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GENERALIZED DIFFERENTIAL MATHEMATICAL MODEL IN STATOR REFERENCE FRAME FOR PMSM AND VRSM SIMULATION

BY

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Abstract. The paper presents the deduction of a novel decoupled form (considering the differential current quantities) of the differential mathematical model in stator reference frame, useful for numeric simulation of control approaches for PMSM (permanent magnet synchronous machines) generalized for both IPMSM and SPMSM (salient and non-salient PMSM). The model is confirmed to be equivalent to the well-known model defined in the rotor synchronous reference frame using a Matlab-Simulink implementation that is verified and validated by simulation during which the power/energy conservation is monitored and the system states’ evolution is compared to the reference model in rotor reference frame using a generator structure.

Keywords: IPMSM; salient-pole; decoupled model; simulation; circular economy.

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1. Introduction

The reliability and efficiency of PMSMs promote the investment in integrating them as components of intensive and long use appliances (*e.g.*, dish washers, laundry machines, air-conditioning/heat-pump compressors, fluid recirculating pumps, industry 4.0 manufacturing actuation etc.) (Szczepanski, 2020; Benzi, 2019; Oprea, 2021 a,b), but also in applications demanding extended autonomy achieved through high efficiency motors, *e.g.*, electric vehicles traction and auxiliary systems, light-weight aircraft, unmanned air vehicles like flying-wing or multi-copter drones with recreational or defence applications, guided or autonomous logistic robots, intelligent vacuum cleaners, radio-controlled toys, etc. (Tummakuri, 2021; Mi, 2017; Morimoto, 2007).

Furthermore, considering their reliability in the current trend of growing circular economy (Tiwari, 2021; Leitner, 2020; Nuno, 2019), it is also of interest to reintegrate existing functional PMSMs from outdated or otherwise faulty devices in new or existing equipment while implementing better control approaches with benefits in power efficiency and Electro-Magnetic Compatibility (EMC) compliance (*e.g.*, refurbished/upgraded spare components).

In line with improving the economic efficiency of PMSM production and exploitation is the advancement of sensorless control approaches for the PMSM that are based on rotor position estimation using observers that are usually based on machine models expressed in the fixed stator reference frame (Xiong, 2021; Popovici, 2019; Andersson, 2018; Han, 2016; Morimoto, 2002; Corley, 1998). Although the states of the model in the stator reference frame vary with the rotor position, they have the advantage to contain quantities that can be determined directly, without knowledge of the rotor position, *i.e.*, the applied phase voltages and measured phase currents.

In this paper there are presented the deduction steps for obtaining a novel approach for expressing the nonlinear dynamic mathematical model of PMSM in the stator reference frame. Although the coupled form of the model is extensively applied as base for sensorless rotor position observer designs (Filho, 2021), the decoupled form obtained in this paper meets the demands for numeric simulation since the electrical equations are decoupled from the point of view of the phase currents differential quantities which eliminates problematic algebraic loops.

The main contribution of the paper consists of the following section that presents in detail the deduction steps that were taken for obtaining the novel form of the differential mathematical model for Synchronous Machines (SM) in the fixed stator reference frame, which is usually denoted by the α and β axes.

Its novelty consists in expressing the electrical differential equations of the phase currents without cross-coupling the differential quantities of the currents, compared to the well-known models (Bodson, 1998). Having this novel form, the model becomes appropriate for numerical simulation which can be further used for analysing the performance and limitations of sensorless observers for rotor position and speed estimation. In its complete form, the model can characterize the Interior Permanent Magnet SM (IPMSM) which presents reluctance anisotropy due to the rotor construction. By setting certain parameters to zero, the model can be simplified to characterise either the Surface mounted Permanent Magnet SM (SPMSM), or the Variable Reluctance SM (VRSM).

The proposed model is validated by simulation in Matlab-Simulink using two methodologies: by checking the power conservation and by comparing the evolution of the model's states against the standard model expressed in the rotor reference frame, usually named *dq* after the direct and quadrature axis of the reference frame linked to the rotor (Bodson, 1998).

The paper is structured in four sections: section 2 describes the steps taken to obtain the decoupled differential mathematical model, section 3 presents the methodology for validating the model together with the simulation results and section 4 states the conclusions.

