MRAS based estimation of stator resistance and rotor flux linkage of permanent magnet generator considering core losses

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Abstract— For maximization of efficiency of interior permanent magnet generators (IPMSG) and optimization of machine control correct parameters of the machine are needed. Parameters used in advanced control of the machine are stator resistance, magnetic flux linkage and inductances of *d* and *q* axes. Alongside them ohmic resistance that represents core losses can be employed to further increase efficiency of control. This work will focus on implementation of MRAS estimator that has adaptive models with and without taking into account core losses. Using Matlab Simulink simulations were conducted and comparison of estimators was made under change of current in *d* and *q* axis and different values of resistance that represents core losses. Results show that value of resistance that represents core losses influences estimated values of parameters and that it is beneficial to take into account core losses for efficient control of the machine.

***Index terms*— permanent magnet synchronous generator, MRAS, core losses, parameter identification**

I. INTRODUCTION

Production of electric energy from renewable energy sources is topic that is becoming increasingly popular in recent times. Generation of electric energy from energy of wind is increasing at a rate of around 30 percent annually [1]. With greater interest in production of electric energy from renewable sources greater efficiency of generators and drives is also coming into focus. Typically, synchronous generators with wound rotor and asynchronous doubly fed generators are being used in electric energy production form the energy of wind alongside surface permanent magnet synchronous generators. These kind of machines utilize slip rings and graphite brushes to transfer electrical current to rotor winding. Current flow in rotor winding creates losses and in turn decreases overall efficiency of the drive. Another drawback is need for periodic replacement of brushes which can be done only while generator is at a standstill.

Because of aforementioned reasons and constant fall of prices of permanent magnets electric drives with permanent magnet synchronous machines (PMSM) are becoming increasingly popular. Furthermore, in order to increase reliability mechanical sensors of rotor speed and position are being abandoned and advanced sensorless algorithms are being developed. Such algorithms are sensitive on machine parameter variation and online methods of machine parameter identification to continuously track their variation through time and various drive conditions are needed [2]. Implementation of online parameter identification methods also increase drive efficiency. Identification of machine parameters during operation of the machine is a difficult task because of nonlinear nature of parameter variation [3-4].

For proper operation of control algorithm correct parameters of the machine are required. Parameters needed for implementation of advanced control algorithms are parameters of classic simplified model of the machine which for interior permanent magnet synchronous machine are ohmic resistance of stator R_s, inductance of *d* axis L_d, inductance of *q* axis L_q and magnetic flux linkage Ψ. To further increase performance and efficiency of control, model of the machine will be extended to account for core losses. This is done by adding ohmic resistance that represents core losses R_c.

One of online parameter identification algorithms is model reference adaptive system (MRAS) algorithms [7], [9], [10], [16]. Algorithm is based on adaptive and reference model of the machine. Reference model of the machine gives reference (real) value of output values while adaptive model gives estimated values at its output. Adaptation mechanism is then used to drive error between outputs to zero. In doing that it estimates correct values of given parameters.

To further increase efficiency of the drive mathematical model of the machine that takes into account core loss is developed. Such models are used in loss minimization control (LMC) algorithms.

This work compares accuracy and stability of MRAS estimator for estimation of stator resistance and magnetic flux linkage with different adaptive models. One neglects core losses and other takes them into account. Both models are verified and comparison was made in simulations using Matlab

Simulink. Simulations were conducted for different values of resistance R_c, different rotor speeds and stator current change. In Section 2 mathematical model of interior permanent magnet synchronous machine is given for both model with taking core losses into account and the one that doesn't. Section 3 presents adaptive models and adaptation mechanisms, section 4 shows how are core losses obtained while section 5 shows simulation setup and discusses results. Conclusions are presented in section 5.

II. MATHEMATICAL MODEL OF INTERIOR PERMANENT MAGNET SYNCHRONOUS MACHINE

For control of permanent magnet synchronous machine it is necessary to develop mathematical model of the machine that is detailed enough for advanced control algorithms but simple enough for fast calculation. For this reasons machine model is constructed in *d* and *q* axis using Clark and Park transformation.

Voltage equations of *d* - *q* system are:

$$u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \tag{1}$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega \Psi_f \tag{2}$$

Figs. 1 and 2 show equivalent circuit of interior permanent magnet synchronous machine in *d* and *q* axis neglecting core losses. Stator current equations in *d* and *q* axis of the machine can be written as:

$$\frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \omega_r \frac{L_q}{L_d} i_q + \frac{1}{L_d} u_d \tag{3}$$

$$\frac{di_q}{dt} = -\omega_r \frac{L_d}{L_q} i_d - \frac{R_s}{L_q} i_q + \frac{1}{L_q} u_q + \omega_r \frac{\Psi_f}{L_q} \tag{4}$$

Equations (4) and (5) will be used in adaptive model of MRAS estimator that neglects core losses.

Figs. 3 and 4 show equivalent circuits of interior permanent magnets synchronous machine in *d* and *q* axis that takes into account core losses [11-15].

