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Loss calculation method for hybrid excited machines

Abstract. *This paper presents an experimental method for determining the main losses components in permanent magnets synchronous machines with hybrid excitation (HPMSM). To model the sources of losses is very important in order to optimize such machines and to develop robust control strategies (minimum losses optimization) which can be used in practical applications. Proposed approach was validated using time domain simulations and experiments. Experimental results clearly exhibit the benefits of including core loss model in control system of HPMSM.*

Streszczenie*. W artykule przedstawiono eksperymentalną metodę wyznaczania głównych składników strat maszyn synchronicznych z magnesami trwałymi i wzbudzeniu hybrydowym (HPMSM). Zamodelowanie źródeł strat jest istotne dla optymalizacji tych maszyn oraz dla opracowania właściwych strategii ich sterowania (przy minimalizacja strat), które mogłyby być zastosowane w praktyce. Zaproponowany algorytm został sprawdzony teoretycznie i doświadczalnie. Wyniki badań eksperymentalnych pokazały zalety uwzględnienia strat mocy w algorytmie sterowania HPMSM.* ***(Metoda wyznaczania strat maszyn wzbudzanych hybrydowo).***

Keywords: HPMSM, hybrid excitation, loss calculation, loss minimization.
Słowa kluczowe: HPMSM, wzbudzenie hybrydowe, wyznaczanie strat, minimalizacja strat.

Introduction

Permanent magnet synchronous machines (PMSM) are often used in drivetrains of pure electric vehicles, but in case of classical PMSM some limitations exist in the flux weakening range and in the low-speed torque production. Therefore hybrid excitation PMS-machines (HPMSM) with an additional excitation field control are of great interest. They are becoming an attractive option, especially due to the lack of limitations in excitation field control. In order to increase the flexibility of the excitation field control (field weakening), a hybrid machine construction was proposed ([1], [2]).

A main feature of permanent magnets hybrid excited synchronous machines (HPMSM) is the existence of additional field source windings supplied by a controlled DC system [1]. The typical areas of possible implementation of HPMS-machines are different mobile applications where is important to achieve a high efficiency over a wide range of load torques and speeds. Due to the possibility of relatively simple resultant flux change, unlike in conventional solutions, higher efficiency in broad range of motor speeds and loads is possible ([4], [5]). In order to analyse all properties of such drivetrain and to synthesize the control strategy taking into account its efficiency, it is important to model various loss sources in the whole system.

Loss model of HPMSM

In order to increase the flexibility of the excitation field control, a hybrid machine construction was proposed ([1], [6], [7], [8]). Overview of proposed solution is presented in Fig. 1 and all details of the construction can be seen in Fig. 2.

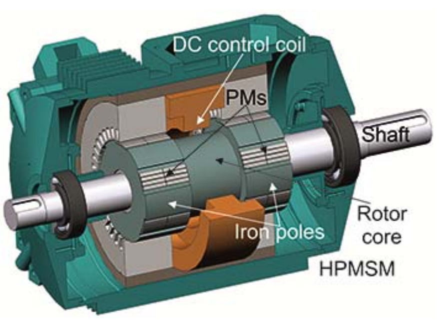

Fig. 1. Construction overview of the HPMSM

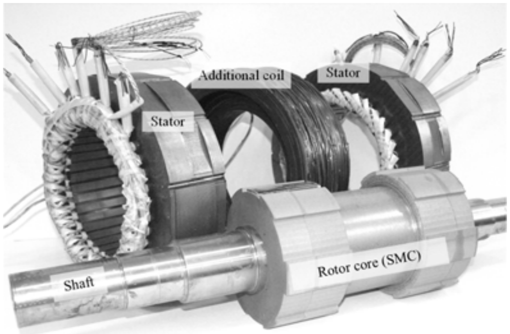

Fig. 2. Components of the prototype machine

The stator consists of two identical cores separated by an additional excitation coil. Rotor poles are magnetized by groups of four rare-earth magnets and the additional DC coil. This machine has already been intensively has already been analyzed and optimized ([1], [7], [8]).