2. Derivation of the Decoupled Mathematical Model for IPMSM

The model deduction starts from the well-known stator flux linkage equations of the IPMSM, that can be viewed as a generalized form of PMSM (Chiasson, 2005; Bodson, 1998). Throughout the paper the following notations are used: λ_α and λ_β are the stator flux linkages, i_α and i_β represent the stator phase winding currents, u_α and u_β are the stator winding voltages, n_{pp} is the number of pole pairs, R is the resistance of each stator winding, K_e is the rotor permanent magnet flux, θ_r and ω_r are the rotor mechanical position and speed, $\theta_e = n_{pp}\theta_r$ and $\omega_e = n_{pp}\omega_r$ are the rotor equivalent electrical position and speed, τ_e is the motoring torque, τ_l is the rotor load torque, L_d and L_q are the equivalent phase inductances when the rotor poles are in direct alignment with the reference stator winding, respectively when they are in quadrature alignment.

System (1) represents the starting point for the model derivation, and is based on (Chiasson, 2005) considering the mentioned notations compared to the original, and that the notations (2) define the average inductance L and the inductance maximum anisotropy deviation L_Δ.

$$\lambda_\alpha = L i_\alpha + K_e \cos(\theta_e) + L_\Delta\big(i_\alpha \cos(2\theta_e) + i_\beta \sin(2\theta_e)\big) \tag{1a}$$

$$\lambda_\beta = L i_\beta + K_e \sin(\theta_e) + L_\Delta\big(i_\alpha \sin(2\theta_e) - i_\beta \cos(2\theta_e)\big) \tag{1b}$$

$$L = \frac{L_d + L_q}{2} \tag{2a}$$

$$L_\Delta = \frac{L_d - L_q}{2} \tag{2b}$$

To obtain the electrical equations, the derivatives with respect to time of the stator flux linkages need to be obtained and substituted in the general form of the electrical model (3).

$$\frac{d\lambda_\alpha}{dt} = u_\alpha - Ri_\alpha \tag{3a}$$

$$\frac{d\lambda_\beta}{dt} = u_\beta - Ri_\beta \tag{3b}$$

After substituting the derivatives and conveniently grouping and rearranging the quantities, the system (4) is obtained, which matches the coupled differential models used in (Han, 2016; Morimoto, 2002; Morimoto, 2001), although the references present it in a matrix form, that is more compact, by using an inline algebraic derivative operator.

$$\begin{aligned}(L + L_\Delta \cos(2\theta_e))\frac{di_\alpha}{dt} &= u_\alpha - Ri_\alpha + \omega_e K_e \sin(\theta_e) \\ &-L_\Delta\left(\frac{di_\beta}{dt}\sin(2\theta_e) - 2\omega_e\big(i_\alpha \sin(2\theta_e) - i_\beta \cos(2\theta_e)\big)\right)\end{aligned} \tag{4a}$$

$$\begin{aligned}(L + L_\Delta \cos(2\theta_e))\frac{di_\beta}{dt} &= u_\beta - Ri_\beta - \omega_e K_e \cos(\theta_e) \\ &-L_\Delta\left(\frac{di_\alpha}{dt}\sin(2\theta_e) + 2\omega_e\big(i_\alpha \cos(2\theta_e) + i_\beta \sin(2\theta_e)\big)\right)\end{aligned} \tag{4b}$$

Unfortunately, the coupling of the differential quantities in the system (4) creates algebraic loops that are challenging when numeric simulation as a state space model is desired (Amiri, 2018), and further processing was required.

The decoupling by cross substitution of the $\frac{di_\alpha}{dt}$ and $\frac{di_\beta}{dt}$ quantities in the right side of the equations (4) leads to a significantly more complicated system, reason for which the complete intermediate result is not included in the text, but it may be noted that the resulting coefficients of both equations are of the form given in the left side of (5) which was transformed to the equivalent simplified form illustrated on the right side of (5).

$$L \pm L_\Delta\left(\cos(2\theta_e) \mp \frac{L_\Delta \sin^2(2\theta_e)}{L \mp L_\Delta \cos(2\theta_e)}\right) = \frac{L^2 - {L_\Delta}^2}{L \mp L_\Delta \cos(2\theta_e)} \tag{5}$$