Stator current equations in *d* and *q* axis of the machine taking into account core losses can be written as:

$$\frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \omega_r \frac{L_q}{L_d} i_q \left(1 + \frac{R_s}{R_c}\right) + \frac{1}{L_d} u_d \tag{5}$$

$$\frac{di_q}{dt} = -\omega_r \frac{L_d}{L_q} i_d \left(1 + \frac{R_s}{R_c}\right) - \frac{R_s}{L_q} i_q + \frac{1}{L_q} u_q + \omega_r \frac{\Psi_f}{L_q} \left(1 + \frac{R_s}{R_c}\right) \tag{6}$$

Equations (3), (4), (5) and (6) are then used to construct adaptive model and to derive adaptation laws for adaptation mechanism.

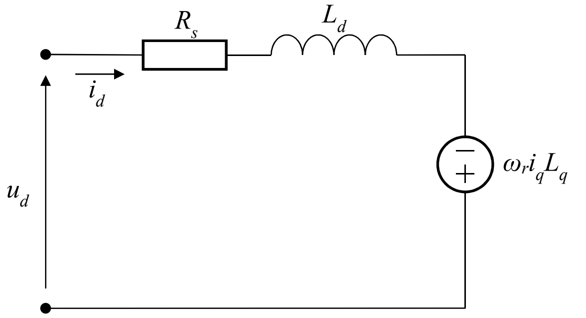

Figure 1 Equivalent circuit of interior permanent magnet synchronous machine in *d* axis

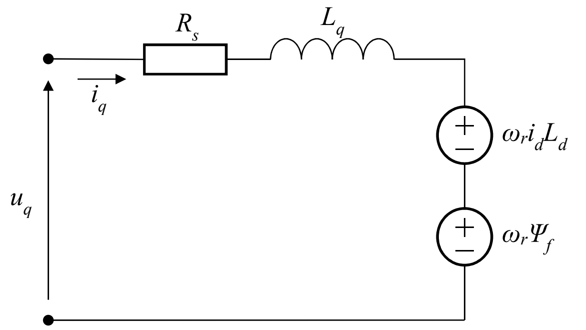

Figure 2 Equivalent circuit of interior permanent magnet synchronous machine in *q* axis

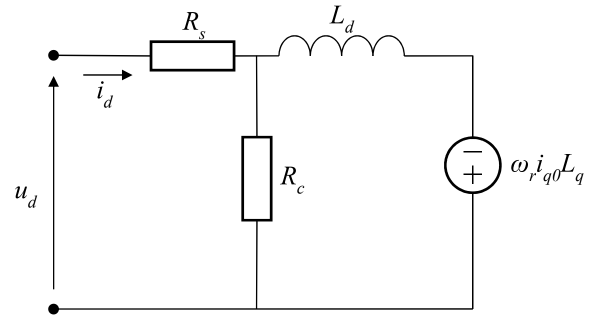

Figure 3 Equivalent circuit of interior permanent magnet synchronous machine in *d* axis taking into account core losses

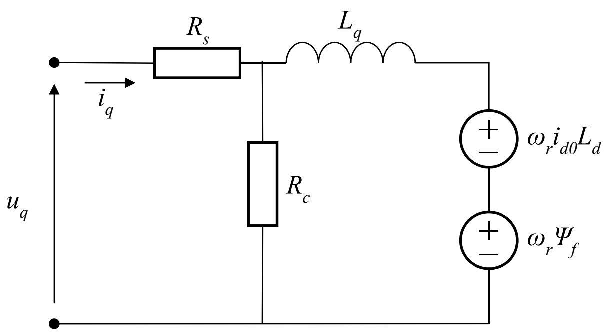

Figure 4 Equivalent circuit of interior permanent magnet synchronous machine in *q* axis taking into account core losses

III. MODEL REFERENCE ADAPTIVE SYSTEM (MRAS) METHOD FOR ESTIMATION OF STATOR RESISTANCE AND MAGNETIC FLUX LINKAGE

A. MRAS adaptive model and adaptation mechanism with neglecting core losses

MRAS methods for parameter estimation consist of reference and adjustable model where reference model provides reference (measured) values of *d* and *q* axis currents and adaptive model provides estimated values. Outputs of both models are compared and error between them is used to drive adaptation mechanism. Adaptation mechanism is then used to drive error between outputs to zero. In doing that it estimates correct values of given parameters [5-7].

Estimated value of stator resistance is obtained by construction of adaptive model and adaptation mechanism.

From equations (3) and (4) state space $d-q$ axis stator currents are:

$$\frac{d}{dt}\mathbf{x} = \mathbf{A}\cdot\mathbf{x} + \mathbf{B}\cdot\mathbf{u} + \mathbf{C} \tag{7}$$

where

$$\mathbf{x} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}; \mathbf{A} = \begin{bmatrix} -\frac{R_s}{L_d} & \frac{L_q}{L_d}\omega_r \\ -\frac{L_d}{L_q}\omega_r & -\frac{R_s}{L_q} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}; \mathbf{u} = \begin{bmatrix} u_d \\ u_q \end{bmatrix}; \mathbf{C} = \begin{bmatrix} 0 \\ -\frac{\Psi_f}{L_q}\omega_r \end{bmatrix}$$