Losses in the HPMSM can be divided into some separate categories:

- in the windings (copper losses),
- the magnetic circuit (core losses),
- mechanical,
- in all other structural elements.

Copper losses result in the dissipation as heat in the windings of the stator resistance R_s:

$$P_{cu} = \frac{3}{2} R_s \left(i_d^2 + i_q^2 \right) \tag{1}$$

and in the additional coil of resistance R_{exc}:

$$P_{exc} = R_{exc} i_{exc}^2 \tag{2}$$

A significant part of losses, especially in the high speed range, is associated with losses in the magnetic circuit of the machine. Total core losses can be modelled by an equivalent (for fixed operating conditions) resistor R_c. It should be noted that the value of R_c depends on the rotational speed of the machine's shaft.

Because of the problematic determination of the material's coefficients required for the losses calculation, the R_c can be determined by experimental measurement of loss P_c as:

(3) $$R_{\mathrm{c}}=\frac{3}{2}\frac{\left(\omega_{\mathrm{e}}\psi_{\mathrm{s}}\right)^{2}}{P_{\mathrm{c}}}$$

and taking into account the frequency-dependent resistance:

(4) $$R_{\mathrm{c}}=k_{\mathrm{c}}\omega_{\mathrm{e}}+R_{\mathrm{c0}}$$

Assuming the resistive torque proportional to the angular speed of the rotor is described as:

(5) $$\begin{aligned}T_{\mathrm{b}}&=T_{\mathrm{b0}}+b\omega_{\mathrm{m}}\\P_{\mathrm{m}}&=T_{\mathrm{b}}\omega_{\mathrm{m}}\end{aligned}$$

where: T_{b0} - the static torque, b - friction coefficient.

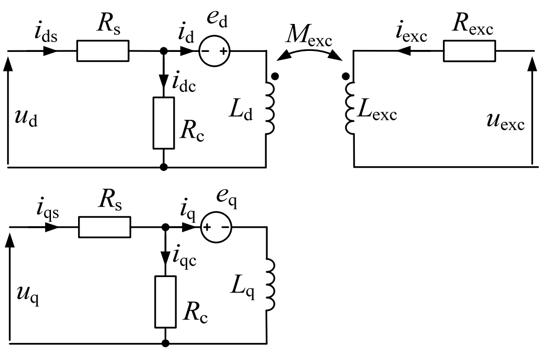

Fig.3. Equivalent circuit of hybrid excitation machine

The proposed method for determining core losses

According to equations (3) and (4) the core losses are the function of the rotational speed of the shaft and the stator linkage flux combination:

(6) $$P_{\mathrm{c}}=\frac{3}{2}\frac{\left(\omega_{\mathrm{e}}\psi_{\mathrm{s}}\right)^{2}}{k_{R\mathrm{c}}\omega_{\mathrm{e}}+R_{\mathrm{c0}}}$$

Simplified methods for determining the value of R_{c} known in the literature are based on the experiment where the shaft of the tested machine is driven (by auxiliary motor) the mechanical power provided over a wide range of speed is measured. It should be noted that as a result the measured values of mechanical power (P_{mech}), besides core loss (P_{c}), also include mechanical losses, which (according to (5)) can be written as:

(7) $$P_{\mathrm{mech}}=\overbrace{T_{\mathrm{b0}}\omega_{\mathrm{m}}+b\omega_{\mathrm{m}}^{2}}^{P_{\mathrm{m}}}+\overbrace{\frac{3}{2}\frac{\left(\omega_{\mathrm{e}}\psi_{\mathrm{s}}\right)^{2}}{k_{R\mathrm{c}}\omega_{\mathrm{e}}+R_{\mathrm{c0}}}}^{P_{\mathrm{c}}}$$

Consequently it is problematic to separate the individual components of the measured losses: mechanical and enclosed in the core.

