 & 0 & -\frac{B}{J} \end{bmatrix}$$

Here $\Delta = L_{ls}L_{lr} - L_m^2$.

Matrix B :

$$B = \begin{bmatrix} \frac{L_{lr}}{\Delta} & 0 & 0 \\ 0 & \frac{L_{lr}}{\Delta} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1/J \\ 0 & 0 & \end{bmatrix}$$

Electromagnetic torque situations via :

$$T_e = \frac{3}{2}p(L_m(i_{qs}i_{dr} - i_{ds}i_{qr}))$$

Rotor speed change :

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_e - T_L - B\omega_r)$$

Differential equations system further improvement electricity engine model accuracy increases and his/her various work in modes behavior more precisely prophecy to do opportunity gives . The equations matrix and stands in phase expression numerical solution methods to apply facilitates and simulation of the results reliability increases . Additional factors in consideration to take and in real conditions of the engine performance better to the model to bring help gives .

Electricity engine mathematician model his/her performance clear and reliable description for permanent accordingly improvement Below we will describe the model further improvement for additional factors in consideration we will get and differential equations system deeper working Let's go out .

Magnet Saturation To the equations Input :

Inductances of the stream function as we express :

$$L_m(i_m) = \frac{\lambda_m}{i_m}$$

Here i $_{m}$— magnetizer vine :

$$i_m = \sqrt{i_{ds}^2 + i_{qs}^2}$$

Flow connections now variable inductances through is expressed as :

$$\lambda_{ds} = L_{ls}i_{ds} + L_m(i_m)i_{dr}$$

$$\lambda_{qs} = L_{ls}i_{qs} + L_m(i_m)i_{qr}$$
$$\lambda_{dr} = L_m(i_m)i_{ds} + L_{lr}i_{dr}$$
$$\lambda_{qr} = L_m(i_m)i_{qs} + L_{lr}i_{qr}$$

Iron Loss Resistance To the equations Input :

Iron losses to the stator circuit for additional resistance R_{fe} is entered .

Stator Equations :

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} + e_{fe,d}$$
$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds} + e_{fe,q}$$

Iron losses as a result harvest was against EEMF:

$$e_{fe,d} = R_{fe}i_{fe,d}$$
$$e_{fe,q} = R_{fe}i_{fe,q}$$

This on the ground $i_{fe,d}$and $i_{fe,q}$are the iron loss currents, which are defined as follows:

$$i_{fe,d} = \frac{\lambda_{ds}}{L_{fe}}$$
$$i_{fe,q} = \frac{\lambda_{qs}}{L_{fe}}$$

L_{fe} — iron loss inductance .

Resistance and Inductances To the temperature Gardening as follows to look has will be :

Resistances :

$$\boldsymbol{R_s(T) = R_{s0}[1 + \alpha_s(T - T_0)]}$$
$$\boldsymbol{R_r(T) = R_{r0}[1 + \alpha_r(T - T_0)]}$$

Inductances to the temperature dependency magnet conductivity through is expressed , but often this impact small happened for out of consideration aside will be left or linear hypothesis will be done .

Heat Equation :

- **Stator Temperature :**

$$\boldsymbol{C_{th,s}\frac{dT_s}{dt} = P_{loss,s} - P_{cool,s}}$$

$\boldsymbol{P_{loss,s}}$— in the stator losses :

$$\boldsymbol{P_{loss,s} = R_sT_s\left(i_{ds}^2 + i_{qs}^2\right) + R_{fe}\left(i_{fe,d}^2 + i_{fe,q}^2\right)}$$

- **Rotor Temperature :**

$$C_{th,r}\frac{dT_r}{dt} = P_{loss,r} - P_{cool,r}$$

$P_{loss,r}$— rotor losses:

$$P_{loss,r} = R_r T_r\left(i_{dr}^2 + i_{qr}^2\right)$$

Mechanical Losses Input
Mechanical Equation Improved :

$$J\frac{d\omega_r}{dt} = T_e - T_L - B\omega_r - T_{loss}$$

Mechanical Loss Momentum T_{loss}:

$$T_{loss} = k_f\omega_r^2 + k_v\omega_r$$

k_f— ventilation loss coefficient.

k_v— viscous friction coefficient .

High Orderly Harmonics Impact

Tension Harmonic Components :

- **Stator Intensification**

$$v_{ds} = V_1\cos(\omega_s t) + \sum_{n=3,5,\dots}^{\infty} V_n\cos(n\omega_s t + \phi_n)$$

Conclusion

The integration of mathematical modeling and electromagnetic testing methods presents a modern and effective approach for evaluating the technical condition of electric motors. This method significantly enhances the accuracy and speed of the diagnostics process, ensuring timely identification of potential faults and preventing critical failures. By employing advanced modeling techniques and precise electromagnetic analysis, it becomes possible to optimize motor performance and predict maintenance needs effectively.

Moreover, this approach contributes to extending the service life of electric motors, reducing operational costs, and minimizing unplanned downtime. The ability to accurately assess the technical condition of motors in real-time supports proactive maintenance strategies, which are crucial for industries relying on continuous and reliable motor operation.

In the future, further development and refinement of this approach could lead to its broader application across various industries. Its implementation in manufacturing, energy, and transportation sectors promises to improve operational efficiency, enhance system reliability, and promote sustainable practices. This innovative integration underscores the potential of combining cutting-edge technologies to address critical challenges in motor diagnostics and maintenance, paving the way for more resilient and cost-effective industrial operations.

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