SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 11, No. 2, June 2014, 257-268

UDC: 621.311-5:621.313.323]:620.9 **DOI: 10.2298/SJEE131227021G**

Towards an Improved Energy Efficiency of the Interior Permanent Magnet Synchronous Motor Drives

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Abstract: This paper investigates the possibility of energy efficiency increase in the drives with high speed permanent magnet synchronous motors. The losses are decreased by the proposed procedure, i.e. proper allocation of the available stator current capacity to the direct and quadrature current components. The approach provides increased energy efficiency by varying the ratio between copper and iron losses.

Keywords: PMSM, Energy Efficiency, Field Weakening.

1 Introduction

More than 60% of produced electrical energy is converted into mechanical energy in the electric drives. Therefore, a high energy efficiency of electric drives is required [1]. Permanent-Magnet Synchronous Motors (PMSMs) gain more attention in variable speed drives due to their good efficiency, fast torque response, high power density, cooling, and lack of maintenance. There are two types of PMSM: motors with surface mounted permanent magnets (SPMSM) and motors with internally mounted permanent magnets (IPMSM). The main difference between these two types is the existence of reluctant torque component which exists only in IPMSM due to the rotor salience [2]. The rotor of IPMSM has high mechanical strength and therefore this type of motor can operate in ultra high speed drives [3].

Losses of IPMSM are divided into the copper losses, the iron losses and the mechanical losses. Copper and iron losses can be controlled by a proper motor control strategy, while mechanical losses depend only on the shaft speed, therefore, they cannot be controlled. Copper losses can be decreased by the strategy which provides maximum torque on the rotor for a given stator current amplitude (MTPA - Maximum Torque per Amperes approach [4]). Iron losses

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depend on square of the flux amplitude, therefore, they can be governed by controlling the flux level, i.e. varying the *d* component of stator current [3]. In order to decrease overall losses in the motor, both copper and iron losses should be controlled simultaneously [5].

The paper proposes the procedure for controlling IPMSM in order to minimize overall losses, i.e. to increase the efficiency. The methodology is suitable for medium performance drives, in which the load torque is changing slowly. In the Section II, a model of IPMSM is given. Two strategies for the minimization of losses are described. The first one is the standard approach in which the stator current components are selected in order to use optimally available current capacity and to preserve voltage margin. The second one is the newly proposed approach in which the overall losses should be decreased. In the Section III, block diagrams of the standard and the proposed approach are presented. Computer simulations, given in the Section IV, show the differences between the two approaches. Conclusion remarks are given in the Section 5, while the parameters of the drive are listed at the end of the paper, in the Appendix.

2 Theoretical Background

An IPMSM has sinusoidal distributed stator windings, therefore, they should be supplied by sinusoidal stator currents. These currents are obtained by the current regulated pulse width modulator (CRPWM), which provides proper stator current vector [4]. Internal permanent magnets can be mounted in such a way that the flux is oriented in radial or lateral direction, as shown in the Fig. 1.

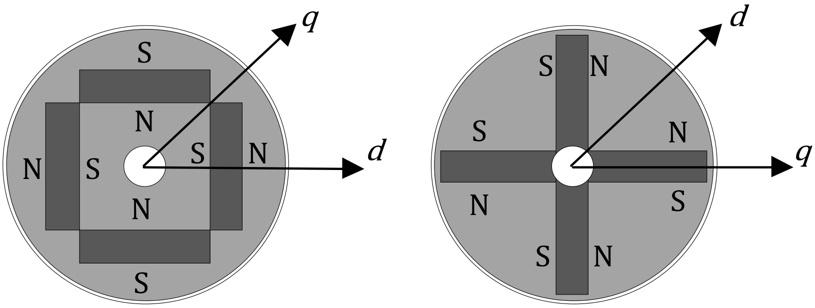

Fig. 1 – *Cross section of an IPMSM with different flux orientations.*

In the IPMSM with buried magnets, the stator quadrature inductance L_q is larger than the direct inductance L_d ($L_q > L_d$). Stator inductance as a function of the shaft position, i.e. the rotor angle (θ_{PM}), can be represented as shown in the Fig. 2 [4].

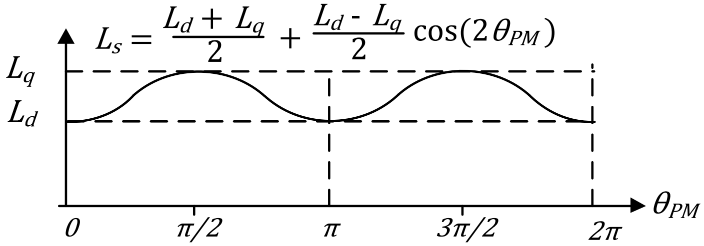

Fig. 2 – *Stator inductance as a function of the rotor angle* (θ_{PM}).