One of control methods for PMSM machines is to change the stator flux linkage for a wide range of rotor speeds [10]. Measured mechanical loss allows the separation of the individual components of loss (at constant speed change of flux linkage affects the level of core losses only). The adjustment of the value of ψ_{s} (at a fixed point of operation) is done by changing the *d*-axis stator current component:

(8) $$\begin{aligned}\psi_{\mathrm{s}}&=\sqrt{\psi_{\mathrm{d}}^{2}+\psi_{\mathrm{q}}^{2}}\\\psi_{\mathrm{d}}&=I_{\mathrm{d}}L_{\mathrm{d}}+\psi_{\mathrm{pm}}\\\psi_{\mathrm{q}}&=I_{\mathrm{q}}L_{\mathrm{q}}\end{aligned}$$

In HPMSM changing the flux linkage can be achieved by controlling the value of the current in additional excitation coil (without the stator current):

(9) $$\begin{aligned}\psi_{\mathrm{s}}&=\sqrt{\psi_{\mathrm{d}}^{2}+\psi_{\mathrm{q}}^{2}}\\\psi_{\mathrm{d}}&=I_{\mathrm{d}}L_{\mathrm{d}}+\psi_{\mathrm{pm}}+\psi_{\mathrm{exc}}\\\psi_{\mathrm{q}}&=I_{\mathrm{q}}L_{\mathrm{q}}\\\psi_{\mathrm{exc}}&=I_{\mathrm{exc}}M_{\mathrm{exc}}\end{aligned}$$

Experimentally, while driving the test machine (mechanically coupled to auxiliary motor), the supplied mechanical power was measured (by torque and speed sensors) at wide ranges of speed and I_{exc} current. The measurement results are shown Fig. 3.

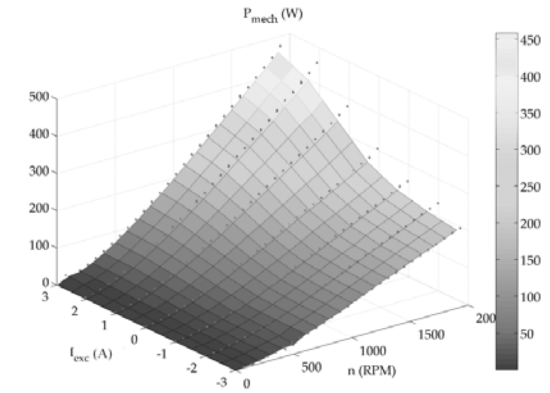

Fig.3. Measurement results of mechanical power supplied as a function of motor speed and the additional coil current (I_{exc})

Using the excitation characteristics of a prototype HPMSM (Fig. 4), linkage flux was read for corresponding values of I_{exc}.

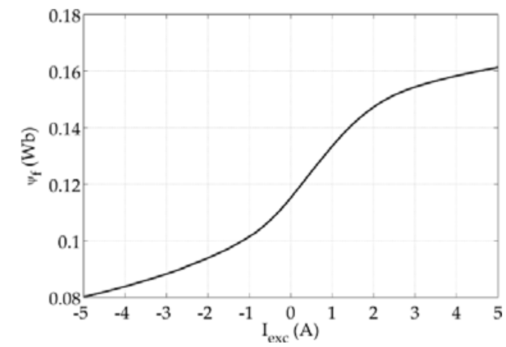

Fig.4. The linkage flux as a function of additional excitation coil current value

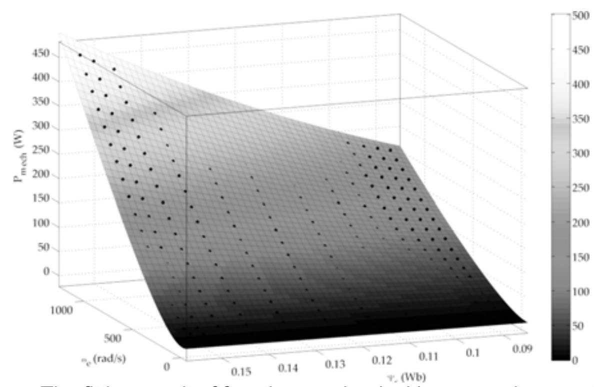

Fig.5. The fitting result of function mechanical losses and magnetic measuring points

By fitting of measurement results to loss model described in relationship (7), individual loss components were determined. Values of the coefficients are: T_{b0} = 0.255Nm, b = 0.832·10^{-3} Nm/rad/s, R_{c0} = 33.8Ω, k_{Rc} = 0.0866Ω/rad/s. Result of fitting is shown Fig. 5.