Even when using the simplifying substitution from (5) the length of the resulting decoupled state space model is impractical for listing without introducing the notations from (6).

$$\widehat{u_\alpha} = u_\alpha - Ri_\alpha + \omega_e K_e \sin(\theta_e) + 2\omega_e L_\Delta\left(i_\alpha \sin(2\theta_e) - i_\beta \cos(2\theta_e)\right) \quad (6a)$$

$$\widehat{u_\beta} = u_\beta - Ri_\beta - \omega_e K_e \cos(\theta_e) - 2\omega_e L_\Delta\left(i_\alpha \cos(2\theta_e) + i_\beta \sin(2\theta_e)\right) \quad (6b)$$

After additional distribution, regrouping and rearrangement of terms, the electrical decoupled (from the point of view of the derivative stator winding current quantities) state space model that isolates the saliency characteristic was obtained in (7), considering the introduced notations in (6).

$$\frac{di_\alpha}{dt} = \frac{L\widehat{u_\alpha} - L_\Delta\left(\widehat{u_\alpha}\cos(2\theta_e) + \widehat{u_\beta}\sin(2\theta_e)\right)}{L^2 - {L_\Delta}^2} \quad (7a)$$

$$\frac{di_\beta}{dt} = \frac{L\widehat{u_\beta} - L_\Delta\left(\widehat{u_\alpha}\sin(2\theta_e) - \widehat{u_\beta}\cos(2\theta_e)\right)}{L^2 - {L_\Delta}^2} \quad (7b)$$

To complete the mathematical model of the IPMSM, the mechanical torque produced by the induced magnetic field needs to be determined. This may be done through several methods (Chiasson, 2005; Oprea, 2021b). The method based on the power conservation was employed, considering that the input electrical energy is transformed in magnetizing power and heating power due to the resistance of the stator winding, while other types of losses were ignored. Assuming that the magnetizing power is converted completely to mechanical power and that magnetic saturation is avoided, after expressing the rotor speed in differential form and applying the chain rule for the differential values of the stator flux linkages, (8) is obtained.

$$\tau_e \frac{d\theta_r}{dt} = i_\alpha \frac{d\lambda_\alpha}{d\theta_r}\frac{d\theta_r}{dt} + i_\beta \frac{d\lambda_\beta}{d\theta_r}\frac{d\theta_r}{dt} \quad (8)$$

By dividing (8) to $\frac{d\theta_r}{dt}$ which is non-zero when mechanical power exists, only the flux linkage differentials are needed to obtain the actual motoring torque, which are obtained in (9) by differentiating (1) in relation to $d\theta_r$.

$$\frac{d\lambda_\alpha}{d\theta_r} = (L + L_\Delta\cos(2\theta_e))\frac{di_\alpha}{d\theta_r} - n_{pp}K_e\sin(\theta_e) +$$
$$+L_\Delta\left(\frac{di_\beta}{d\theta_r}\sin(2\theta_e) - 2n_{pp}\left(i_\alpha\sin(2\theta_e) - i_\beta\cos(2\theta_e)\right)\right) \quad (9a)$$

$$\frac{d\lambda_\beta}{d\theta_r} = (L - L_\Delta\cos(2\theta_e))\frac{di_\beta}{d\theta_r} + n_{pp}K_e\cos(\theta_e) +$$
$$+L_\Delta\left(\frac{di_\alpha}{d\theta_r}\sin(2\theta_e) + 2n_{pp}\left(i_\alpha\cos(2\theta_e) + i_\beta\sin(2\theta_e)\right)\right) \quad (9b)$$

Considering the simplifying assumption that the magnitude of the rotating stator current vector is invariant when differentiating its projections i_α and i_β in relation to θ_r the expressions (10) were obtained.

$$\frac{di_\alpha}{d\theta_r} = -n_{pp} i_\beta \tag{10a}$$

$$\frac{di_\beta}{d\theta_r} = n_{pp} i_\alpha \tag{10b}$$

By substituting expressions (10) in (9) and then (9) in (8), followed by grouping and cancellation of terms, the motoring torque expression (11) is obtained.