2.1 Mathematical model

Mathematical model of an IPMSM consists of the equation of voltage balance (1), the equations of flux linkage (2-3), and the torque equation (4).

$$\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} + \omega_r \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix}, \tag{1}$$

$$\psi_{sd} = L_d i_{sd} + \psi_{PM}, \tag{2}$$

$$\psi_{sq} = L_q i_{sq}, \tag{3}$$

$$m_{el} = \frac{3}{2} P\left(\psi_{PM} i_{sq} + \left(L_d - L_q\right) i_{sd} i_{sq}\right), \tag{4}$$

where: $\omega_r = P\frac{\mathrm{d}\theta_m}{\mathrm{d}t} = P\omega_m$ is the electrical angular speed, R_s is the stator resistance, L_d is the direct axis stator inductance, L_q is the quadrature axis stator inductance, and Ψ_{PM} is the permanent magnet flux. The expression for torque (4) contains both synchronous and reluctant components.

The torque balance equation is given as:

$$J\frac{\mathrm{d}\omega_r}{\mathrm{d}t} = m_{el} - m_l, \tag{5}$$

where J is the inertia and m_l is the load torque.

2.2 Selection of d component of stator current vector in order to obtain maximum torque per amps

Since the expression for the IPMSM torque (4) has two components, the same stator current can produce different torque values. Synchronous torque is controlled by the q component of stator current ($\sim\Psi_{PM} i_{sq}$), while the d stator current component controls the reluctant torque ($\sim(L_d - L_q) i_{sd} i_{sq}$). Because of this the optimal angle between the stator current vector and the permanent magnet in IPMSM drives is not equal to 90°, i.e. it is larger. This angle defines the ratio between the stator current components i_q and i_d, for a given stator current amplitude (4) and the maximum achievable torque. The MTPA strategy should provide maximum torque for a given stator current amplitude by the proper choice of the stator current components. The MTPA strategy is non-linear , but it provides smaller stator current amplitude for the required torque. Copper losses that are in a steady state, in the constant flux region, are decreased.

Optimal components of the stator currents in the MTPA algorithm can be calculated from the first derivative of the torque (4), as a function of the stator current,

$$\frac{\mathrm{d}m_{el}}{\mathrm{d}i_s} = 0, \tag{6}$$

with $|i_s| = \sqrt{i_{sd}^2 + i_{sq}^2}$.

The solution of (6) is optimal value of i_d for a given value of stator current vector i_{st} [4]:

$$i_{sd}^{MTPA} = \frac{\psi_{PM} - \sqrt{\psi_{PM}^2 + 8\left(L_q - L_d\right)^2 i_{st}^2}}{4\left(L_q - L_d\right)} . \tag{7}$$

Quadrature component of the stator current i_q is calculated from a given stator current amplitude i_{st} and the optimal value of the current i_d (7), while keeping the sign of a required torque reference:

$$i_{sq}^{MTPA} = sign(i_{st})\sqrt{|i_{st}|^2 - \left(i_{sd}^{MTPA}\right)^2} . \tag{8}$$

2.2 Selection of the *d* component of stator current vector in order to preserve available voltage margin

At high speeds, back electromotive force (BEMF) of an IPMSM must be kept below the rated voltage, by decreasing the flux, in the field weakening regime. Rotor flux cannot be changed, because of the permanent magnet on the rotor, but the stator flux (2-3) and the stator BEMF can be changed by changing the stator current i_d. By decreasing the stator flux, the stator BEMF is kept below the maximum available phase voltage of the inverter ($\approx U_{DC} / \sqrt{3}$), and a proper operation of stator current regulators is preserved. The Stator flux is decreased by injecting negative *d* component of the stator current, as follows:

$$i_{sd} < 0 \xrightarrow{gives} \psi_{sd} = L_d i_{sd} + \psi_{PM} < \psi_{PM} . \tag{9}$$

Regulator for a field weakening regime can be given by the following equation:

$$\Delta i_{sd} = K_{fw}\left(u_s^{\max} - \sqrt{u_{sd}^2 + u_{sq}^2}\right), \tag{10}$$

where: K_{fw} is the integral gain of the flux regulator, u_{sd}, u_{sq} are the outputs of current regulators, and $u_s^{\max} = k_u U_{DC} / \sqrt{3}$ is the maximum value of inverter phase voltage. The parameter k_u should be chosen so as to preserve sufficient voltage margin for proper operation of current regulators.

