EAA Lehrstuhl für Elektrische Antriebstechnik und Aktorik

Chair of Electrical Drives and Actuators

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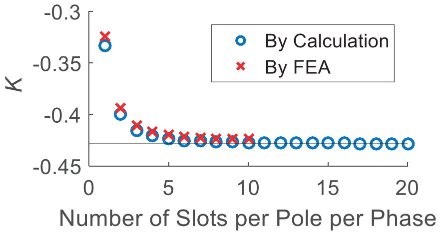
Hrsg.: Prof. Dr.-Ing. Dieter Gerling

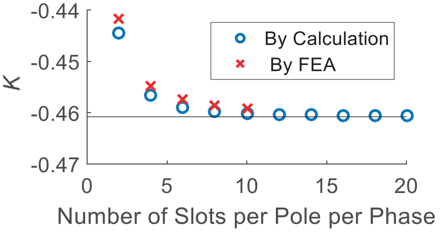
Fei Lu

Induction Machine Control: State Observation, Electromagnetic Analysis, Modeling for Control, Finite Element Simulation, and Rotor Temperature Estimation.

$$\dot{\mathbf{x}} = \mathbf{f}\left(\mathbf{x}, R_r, L_m(\mathbf{x})\right) + \mathbf{m}\left(\mathbf{x}, R_r, L_m(\mathbf{x})\right)$$



(a) Mutual inductance Factor, single-Layer.



(b) Mutual inductance Factor, double-Layer.

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Mom,
forever, your encouragement stays with me.

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31. 03. 2021

ABSTRACT

The main topic of this work is induction motor (IM) control and rotor temperature estimation, which consists of 4 parts.

The first part is IM rotor flux linkage observation based on Luenberger Observer approach. IM saturation model is used, thus, mutual saturation in the air-gap is considered. Rotor resistance uncertainty is considered and estimated with high accuracy as well, via a PI controller or a discrete tuning algorithm. When using IM saturation model, a specific procedure in order to avoid iterative calculation for inductance is used; however, the magnetizing curve measurement error could be significantly 'amplified' through this procedure. The solution to overcome this 'amplification phenomenon' is proposed here in order to enhance the estimation accuracy of rotor resistance as well, which could further used for rotor temperature calculation.

Also, in the first part, the system stability is investigated in detail. The reason that causes system unstable is found. The corresponding solution to achieve system global stable is provided.

The second part is IM electromagnetic analysis, and IM modeling by using rotor mesh current approach. IM is remodeled based on the concept that the magnetomotive force (MMF) in the air gap is step wave, not sine wave. The stator mutual inductance factor is recalculated; it is found that this factor is also influenced by stator winding topology, not always -0.5. Also, IM modeling by using rotor mesh current concept is performed in detail, stator winding topology and rotor skew are considered during the modeling. The advantage of the new IM model is, the rotor resistance has a clear physical meaning, both rotor bar and end ring resistance can be included in the voltage equation.

The third part is about IM finite element analysis (FEA). A sweeping free procedure for IM FEA simulation is proposed, in order to check the correctness of the derived IM model, which based on rotor mesh current concept. As rotor resistance has clear physical meaning by the new IM model, thus, it can be directly calculated, so is the rotor slip angular frequency. The commonly used sweeping method for rotor slip angular frequency to drive IM FEA simulation to the expected operating point is not required anymore. Significant amount of time can be saved when performing IM FEA simulation, especially useful for drawing efficiency map.

The fourth part is about rotor temperature estimation. Via the estimated rotor resistance value from the first part, by using the derived IM model which based on rotor mesh current concept derived in the second part, which validated by the sweeping free procedure proposed in the third part, the rotor temperature calculation can be performed. Rotor thermal sensor can be eliminated, for reducing cost, and enhancing system reliability.

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TABLE of CONTENTS

X

NOMENCLATURE

Scalars

B	Magnetic flux density in air gap, in T.
f_s	Slip angular frequency, in Hz.
g	Air-gap length, in m.
i_A	Stator phase A current, in A.
i_1	Stator current in each parallel branch, in A.
i_r'	Rotor mesh current, in A.
K	Mutual inductance factor.
K_{copper}	Copper temperature coefficient, in 1/K.
K_p	Gain value of the discrete tuning algorithm, for rotor resistance estimation, in Ω/(Vs).
K_{sr}	Scaling factor (or known as transformation ratio) between stator and rotor.
l	Stator number of layers.
L	Machine axial length, in m.
L_s	Stator inductance, after dq transformation, in H.
L_{ss}	Stator inductance by rotor mesh current method, after dq transformation, in H.
L_r	Rotor inductance, after dq transformation, in H.
L_{rr}	Rotor inductance by rotor mesh current method, after dq transformation, in H.
L_m	Mutual inductance, after dq transformation, in H. (In chapter 2-4) Mutual inductance by rotor mesh current method, after dq transformation, in H. (In chapter 6-9)
L_{sr} , L_{rs}	Mutual inductances by rotor mesh current method, after dq transformation, in H.
L_{sm}	Stator single phase inductance, in H.