$$\tau_e = n_{pp}\left(\left(K_e\left(i_\beta \cos(\theta_e) - i_\alpha \sin(\theta_e)\right)\right) + \right.$$
$$\left. + L_\Delta\left(\left({i_\beta}^2 - {i_\alpha}^2\right)\sin(2\theta_e) + 2 i_\alpha\, i_\beta \cos(2\theta_e)\right)\right) \tag{11}$$

The mechanical part of the IPMSM model is obtained by substituting (11) in (12), which together with the electrical part given by (6) and (7) describe the differential decoupled mathematical model of the IPMSM in the stator reference frame. Considering $L_\Delta = 0$ the system simplifies and models the isotropic rotor of SPMSM, while considering only $K_e = 0$ would characterize VRSM.

$$\frac{d\theta_r}{dt} = \frac{\tau_e - \tau_l}{J} \tag{12}$$

3. Experimental Simulation for Implementation Verification and Model Validation

Considering the complexity of the resulted equations it was useful to perform certain steps to check the obtained model. Besides the careful theoretical deduction of the model supported by symbolic calculus using Matlab, two experimental methods were considered that can be applied during a single simulation using the Matlab-Simulink experimental setup depicted in Fig. 1. which is designed to verify the correctness of the model implementation and validating its equivalence to the *dq* model in rotor-synchronous reference frame.

An immediate method, independent of the existence of a reference model is to check that at every simulation moment the power conservation law is holding for the operating scenario, which can be a good indicator of the simulation accuracy, although not necessarily sufficient (Eastman, 2016). To further simplify the test case, it is considered that the motor is exploited in an uncontrolled generator mode by applying a negative load torque on the rotor and having its phases short-circuited together, equivalent to holding null the

u_α and u_β voltages. The experimental setup is presented in Fig. 1 and the simulation model parameters are presented in Table 1.

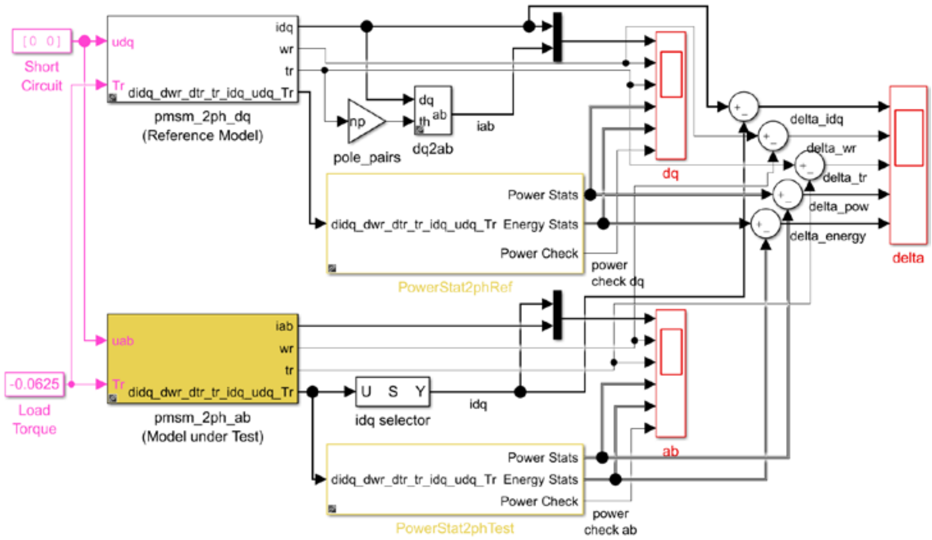

Fig. 1 – Experimental Matlab simulation setup used for verifying the implementation and validating the mathematical model trough two methods (power/energy conservation and state evolution comparison against a reference model).