2.2 Selection of the *d* component of stator current vector in order to obtain minimum of the total losses

Power losses in an IPMSM exist on the stator, such as stator winding copper losses (P_{Cu}) and stator iron losses (P_{Fe}). Due to the friction and ventilation (P_{fv}), mechanical losses depend on the speed, while there are no losses on the rotor of an IPMSM. The losses and conversion power (P_c) can be calculated as [5 – 10]:

$$P_{Cu} = \frac{3}{2} R_s \left(i_{sd}^2 + i_{sq}^2\right), \tag{11}$$

$$P_{Fe} = \left(k_1 \omega + k_2 \omega^2\right) \psi_s^2 , \tag{12}$$

$$P_{fv} = k_3 \omega^2 , \tag{13}$$

$$P_c = m_{el} \omega , \tag{14}$$

where the stator flux amplitude is:

$$\psi_s = \left(\psi_{PM} + L_d i_{sd}\right)^2 + \left(L_q i_{sq}\right)^2 . \tag{15}$$

Iron losses depend on the square of the stator flux, and they increase as the load increases. Those losses can be treated as mechanical losses, by modeling them with equivalent braking torque, and they can be added to the load torque. In that case, the balance of the IPMSM losses can be represented as in the Fig. 3

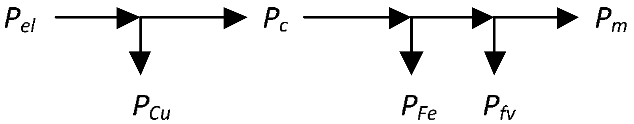

Fig. 3 – *Balance of the losses of an IPMSM.*

The efficiency of a motor is given as the ratio between output mechanical power (P_m) and input electrical power (P_{el}):

$$\eta = \frac{P_m}{P_{el}} = \frac{P_c - P_{Fe} - P_{fv}}{P_c + P_{Cu}} . \tag{16}$$

In order to provide the best efficiency in a steady state, an optimal allocation of the losses (11 – 13) should be provided by a proper selection of the *d* and *q* components of the stator current vector. This ratio can be found from the derivative of (16), under the condition that the output power, in a steady state, shall be constant:

$$\frac{\partial \eta}{\partial i_{sd}} = 0, \tag{17}$$

$$\frac{\partial P_m}{\partial i_{sd}} = 0. \tag{18}$$

From (11 – 18) the stator current components i_d and i_q can be calculated, and they will produce minimum losses for a given torque and speed.

The complete solution, of the system of equations (11 – 18), results in a very complicated and parameter dependent expression for the stator current component. These expressions are extremely hard to implement on the real drive. Because of this, an alternative approach is suggested here, by observing expressions for the iron losses (12) and (15). Even these losses depend on both stator current components, they are prevalently dependent on the permanent magnet flux, which is placed in the *d* axis. This is the reason why variations of the stator flux, caused by the changes of stator current i_q, or load, can be neglected. By using the assumption that the iron losses do not depend on active current component, the efficiency of the drive can be increased by changing the independent losses to become equal to the value of load dependent losses. Then, the optimization procedure should provide the proper current i_d in order to tune the stator flux and the load independent losses, to the value when dependent and independent losses are equal. It is assumed that tuning the load independent losses closer to load dependent losses will result in better efficiency, i.e. smaller overall losses for the same output conditions [6].

Proposed approach can be realized by using a simple linear regulator of an integral (I) type. The input to the regulator is the difference between copper and iron losses, while the output is the optimal value of stator current i_{sd}^{OPT}. The proposed structure will provide load independent and load dependent losses to be equal in a steady state. To prevent eventual stability issues, the control structure for the stator current i_{sd} should yield much slower dynamics than the speed and torque regulation contours.

When the proper *d* value of stator current is found, the *q* component of stator current can be found from:

$$i_{sq}^{OPT} = sign(i_{st})\sqrt{i_{st}^2 - i_{sd}^2}, \tag{20}$$

where the current i_{st} is obtained from a speed regulator, the same way as in the MTPA algorithm in the base speed region. The proposed optimization algorithm (MOPT) of the stator current i_d is shown in the Fig. 4.