State space for *d* and *q* axis stator currents for adaptive model are:

$$\frac{d}{dt}\hat{\mathbf{x}} = \hat{\mathbf{A}}\cdot\hat{\mathbf{x}} + \mathbf{B}\cdot\mathbf{u} + \mathbf{C} \tag{8}$$

where

$$\hat{\mathbf{x}} = \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix}; \hat{\mathbf{A}} = \begin{bmatrix} -\frac{\hat{R}_s}{L_d} & \frac{L_q}{L_d}\omega_r \\ -\frac{L_d}{L_q}\omega_r & -\frac{\hat{R}_s}{L_q} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}; \mathbf{u} = \begin{bmatrix} u_d \\ u_q \end{bmatrix}; \mathbf{C} = \begin{bmatrix} 0 \\ -\frac{\Psi_f}{L_q}\omega_r \end{bmatrix}$$

The operator ^ denotes estimated value.

After implementation of reference and adaptive model for *d* and *q* axis stator currents it is necessary to model adaptive mechanism that will adjust adaptive model parameters to minimize error between *d* and *q* axis stator currents by estimating stator resistance.

Errors between $d-q$ axis currents of reference and adaptive system are defined as:

$$\varepsilon_d = i_d - \hat{i}_d \tag{9}$$

$$\varepsilon_q = i_q - \hat{i}_q \tag{10}$$

Error between real and estimated value of armature resistance is defined as:

$$\Delta R_s = R_s - \hat{R}_s \tag{11}$$

State space for *d* and *q* axis stator current errors can be written as:

$$\begin{bmatrix} \frac{d\varepsilon_d}{dt} \\ \frac{d\varepsilon_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{\hat{R}_s}{L_d} & \omega_r\frac{L_q}{L_d} \\ -\omega_r\frac{L_q}{L_d} & -\frac{\hat{R}_s}{L_q} \end{bmatrix} \begin{bmatrix} \varepsilon_d \\ \varepsilon_q \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_d}i_d \\ -\frac{1}{L_q}i_q \end{bmatrix} \left(R_s - \hat{R}_s\right) \tag{12}$$

Or:

$$\frac{d}{dt}\boldsymbol{\varepsilon} = \mathbf{A_1}\cdot\boldsymbol{\varepsilon} + \mathbf{W_1} \tag{13}$$

where

$$\mathbf{A_1} = \begin{bmatrix} -\frac{\hat{R}_s}{L_d} & \omega_r\frac{L_q}{L_d} \\ -\omega_r\frac{L_d}{L_q} & -\frac{\hat{R}_s}{L_q} \end{bmatrix}; \mathbf{W}_1 = \begin{bmatrix} -\frac{1}{L_d}i_d \\ -\frac{1}{L_q}i_q \end{bmatrix} \left(R_s - \hat{R}_s\right) \tag{14}$$

By using Popov criterion of stability [7]:

$$\int_0^{t_0} \boldsymbol{\varepsilon}^{\mathbf{T}}\cdot\mathbf{W_1}dt \geq -\gamma_0^2 \tag{15}$$

were $t_0 \geq 0$ and $\gamma_0 \geq 0$.

and by assuming:

$$\hat{R}_s = A_2\cdot\boldsymbol{\varepsilon} + \int_0^{t_0} A_3(\varepsilon)dt \tag{16}$$

It can be shown that observed armature resistance satisfies following adaptation laws:

$$A_2 = K_1\left[-\frac{1}{L_d}i_d\varepsilon_d - \frac{1}{L_q}i_q\varepsilon_q\right] \tag{17}$$

$$A_3 = K_2\left[-\frac{1}{L_d}i_d\varepsilon_d - \frac{1}{L_q}i_q\varepsilon_q\right] \tag{18}$$

By inserting equations (17) and (18) into (16) equation for estimating stator resistance is obtained:

$$\hat{R}_s = K_1\left[-\frac{1}{L_d}i_d\varepsilon_d - \frac{1}{L_q}i_q\varepsilon_q\right] + \int_0^{t_0} K_2\left[-\frac{1}{L_d}i_d\varepsilon_d - \frac{1}{L_q}i_q\varepsilon_q\right]dt + \hat{R}_s(0) \tag{19}$$

where $\hat{R}_s(0)$ is integration constant. Coefficients K_1 and K_2 are choosen so that they ensure stable system response.

Estimated value of magnetic flux linkage can be determined in the same way.

Error between real and estimated value of magnetic flux linkage is defined as:

$$\Delta\Psi_f = \Psi_f - \hat{\Psi}_f \tag{20}$$

State space for *d* and *q* axis stator current errors can be written as:

$$\begin{bmatrix} \frac{d\varepsilon_d}{dt} \\ \frac{d\varepsilon_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_r\frac{L_q}{L_d} \\ -\omega_r\frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} \varepsilon_d \\ \varepsilon_q \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\omega_r}{L_q} \end{bmatrix} \left(\Psi_f - \hat{\Psi}_f\right) \tag{21}$$

Final relation for estimation of magnetic flux linkage can be written as:

$$\hat{\Psi}_f = K_3\left[-\frac{\omega_r}{L_q}\varepsilon_q\right] + \int_0^{t_0} K_4\left[-\frac{\omega_r}{L_q}\varepsilon_q\right]dt + \hat{\Psi}_f(0) \tag{22}$$

Coefficients K_3 and K_4 are choosen so that they ensure stable system response.