Table 1
Simulation Parameters

Attribute	Value	Notes
Motor model	*DB42S03*	
Manufacturer	*Nanotec Electronic*	
Pole Pairs	*4*	
Phases	*3*	
Lq Inductance	*1.05 mH*	*2 phase, power invariant equ.*
Ld Inductance	*0.84 mH*	*estimated*
Phase resistance	*0.75 Ohm*	
Identified PM flux	*5.872 mWb*	*2 phase, power invariant equ.*
Nominal Power	*26 W*	
Nominal Speed	*4000 rpm*	*mechanical*
Nominal Torque	*0.0625 N·m*	
Rotor Inertia	*2.5e-6 kg·m^2*	*including a static load model*
Viscous Friction	*1.77e-6 N m·s·rad^{-1}*	*including a static load model*
Static Friction	*3.02e-3 N·m*	*including a static load model*
Simulation solver	*ode5*	*Dormand-Prince method*
Simulation step	*6.25e-6 s*	*fixed step*

The experimental results of the simulation are depicted in Fig. 2 which represents the evolution of the model's states (subfig. a, b, c) together with the calculated power and energy statistics, including an input to output power check-sum that offers the initial validation of the model (subfig. d, e, f).

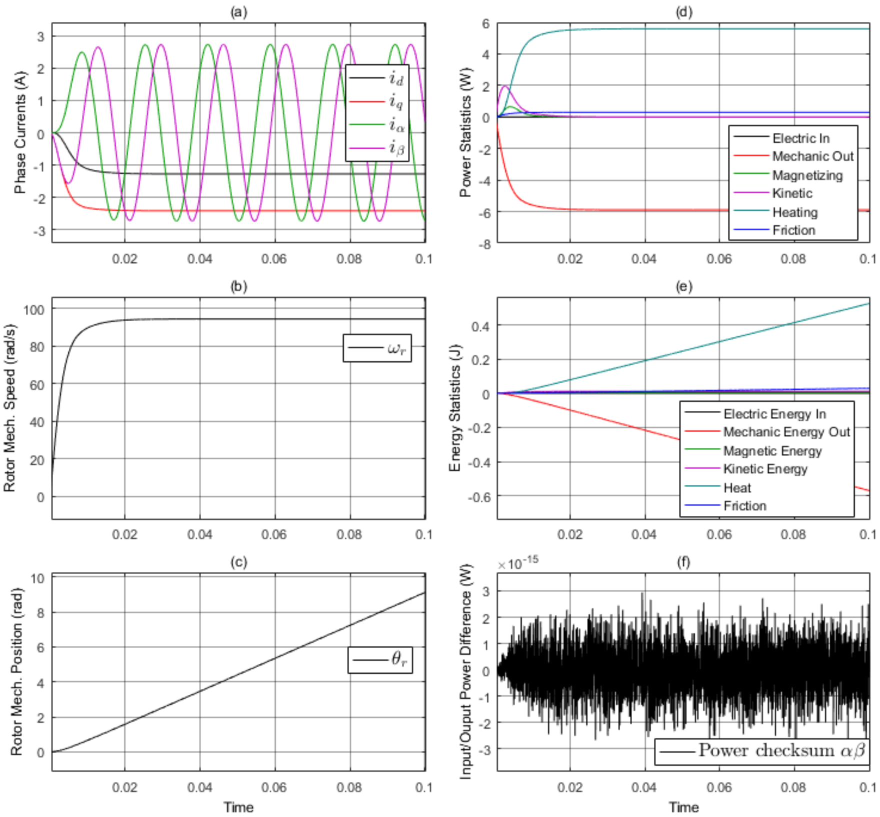

Fig. 2 – Simulation results of the proposed mathematical model in an uncontrolled generator setup with the phases in short-circuit – (a) the obtained phase currents in both rotor and stator reference frame, (b) the mechanical rotor speed evolution, (c) the rotor mechanical position, (d) power statistics, (e) energy statistics, (f) power check-sum accounting the input power conversion to magnetizing, thermal, friction and kinetic powers.

An additional validation method, using a reference model, is to compare the evolution of the proposed model's system states to the evolution of the states of the well-known *dq* model by using the same simplified setup as for the previous method (uncontrolled generator operation in short-circuit). While some of the states are directly comparable, like the mechanical rotor position and speed, the stator winding currents require an appropriate coordinate transformation.