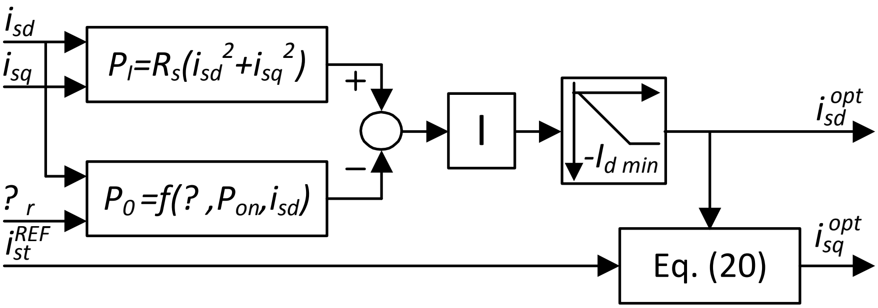

Fig. 4 – *Proposed MOPT algorithm for energy efficiency improvement.*

3 Comparison of the Conventional and Proposed Algorithm

Conventional speed control scheme of the IPMSM drive for both the base speed region and for the field weakening region is given in the Fig. 5 [4]. The speed is regulated by a linear proportional – integral (PI) regulator which provides the stator current amplitude reference i_{st}^{REF}. This stator current should minimize the difference between the required and the measured rotor speed, which will result to the zero error in the steady state. The reference is limited to the maximum value allowed by the inverter, and after that it is set as an input to the MTPA block which calculates optimal ratio between *d* and *q* current components, which provides the maximum torque of IPMSM for the given current amplitude.

In the proposed algorithm, depicted on the Fig. 6, instead of the MTPA, the losses optimization MOPT block is used.

Within both algorithms, the stator BEMF is monitored and kept below the maximum available inverter output voltage in the field weakening region. If the BEMF becomes larger than available inverter voltage, $u_s^{\max}$, field weakening regulator reacts and additionally decreases the *d* component of the stator current. In that case, the *d* component of stator current is calculated, the Fig. 5 and the Fig. 6, as:

$$i_{sd}^{REF} = i_{sd}^{MTPA} + \Delta i_{sd}^{u}, \tag{21}$$

$$i_{sd}^{REF} = i_{sd}^{MOPT} + \Delta i_{sd}^{u}. \tag{22}$$

In both cases, the *q* component of stator current is calculated by using the current amplitude reference obtained from the speed regulator:

$$i_{sq}^{REF} = \mathrm{sign}(i_{st})\sqrt{i_{st}^2 - i_{sd}^2} \ . \tag{22}$$

Stator current component references, i_d and i_q, are fed to the CRVSI block (*Current Regulated Voltage Source Inverter*), as shown in the Fig. 5 and the Fig. 6.