B. MRAS adaptive model and adaptation mechanism with taking into account core losses

Machine model that takes core losses into account is constructed by inserting ohmic resistance R_c into transversal axis. Power dissipated on it is equal to core losses and its value is determined by no load test. Procedure of building adaptive model and adaptation mechanism is equal to procedure when building adaptive model and adaptation mechanism for machine model that neglects core losses but voltage and current equations are different. Reference model ohn its output gives reference (measured) values of *d* and *q* axis currents and adaptive model gives estimated values. Outputs of both models are compared and error between them is sent to input of adaptation mechanism. Adaptation mechanism then drives error between outputs to zero and in doing that it estimates correct values of given parameters

From equations (5) and (6) state space d – q axis stator currents are:

$$\frac{d}{dt}\mathbf{x} = \mathbf{A}\cdot\mathbf{x} + \mathbf{B}\cdot\mathbf{u} + \mathbf{C} \tag{23}$$

where

$$\mathbf{x} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}; \mathbf{A} = \begin{bmatrix} -\frac{R_s}{L_d} & \frac{L_q}{L_d}\omega_r\left(1+\frac{R_s}{R_c}\right) \\ -\frac{L_d}{L_q}\omega_r\left(1+\frac{R_s}{R_c}\right) & -\frac{R_s}{L_q} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}; \mathbf{u} = \begin{bmatrix} u_d \\ u_q \end{bmatrix}; \mathbf{C} = \begin{bmatrix} 0 \\ -\frac{\Psi_f}{L_q}\omega_r\left(1+\frac{R_s}{R_c}\right) \end{bmatrix}$$

State space for *d* and *q* axis stator currents for adaptive model are:

$$\frac{d}{dt}\hat{\mathbf{x}} = \hat{\mathbf{A}}\cdot\hat{\mathbf{x}} + \mathbf{B}\cdot\mathbf{u} + \hat{\mathbf{C}} \tag{24}$$

where

$$\hat{\mathbf{x}} = \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix}; \hat{\mathbf{A}} = \begin{bmatrix} -\frac{\hat{R}_s}{L_d} & \frac{L_q}{L_d}\omega_r\left(1+\frac{\hat{R}_s}{R_c}\right) \\ -\frac{L_d}{L_q}\omega_r\left(1+\frac{\hat{R}_s}{R_c}\right) & -\frac{\hat{R}_s}{L_q} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}; \mathbf{u} = \begin{bmatrix} u_d \\ u_q \end{bmatrix}; \mathbf{C} = \begin{bmatrix} 0 \\ -\frac{\Psi_f}{L_q}\omega_r\left(1+\frac{\hat{R}_s}{R_c}\right) \end{bmatrix}$$

Errors between d – q axis currents of reference and adaptive system are given by (9) and (10). Error between real and estimated value of stator resistance is given by (11).

State space for *d* and *q* axis stator current errors can be written as:

$$\begin{bmatrix} \frac{d\varepsilon_d}{dt} \\ \frac{d\varepsilon_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{\hat{R}_s}{L_d} & \omega_r\frac{L_q}{L_d}\left(1+\frac{\hat{R}_s}{R_c}\right) \\ -\omega_r\frac{L_q}{L_d}\left(1+\frac{\hat{R}_s}{R_c}\right) & -\frac{\hat{R}_s}{L_q} \end{bmatrix}\begin{bmatrix} \varepsilon_d \\ \varepsilon_q \end{bmatrix} + \begin{bmatrix} \frac{\omega_r}{R_c}\frac{L_q}{L_d}i_q - \frac{1}{L_d}i_d \\ -\frac{\omega_r}{R_c}\frac{L_d}{L_q}i_d - \frac{1}{L_q}i_q - \frac{\omega_r}{R_c}\frac{\Psi_f}{L_q} \end{bmatrix}\left(R_s - \hat{R}_s\right) \tag{25}$$

or:

$$\frac{d}{dt}\boldsymbol{\varepsilon} = \mathbf{A_1}\cdot\boldsymbol{\varepsilon} + \mathbf{W_1} \tag{26}$$

where

$$\mathbf{A_1} = \begin{bmatrix} -\frac{\hat{R}_s}{L_d} & \omega_r\frac{L_q}{L_d} \\ -\omega_r\frac{L_d}{L_q} & -\frac{\hat{R}_s}{L_q} \end{bmatrix}; \mathbf{W_1} = \begin{bmatrix} \frac{\omega_r}{R_c}\frac{L_q}{L_d}i_q - \frac{1}{L_d}i_d \\ -\frac{\omega_r}{R_c}\frac{L_d}{L_q}i_d - \frac{1}{L_q}i_q - \frac{\omega_r}{R_c}\frac{\Psi_f}{L_q} \end{bmatrix}\left(R_s - \hat{R}_s\right) \tag{27}$$

Nonlinear feedback loop has to satisfy Popov criterion of stability [7]:

$$\int_0^{t_0} \boldsymbol{\varepsilon}^{\mathbf{T}}\cdot\mathbf{W_1}dt \geq -\gamma_0^2 \tag{28}$$

where $t_0 \geq 0$ and $\gamma_0 \geq 0$.