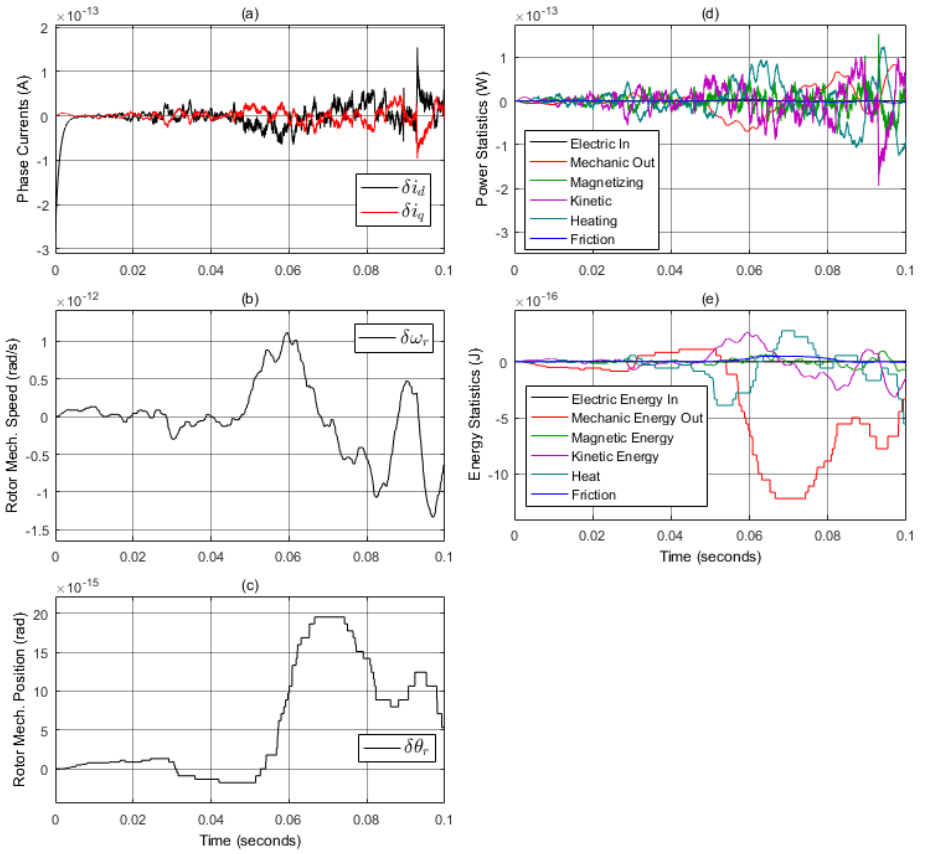

Fig. 3 – Differences between the states and power statistics of the reference model in rotor reference frame and the proposed mathematical model in stator reference frame, simulated in the same conditions; (a) differences between the phase currents evaluated in a common rotor reference frame; (b) difference between mechanical rotor speed; (c) difference between rotor mechanical positions; (d) differences between power statistics; (e) difference between energy statistics.

The evolution of the states from the results in Fig. 2 match the expected response for an uncontrolled PMSM exploited in a generator mode having the phases in short-circuit, while the subfigure (f) records a noisy signal for the checksum of the input-output powers, centred around zero and having an amplitude with several orders of magnitude lower than the total power. The noise can be assumed to be caused by numerical computation due to finite representation precision and integration errors due to finite time step and model non-linearities. Considering the ratio between the actual monitored powers and the checksum noise the basic verification of the model can be confirmed, especially since similar characteristics were identified for the power checksum of the reference *dq* model.

The results from the Fig. 3 further validate that the proposed model has a response that closely follows the reference *dq* model since the measured differences between the system's states and also the power statistics of the compared models are bounded to significant lower values compared to the values of the monitored signals.

The block for power and energy statistics computation is presented in Fig. 4. For its outputs to be relevant when modelling a real synchronous machine, which usually has three phases, appropriate power-invariant coordinates transformations need to be used for obtaining equivalent applied phase voltages and measured phase currents, and also proper scaling for equivalent values for the phase inductances and the permanent magnet flux.