The presented method allows the separation of the individual components of losses. Mean square error of the fitting function is 3.4W.

Experimental studies and conclusions

Possibility of taking into account the HPMSM loss models in the control strategy were analyzed using the searching algorithm described in [2], [10], [11] and [12].

The starting point of proposed approach is the evaluation of efficiency maps of the machine, including mechanical, iron and copper losses. Power electronic system losses are calculated too. In order to compare, the core loss model of machine can be excluded from searching algorithm, but it always included in efficiency map.

Machine efficiency maps for all possible torque-angular speed points were calculated for iteratively varied I_{exc}, I_d and I_q. Mechanical friction based torque and mechanical power loss were also taken into account. After calculating machine copper and iron losses operation, from resulting operation point maps, elements exceeding maximum allowable voltage and/or current values are eliminated. It should be noticed that such operations were performed for all I_{exc}, I_d and I_q combinations. Finally, having the efficiency map of the machine, efficiency marker is calculated for every current combination. At this point, for all mechanical load and angular speed combinations, the overall efficiency maps are searched for current combinations leading to maximized system efficiency. A graphical representation of the optimization process is depicted in Fig. 6.

In order to verify the method, simulation and measurements data were compared. Experimental test-stand was constructed in order to examine practical properties and implementation procedures of proposed approach. Optimization results were implemented as look-up-tables in the memory of the control unit. Test stand construction is graphically presented in Fig. 7.

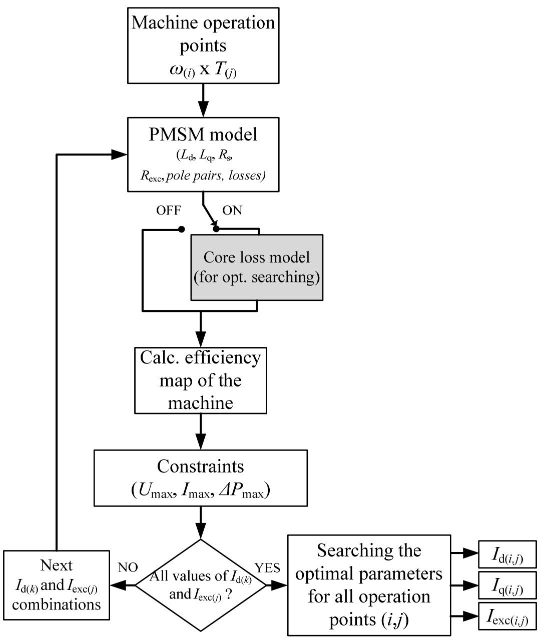

Fig.6. Searching algorithm flowchart

A broad experimental program was led in order to verify the benefits of proposed overall optimization procedure. Experimental efficiency data for speed range 0÷3000 rpm (test bench limit) is depicted in Fig. 8.

It can be seen that the correspondence between simulation efficiency of the machine model and the measurement of the prototype machine is very high (Fig. 9).

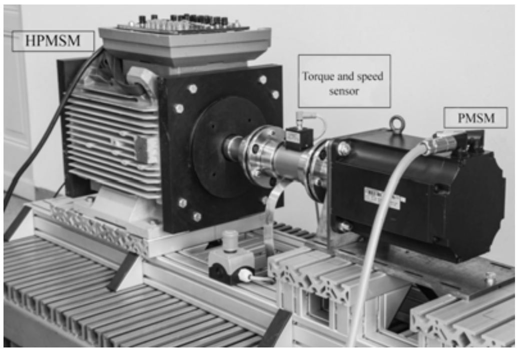

Fig.7. Test stand construction

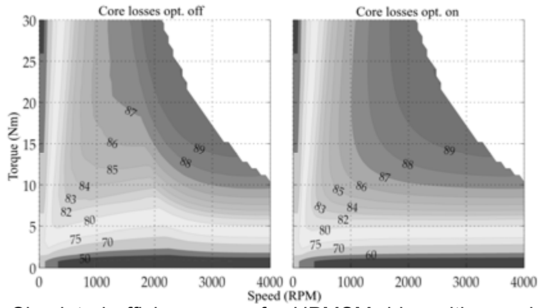

Fig.8. Simulated efficiency map for HPMSM drive with core losses optimization: off (left) on (right)