By assuming:

$$\hat{R}_s = A_2\cdot\boldsymbol{\varepsilon} + \int_0^{t_0} A_3(\varepsilon)dt \tag{29}$$

It can be shown that stator resistance satisfies following laws:

$$A_2 = K_1\left[\left(\frac{\omega_r}{R_c}\frac{L_q}{L_d}i_q - \frac{1}{L_d}i_d\right)\varepsilon_d + \left(-\frac{\omega_r}{R_c}\frac{L_d}{L_q}i_d - \frac{1}{L_q}i_q - \frac{\omega_r}{R_c}\frac{\Psi_f}{L_q}\right)\varepsilon_q\right] \tag{30}$$

$$A_3 = K_2\left[\left(\frac{\omega_r}{R_c}\frac{L_q}{L_d}i_q - \frac{1}{L_d}i_d\right)\varepsilon_d + \left(-\frac{\omega_r}{R_c}\frac{L_d}{L_q}i_d - \frac{1}{L_q}i_q - \frac{\omega_r}{R_c}\frac{\Psi_f}{L_q}\right)\varepsilon_q\right] \tag{31}$$

By inserting equations (30) and (31) into (29) equation for estimating stator resistance is obtained:

$$\hat{R}_s = K_1\left[\left(\frac{\omega_r}{R_c}\frac{L_q}{L_d}i_q - \frac{1}{L_d}i_d\right)\varepsilon_d + \left(-\frac{\omega_r}{R_c}\frac{L_d}{L_q}i_d - \frac{1}{L_q}i_q - \frac{\omega_r}{R_c}\frac{\Psi_f}{L_q}\right)\varepsilon_q\right] + \int_0^{t_0} K_2\left[\left(\frac{\omega_r}{R_c}\frac{L_q}{L_d}i_q - \frac{1}{L_d}i_d\right)\varepsilon_d + \left(-\frac{\omega_r}{R_c}\frac{L_d}{L_q}i_d - \frac{1}{L_q}i_q - \frac{\omega_r}{R_c}\frac{\Psi_f}{L_q}\right)\varepsilon_q\right]dt + \hat{R}_s(0) \tag{32}$$

Coefficients K_1 and K_2 are choosen so that they ensure stable system response.

Estimated value of magnetic flux linkage can be determined in the same way. Error between real and estimated value of magnetic flux linkage is given by (20).

State space for *d* and *q* axis stator current errors can be written as:

$$\begin{bmatrix}\frac{d\varepsilon_d}{dt}\\ \frac{d\varepsilon_q}{dt}\end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_r \frac{L_q}{L_d}\left(1+\frac{\hat{R}_s}{R_c}\right) \\ -\omega_r\frac{L_d}{L_q}\left(1+\frac{\hat{R}_s}{R_c}\right) & -\frac{R_s}{L_q}\end{bmatrix}\begin{bmatrix}\varepsilon_d\\ \varepsilon_q\end{bmatrix} + \begin{bmatrix}0\\ -\frac{\omega_r}{L_q}\left(1+\frac{\hat{R}_s}{R_c}\right)\end{bmatrix}\left(\Psi_f - \hat{\Psi}_f\right) \qquad (33)$$

Final relation for estimation of magnetic flux linkage can be written as:

$$\hat{\Psi}_f = K_3\left[-\frac{\omega_r}{L_q}\left(1+\frac{\hat{R}_s}{R_c}\right)\varepsilon_q\right] + \int_0^{t_0} K_4\left[-\frac{\omega_r}{L_q}\left(1+\frac{\hat{R}_s}{R_c}\right)\varepsilon_q\right]dt + \hat{\Psi}_f(0) \qquad (34)$$

Coefficients K_3 and K_4 are choosen so that they ensure stable system response.

IV. ASSESMENT OF VALUE OF RC

Value of resistance R_c was experimentaly determined under no load test at different rotor speeds. Measurements of the back emf voltage, rotor speed and shaft torque were taken and value of resistance R_c was derived. Core losses can be expressed as:

$$P_c = \frac{E^2}{R_c} \qquad (35)$$

From (35) value of resistance Rc can be exspressed as:

$$R_c = \frac{E^2}{T \cdot \omega} \qquad (36)$$

where E is phase value of back EMF voltage, T is shaft torque measured by torque transducer and ω is electrical angular velocity measured by encoder. Value of Rc is an aproximation since mechanical losses were neglected. To get more accurate value of Rc mechanical losses should be taken into account and substracted from mechanical power to obtain electrical power.

From the Fig. 5. it can be seen that the value of R_c changes from 19 Ω to 30 Ω at rotor speed from 500 to 1500 rpm which is the speed range that will be mostly used during operation of IPMSG in wind applications.