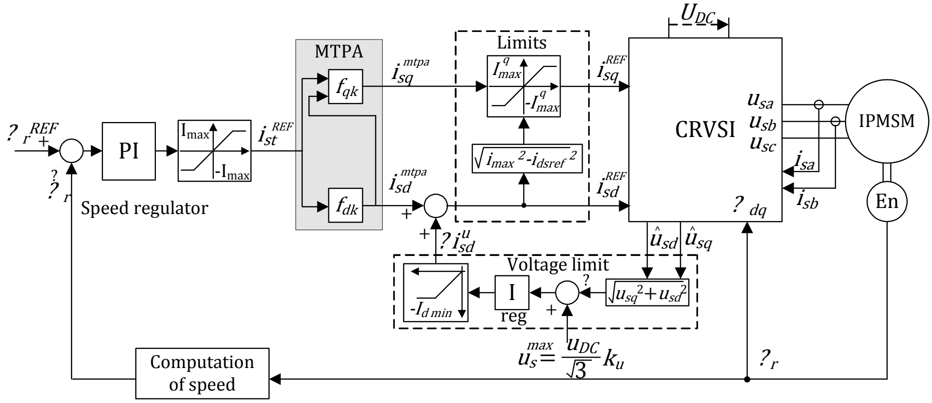

Fig. 5 – *Standard MTPA approach for controlling IPMSM.*

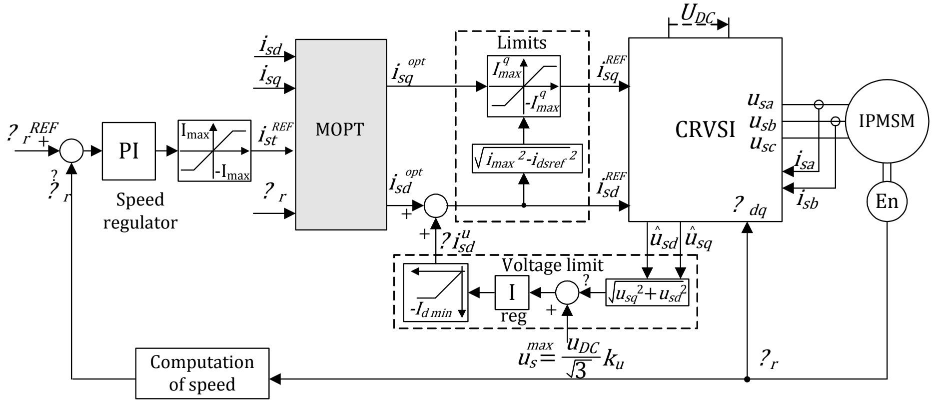

Fig. 6 – *Proposed MOPT approach for controlling an IPMSM with improved efficiency.*

4 Simulation Results

The proposed approach is tested by computer simulations, using *Matlab Simulink Toolbox*. Input data and the load independent losses are found from the no load test of the drive, by using hysteresis and eddy current losses coefficients [8].

The results of simulation of the IPMSM drive with the MTPA approach and with the proposed MOPT approach are given in the Figs. 7 and 8. In both simulations the drive starts in the MTPA structure, the Fig. 5, and enters the steady state. After operating for 1.6 s, the control is then switched to the MTPA, the Fig. 6. Speed reference is set to 6000 rpm, while torque reference is 1 Nm, the Fig. 7, and 1.5 Nm, the Fig. 8, which corresponds to 30% and 50% of the rated torque, respectively.

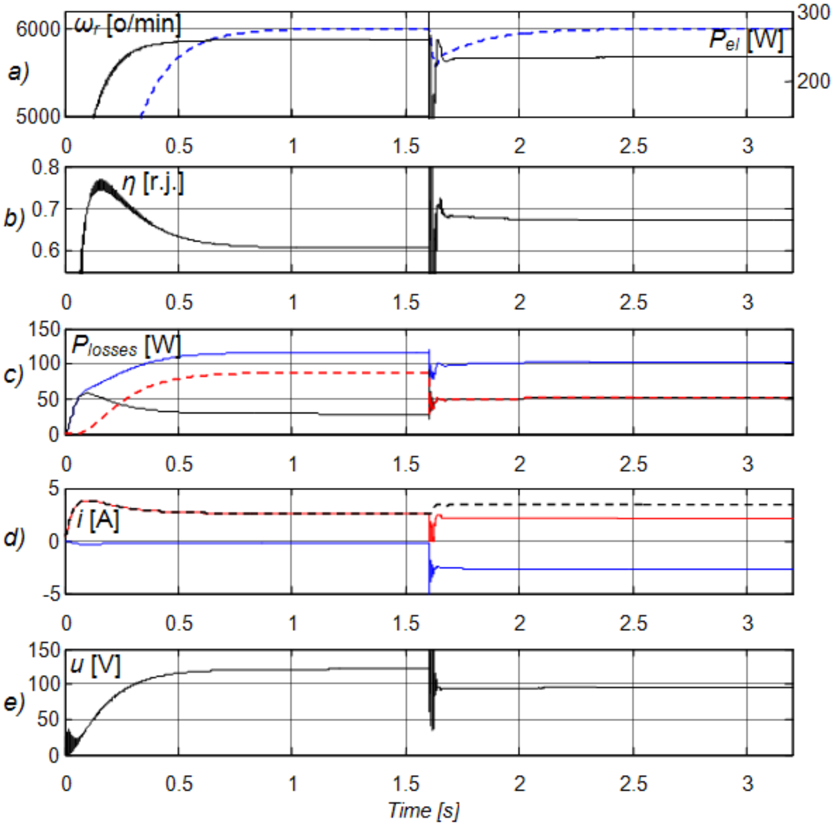

Fig. 7 – *Results of simulation of MTPA and MOPT algorithms for speed reference* ω_r^{REF} = 6000 o/min *and torque 1.0* Nm.

In the Fig. 7 and 8 the following is shown: a) speed (blue, dashed) and input power (black), b) efficiency, c) load dependent losses (black), load independent losses (red, dashed) and total losses (blue), d) stator current references, *d* (red), *q* (blue) and reference amplitude (black, dashed), e) motor voltage.