L_{sl}	Stator leakage inductance, in H.
L_{rl}	Rotor leakage inductance, in H.
m	Number of slots being short pitched. Number of phases.
n_s	Slip angular speed, in rpm.
N_A	Stator number of turns of each parallel branch each phase.
N_1	Stator number of turns per single coil.
p	Pole pair number.
q	Stator number of slots per pole per phase.
Q_s	Stator number of slots.
Q_r	Rotor number of slots.
r	Stator inner radius or rotor outer radius, in m.
R_s	Stator resistance in voltage equation, in Ω.
R_r	Rotor resistance in voltage equation, in Ω.
R_{bar}	Resistance of rotor solid bar, in voltage equation, in Ω.
R_{end}	Resistance of rotor end ring, in voltage equation, in Ω.
t	Time, in s.
T_e	Electrical torque, in Nm.
T	Temperature, in °.
z_p	Number of parallel branch of each stator phase.
z_s	Number of pole-phase sections connected in series in each parallel branch.
α	Mechanical angle between two adjacent slots. (In chapter 5) Mechanical angle used for integration. (In chapter 6-9)
β	Percentage value of the winding being short-pitched.
γ	Mechanical angle used for integration. (In chapter 5) Mechanical angle between two adjacent slots. (In chapter 6-10)

φ	Initial angle between d axis and the center of the first coil of phase A pole-phase section winding, mechanical, in rad.
ξ	Estimated value. (In chapter 3,4) Winding factor. (In chapter 7-10)
ξ_d, ξ_s	Distributed factor and short-pitch factor of stator winding.
ξ_{sk}	Rotor skew factor.
ζ	Estimated value with high accuracy.
θ_1	The mechanical angle shift of center of the stator pole-phase section winding, due to distributed winding and short-pitched winding, in rad.
θ_2	The mechanical angle shift of center of the rotor mesh, due to rotor skew, in rad.
ω_1	System synchronous angular speed, electrical, in rad/s.
ω_r	Rotor angular speed, electrical, in rad/s.
ω_s	Slip angular speed, electrical, in rad/s.
μ	The angle between magnetizing flux linkage $\boldsymbol{\psi}$ and d axis, in rad.
μ_0	Magnetic permeability of free space, in H/m.
τ	Rotor time-constant, Ω/H.
Φ	Flux, in Vs.
ψ	Flux linkage, in Vs.
Θ	Magnetomotive force (MMF) in air gap, in A.
Λ	A scalar used when deriving IM saturation model, in H.

Matrices and Vectors

$\mathbf{A}, \mathbf{B}, \mathbf{C}$	System state matrix, input matrix, and output matrix.
$\mathbf{A}_{ELO}$	System extended state matrix, when Extended Luenberger Observer is used.
$\mathbf{C}_1$	DQ transformation matrix for stator.
$\mathbf{C}_2$	DQ transformation matrix for rotor.
$\mathbf{C}_{ELO}$	System extended output matrix, when Extended Luenberger Observer is used.

$\mathbf{D}$	Partial derivative of system state equation to rotor resistance, when Luenberger Observer is used, vector.
$\mathbf{e}$	Error between vector $\mathbf{z}$ and vector $\mathbf{Tx}$, vector.
$\mathbf{E}_2$	Matrix which influences system error dynamics, when Luenberger Observer is used.
$\mathbf{F},\mathbf{K},\mathbf{T}$	Matrices used for building up Luenberger Observer.
$\mathbf{g}$	Partial derivative of system extended state equation to rotor resistance, when Extended Luenberger Observer is used, vector.
$\mathbf{i}_s = i_{sd} + ji_{sq}$	Stator current, vector, in A.
$\mathbf{i}_s^* = i_{sd}^* + ji_{sq}^*$	Command value for stator current controller, vector, in A. (In chapter 3)
$\mathbf{i}_r = i_{rd} + ji_{rq}$	Rotor current, vector, in A.
$\mathbf{i}_m = i_{md} + ji_{mq}$	Magnetizing current, vector, in A.
$\mathbf{L}_{ss},\mathbf{L}_{rr},\mathbf{L}_{sr},\mathbf{L}_{rs}$	Inductance matrices in flux linkage equation. In (Chapter 6-7)
$\mathbf{M},\mathbf{N}$	Matrices in system state equation of IM saturation model.
$\mathbf{R}_2$	Rotor resistance matrix, by rotor mesh current method, in Ω.
$\mathbf{u}_s = u_{sd} + ju_{sq}$	Stator voltage, vector , in V.
$\mathbf{u}_r = u_{rd} + ju_{rq}$	Rotor voltage, vector, in V.
$\mathbf{x}$	System state variable, vector.
$\hat{\mathbf{x}}$	Estimated value of system state variable, vector.
$\mathbf{y}$	System output, vector
$\mathbf{z}$	Luenberger Observer output, vector.
$\boldsymbol{\psi}_s = \psi_{sd} + j\psi_{sq}$	Stator flux linkage, vector, in Vs.
$\boldsymbol{\psi}_r = \psi_{rd} + j\psi_{rq}$	Rotor flux linkage, vector, in Vs.
$\boldsymbol{\psi}_m = \psi_{md} + j\psi_{mq}$	Mutual flux linkage, vector, in Vs.
$\boldsymbol{\psi} = \psi_d + j\psi_q$	Magnetizing flux linkage, vector, in Vs.
$\boldsymbol{\xi}$	Estimated value of system state variable, vector.
$\boldsymbol{\chi}$	Error of rotor flux linkage estimation, vector.