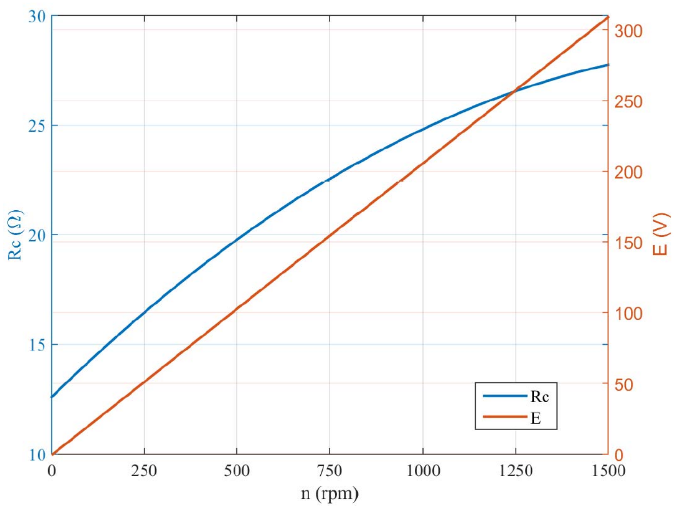

Figure 5 No load test results

V. SIMULATION RESULTS FOR MRAS STATOR RESISTANCE AND MAGNETIC FLUX LINKAGE ESTIMATION

To verify and compare proposed MRAS estimators for identification of stator resistance and magnetic flux linkage simulation studies were conducted. IPMSG and MRAS estimators were modeled using Matlab Simulink. Parameters of the IPMSG are given in Tab. 1.

TABLE I. IPMSG PARAMETERS

Parameter	Value
Rated power	P_r = 375 kW
Rated current	I_r = 596 A
Back EMF	EMF=266 V/krpm
Rated torque	M_r = 2389 Nm
Rated frequency	f_r = 75 Hz
Rated speed	n_r = 1500 rpm
Stator resistance	R_s = 8.05 mΩ
Inductance of d axis	L_d = 0.72 mH
Inductance of q axis	L_q = 1.06 mH
Permanent magnet flux linkage	Ψ_m = 0.69 Wb
Weight of the machine	m = 930 kg

For simulation purposes thermal model of the machine was built. The estimated rate of change of stator resistance was defined by:

$$R = R_0(1+\alpha\cdot\Delta T) \qquad (37)$$

where R_0, α, and ΔT are the initial stator resistance, temperature coefficient of stator resistance and deviation of temperature, respectively. If temperature changes for 150 degrees kelvin and windings are made of copper, the resistance will change close to 50 percent. Assuming that the machine works at the rated power with efficiency of 92 percent power dissipation of the machine is 36 kW it can be shown that it would take about 11 seconds for one degree kelvin of temperature increase. That means that resistance would change by 0.03 percent each second. This is a rough approximation because it assumes linear increase of temperature (which is almost correct around initial temperature), no ventilation and cooling, and homogenous distribution of heat through machine was assumed for simulation studies. This assumption is not true in case of overload because value of resistance would change more steeply.

Simulation experiments were conducted for step change of the *d* and *q* current references from 200A to 50A and from 500A to 100A respectively, different rotor speeds, stator resistance change given by (37) and for different values of resistance R_c. Primarily, value magnetic flux linkage depends on temperature so for simulation purposes value of magnetic flux linkage is assumed to decrease by 0,002 percent each second.

Fig. 6. shows simulation results for constant change of stator resistance, step change of *d* and *q* currents from 200A to 50A and from 500A to 100A respectively at t = 2s, rotor speed is equal to 500 rpm. Fig. 6 shows simulation results for rotor speed equal to 1500 rpm and same change of stator resistance and currents in *d* and *q* axes. Curves denoted with orange, purple, green and light blue colour show estimation of MRAS estimator that neglects core losses for various values of resistance R_c.

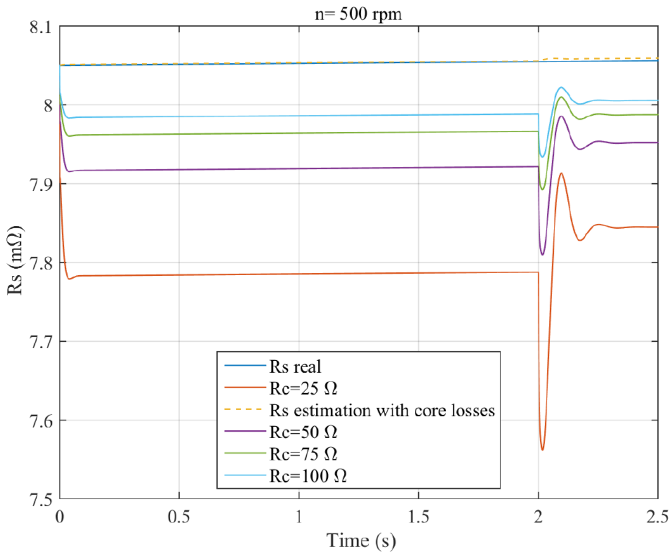

Figure 6 Real and estimated values of stator resistance for rotor speed of 500 rpm