From the Figs. 7a and 8a it can be seen that the required speed reference is maintained in both algorithms, as well as the torque and the output power. The proposed MTPA algorithm provides decreased input power, which results in the increased efficiency, the Figs. 7b and 8b, and decreased total losses, the Figs. 7c and 8c. Load dependent and load independent losses become equal in the MOPT algorithm. In the MOPT algorithm motor voltage is decreased, the Fig. 7e and 8e. This results in the decreased stator flux and the decreased iron losses. From the other hand, the stator current, the Figs. 7c and 8c, is increased, as well as the copper losses, but the total losses are still decreased.

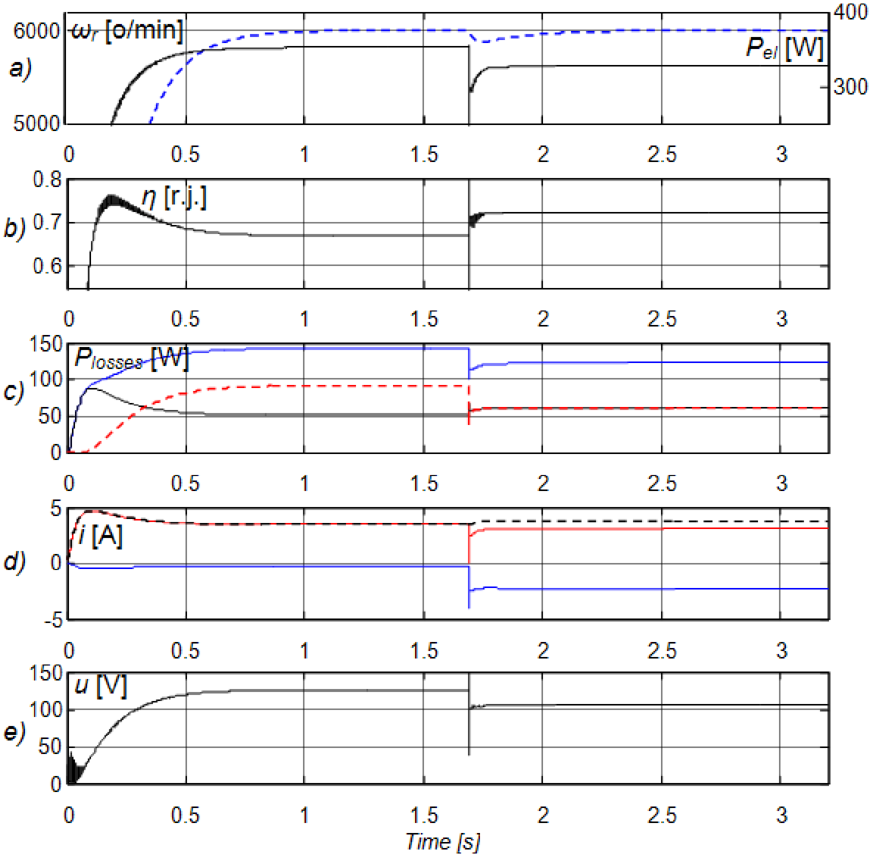

Fig. 8 – *Results of simulation of the MTPA and the MOPT algorithms for speed reference* $\omega_r^{REF} = 6000$ o/min *and torque 1.5 Nm.*

It can be observed from the Figs. 7 and 8 that the MTPA algorithm provides faster response, since it provides larger torque for the same stator current amplitude as the MOPT, but it has increased losses compared to the MOPT.

5 Conclusion

The paper presents a simple approach for the improvement of IPMSM drive efficiency. The approach is based on the assumption that variations in the *q* component of stator current have negligible influence to the stator flux. By using this assumption, the losses in an IPMSM are separated into the load dependent and the load independent losses. By the proper balancing between these losses, i.e. forcing them to be equal in a steady state, total losses are decreased, and the efficiency is improved.

Computer simulations show that the proposed MOPT approach can be used for the efficiency improvement in some drives. The approach is simple to implement in the low cost drives with slowly changing loads. It has slower response than the MTPA, which is expected, since the balance between the current components is made in order to obtain a maximum available torque, but this should not be an issue in the general purpose drives which do not exhibit fast torque changes.

6 Acknowledgment

This research was co-funded by the Ministry of Education, Science and Technological Development. of Republic of Serbia under contract No. III 042004.

7 Appendix

The motor parameters are as follows: 1 kW, 195 V, Y, $p = 4$, $R_s = 1.42\ \Omega$, $\Psi_m = 0.1\text{Wb}$, $L_d = 9\text{mH}$, $L_q = 11.3\text{mH}$.

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