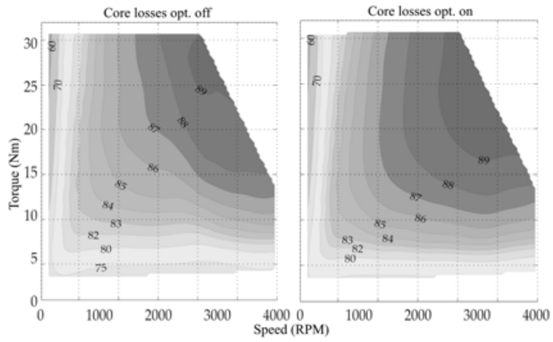

Fig.9. Experimentally validated efficiency map for HPMSM drive with core losses optimization: off (left) on (right)

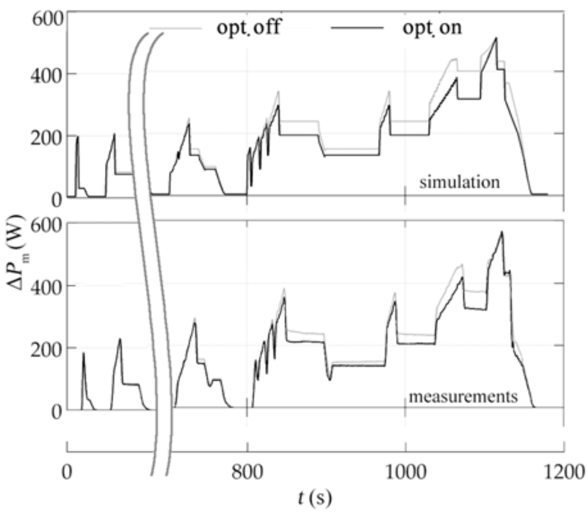

Fig.10. Machine total losses measurement results for NEDC

Optimization results and different optimization loss component sensitivity were also examined using a standardized drive cycle modelling. The NEDC (New European Drive Cycle) cycle was used. Due to test stand limitations a carefully chosen set of parameters of the test vehicle was used. In addition no energy recovery possibility was assumed. NEDC loss component measurements confirm previously led efficiency analyses (Fig. 10).

In order to simplify further analyses a major loss component distribution (accumulated losses), with and without core losses optimization goal, is shown in Fig. 11.

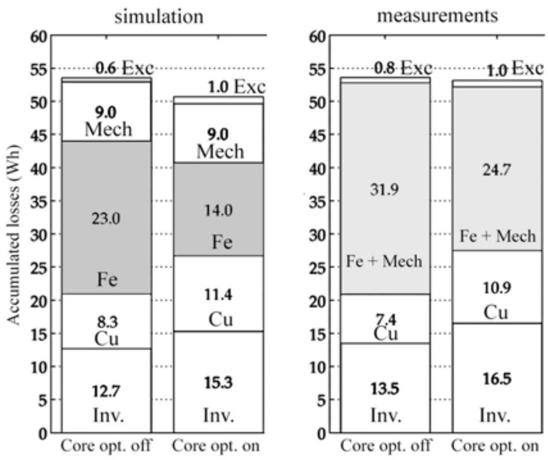

Fig.11. Simulated and measured accumulated losses for NEDC

Including the core loss model in the optimization process results in the best machine performance (from the efficiency point of view), however, due to strong increase of calculated I_d current values power electronic inverter losses were increased, but overall efficiency was increased.

Proposed approach was validated using time domain simulations and experiments ([13], [14]). It includes a non-linear dependence of excitation flux as a function of additional coil current and the description of material properties for core loss calculation. Experimental results clearly exhibit the benefits of including core loss model in control system of HPMSM. A decrease of total losses was measured, mostly in the high speed range of the machine.

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