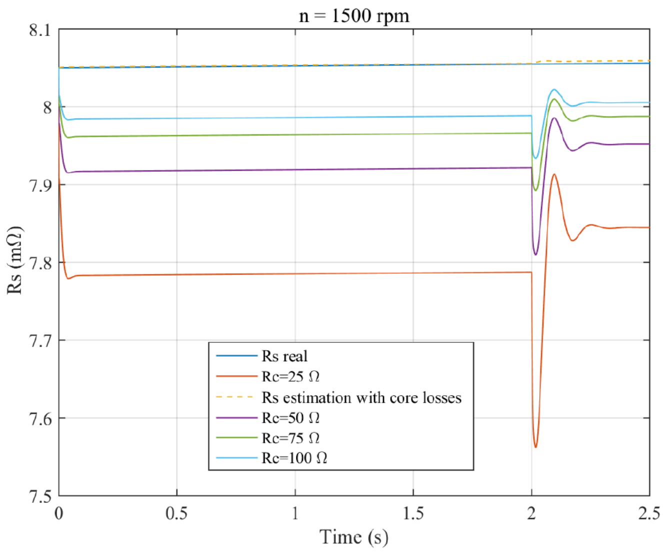

Figure 7 Real and estimated values of stator resistance for rotor speed of 1500 rpm

Simulation shows that MRAS estimator that takes into account core losses follows real value of stator resistance closely and with minimal error. Also, it can be also seen that estimator that takes into account core losses has significantly smaller estimation error.

On the other hand, MRAS estimator that neglects core losses has larger error and its output is influenced by disturbances and real values of resistance R_c. Also, it can be seen that for larger values of resistance R_c estimation error for estimator without taking into account core losses is smaller. Estimation error ranges from 3,3 percent to 0,8 percent for estimator that neglects core losses and error for estimator that takes into account core losses error is virtually zero. Also, by comparing Figs. 6. and 7. it can be seen that rotor speed has no effect on estimation of stator resistance.

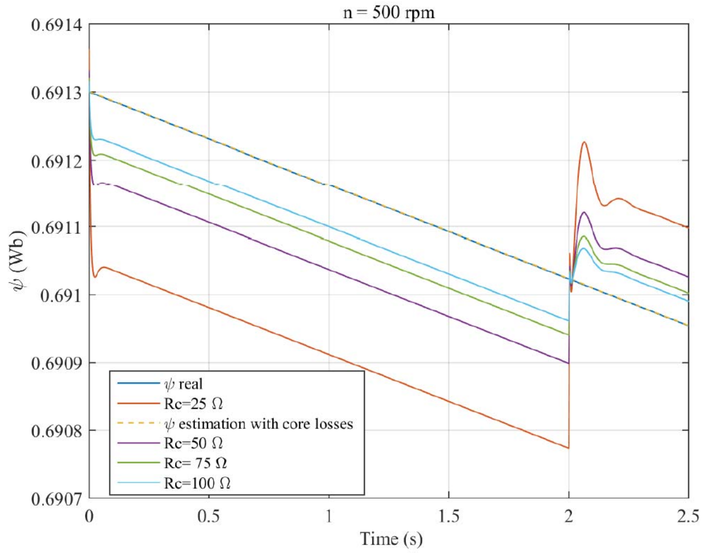

Figure 8 Real and estimated values of magnetic flux linkage for rotor speed of 500 rpm

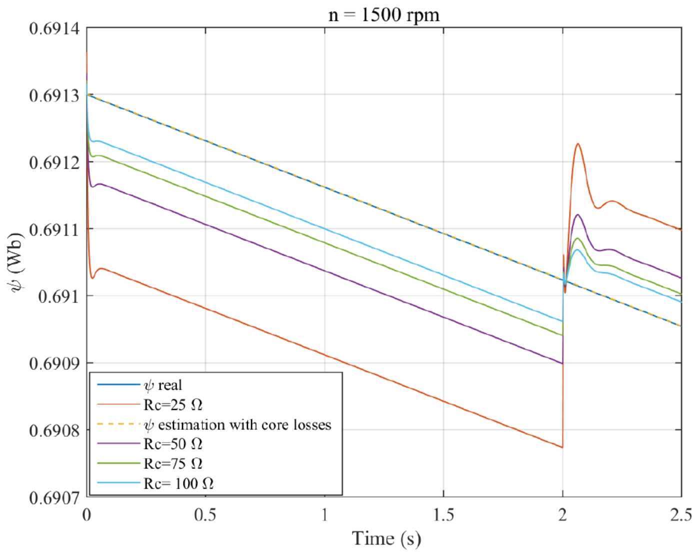

Figure 9 Real and estimated value s of magnetic flux linkage for rotor speed of 1500 rpm

Figs. 8. and 9. show simulation results for constant change of magnetic flux linkage by 0,002 percent each second, step change of d and q axis currents from 200A to 50A and from 500A to 100A respectively in time moment 2s and for rotor speeds equal to 500 rpm and 1500 rpm. Curves denoted with orange, purple, green and light blue colour show estimation of MRAS estimator that neglects core losses for various values of resistance R_c. It can be seen that MRAS estimator that takes into account core losses follows real value of magnetic flux linkage with almost no error under constant change of parameter and disturbances. MRAS estimator that neglects core losses has larger error and its estimated value of magnetic flux linkage is influenced by disturbances and real values of resistance R_c. Also, it can be seen that for larger values of resistance R_c estimation error for estimator without taking into account core losses is smaller while change of rotor speed has no effect on estimation. Estimation error for estimator that neglects core losses is less than 0,1 percent and error for estimator that takes into account core losses error is virtually zero.