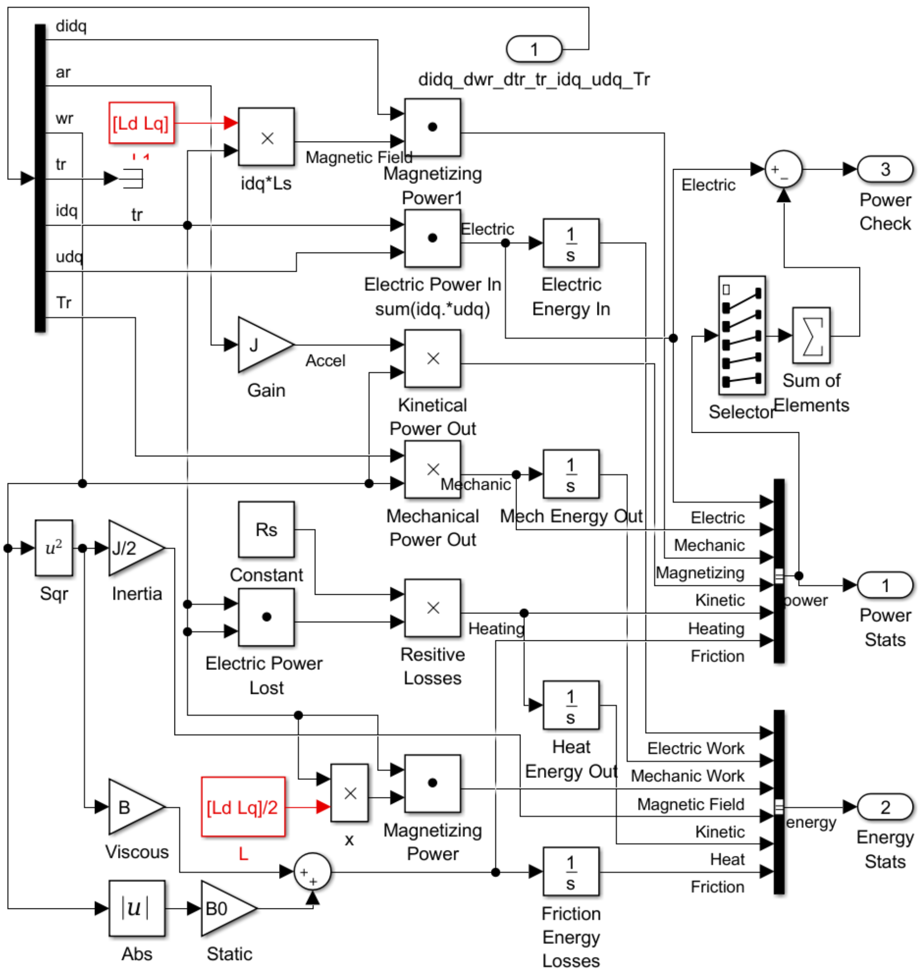

Fig. 4 – Matlab-Simulink block for computing the power and energy statistics based on the inputs received from the monitoring port of the electric machine containing all the needed signals and states.

4. Conclusions

The paper presented the main deduction steps for a novel form of differential nonlinear mathematical model, that is decoupled from the point of view of the differential phase current quantities expressed in the stator reference frame, useful for numeric simulation of PMSM (IPMSM and SPMSM) and also for VRSM. An implementation of the proposed model alongside with the reference *dq* model was done using Matlab-Simulink and a simple verification and validation design was proposed and used for simulation of a sample SPMSM based on the characteristics of a small size commercial motor.

The verification and validation design allowed applying two methods in parallel during a single simulation: power/energy conservation check and state evolution comparison against a well-known reference model.

The simulation results confirmed that the proposed model matches well the reference model since the recorded differences are significantly smaller relative to the state values.

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MODEL MATEMATIC DIFERENŢIAL GENERALIZAT PENTRU SIMULAREA PMSM ŞI VRSM ÎN SISTEMUL DE COORDONATE AL STATORULUI

(Rezumat)

Lucrarea prezintă deducerea unei noi forme decuplate (din punctul de vedere al cantităților diferențiale ale curenților din înfășurările statorului) a modelului matematic diferențial exprimat în sistemul de referință al statorului util pentru simularea de metode de control pentru motoare electrice sincrone cu magneți permanenți (atât varianta cu poli îngropați, cât și pentru cea cu poli aparenți). Este demonstrată echivalența cu modelul bine cunoscut exprimat în sistemul de coordonate sincron cu rotorul printr-o implementare Matlab-Simulink care este verificată și validată prin simulare folosind monitorizarea conservării puterii/energiei și comparația evoluțiilor stărilor în raport cu modelul de referință (în sistemul de referință sincron cu rotorul) într-o structură de generator necontrolat.