VI. Conclusion

This work presents comparison between two MRAS estimators for identification of stator resistance and magnetic flux linkage. One of them uses adaptive model and adaptation mechanism that neglect core losses and other uses adaptive model and adaptation mechanism that takes them into account when estimating stator resistance and magnetic flux linkage of the machine. In order to compare estimators machine models and adaptive mechanisms were constructed for each type of MRAS estimator. Responses and estimated values were compared for different values of resistance R_c, step change od *d* and *q* axis currents and different rotor speeds alongside continuous change of stator resistance and magnetic flux linkage. Core losses were measured experimentally under no load test at different rotor speeds and from them value of R_c was determined. Simulation results show fast and stable response of both MRAS estimators for wide range of operating points and disturbances. It is shown that it is beneficial to take into account core losses as it gives better results for estimated parameters. This is more apparent when machine has larger core losses (resistance R_c is lower) as MRAS estimator that doesn't take into account core losses has larger estimation error.

Future work will focus on modeling and implementation of MRAS estimator that will take into account dynamic change of resistance R_c depending on operating point, studying influence of PWM switching on estimated parameters and testing on large power IPMSG.

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References

[1] H. Li, Z. Chen, "Overview of different wind generator systems and their Comparisons", *IET Renewable Power Generation*., vol.2, no. 2, pp. 123-138, 2008.

[2] A. Luna, G. Vazquez, D. Aguilar, G. Azevedo, "Modeling of a variable speed wind turbine with a Permanent Magnet Synchronous Generator" *2009 IEEE International Symposium on Industrial Electronics,* 2009.

[3] Z. Q. Zhu, David A. Stone, "Parameter Estimation for Condition Monitoring of PMSM Stator Winding and Rotor Permanent Magnets" *IEEE Transactions on Industrial Electronics* vol. 60, no. 12, pp. 5902 – 5913, 2013.

[4] F. Wang, C. Jilin, C. Chang, B. Liu ,"Analysis of PMSM control performance based on the mathematical model and saturated parameters", *Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), 2014 IEEE Conference and Expo*, Bejing, pp. 1-5, 2014

[5] R. Bojoi, M. Popescu, A. Tenconi, „Parameter identification and self-commissioning of AC permanent magnet machines - A review", *Electrical Machines Design, Control and Diagnosis (WEMDCD), 2015 IEEE Workshop on*, Torino, pp. 195-203, 2015.

[6] T. Senjyu, Y. Noguchi, N. Urasaki, A. Yona, H. Sekine, "Parameter identification for interior permanent-magnet synchronous motor", *Electrical Machines and Systems, 2007. ICEMS*, Seoul, pp. 566–571., 2007.

[7] T. Barisa, I. Erceg, I. Markovic, "Estimation of Stator Resistance and Rotor Speed for IPMSG Using Model Reference Adaptive System", *Energycon 2016*, Leuven, 2016.

[8] S. Underwood, I. Husain, „Online Parameter Estimation and Adaptive Control of Permanent-Magnet Synchronous Machines", *IEEE Transactions on Industrial Electronics,* vol. 57 , no. 7, 2010.

[9] T. Boileau, N. Leboeuf, B. Nahid-Mobarakeh, "Online Identification of PMSM Parameters: Parameter Identifiability and Estimator Comparative Study", *Industry Applications, IEEE Transactions on*, vol. 47, no. 4, 2011.

[10] T. Boileau, B. Nahid-Mobarakeh, F. Meibody-Tabar, „On-line Identification of PMSM Parameters: Model-Reference vs EKF*", Industry Applications Society Annual Meeting, 2008. IAS '08. IEEE*, October 2008.

[11] W. Hassan, B. Wang, „Efficiency Optimization of PMSM Based Drive System", *2012 IEEE 7th International Power Electronics and Motion Control Conference - ECCE Asia*, 2012.

[12] Young-Kyoun Kim, „Analytical Study Considering Both Core Loss Resistance and Magnetic Cross Saturation of Interior Permanent Magnet Synchronous Motors", *Journal of Magnetics,* vol. 17, no. 4, 2012.

[13] Z.Q. Zhu, K. Schofield, N. Howe; "Improved analytical modeling rotor eddy current loss in brushless machines equipped with surface- mounted permanent magnets", *IEE Proceedings - Electric Power Applications*, vol. 151, no. 6, 2004.

[14] S.H. Han, T.M. Jahns, Z.Q. Zhu, "Analysis of Rotor Core Eddy Current Losses in Interior Permanent Magnet Synchronous Machines", *Industry Applications Society Annual Meeting, 2008. IAS '08. IEEE,* Alta, 2008.

[15] R. Colby, D. Novotny, "Efficient operation of pm synchronous motors," *IEEE Transactions on Industry Applications*, vol. 23, no. 6, pp. 1048–1054, 1987.

[16] Y.P. Landau, "Adaptive Control: The Model Reference Approach", *M Dekker Inc.*, New York, 1979.