EFFICIENCY IMPROVEMENT OF INVERTER-FED PERMANENT MAGNET SYNCHRONOUS MOTORS

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Abstract

In this paper a control algorithm for the efficiency improvement of inverter-fed permanent magnet synchronous motors (PMSMs) is presented. The proposed algorithm allows reducing the losses of the drive without reduction of its dynamic performances. In details, after recalling a dynamic model of the PMSM, which has been purposely modified and that takes into account the iron losses, the basic equations and the constraints to obtain the loss minimization are presented and discussed. Some simulations of a specific PMSM drive employing the proposed algorithm are performed. The results of these simulations show that the dynamic performances are maintained, and enhancement of the efficiency up to 5% can be reached in comparison to a PMSM drive using a more traditional control strategy.

INTRODUCTION

Permanent magnet synchronous motors (PMSMs) fed by inverters are widely used in industrial applications for their high performances. The main reasons rely on their optimal characteristics, which are, for example, higher efficiency and higher power-weight ratio than dc and induction motors. PMSMs are convenient because they have a loss-free rotor, and the power losses are mainly related to the stator windings and the stator core. The ratio of the copper and iron power losses is a key issue in determining the maximum efficiency point as function of the mechanical load that is connected to the motor shaft. In the case of constant-speed motors fed by the main, the motor designer performs a trade-off to obtain the maximum of the efficiency at given load conditions, according to the user requirements. Unfortunately, this advantageous condition is lost as long as the motors operate at variable-torque and variable-speed.

This paper deals with a control algorithm, which is able to improve the efficiency of permanent magnet synchronous motor drives by reducing the motor losses (copper and iron losses) through an optimal management of the current space vector in the stator winding, in the case of variable-speed variable-torque applications. In particular, after a brief recall of two loss minimization control strategies [1-5] (the so-called "search control" and "loss-model control" algorithms), both a modified dynamic model of the PMSM, which takes into account the iron losses, and an improved "loss-model" control strategy are presented. The control algorithm here proposed allows determining the optimal current space vector according to the operating speed and the load conditions.

The proposed approach is suitable to be applied to machines with salient or non-salient rotor structure types. The control algorithm is devoted to improve the efficiency in steady-state condition, which is a major opportunity for energy savings. By applying the proposed loss minimization algorithm to a specific drive, the simulation results have shown that its dynamic performances are maintained, and enhancement of the efficiency up to 5% can be reached in comparison to a PMSM drive equipped with a more traditional control strategy (i.e. i_d=0).

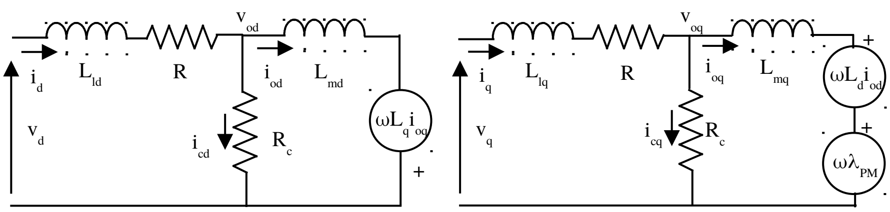
LOSS MINIMIZATION TECHNIQUES: STATE-OF-THE-ART

Control techniques aiming to obtain the loss minimization have been extensively investigated in literature [4-8]. However, despite the huge of papers they can strictly be summarized into two main categories: papers, which deal with the "loss model control" technique, and papers, which apply the "search control" algorithm. The "loss model control" technique is based on the development of a mathematical model, which allows estimating the energy losses occurring during the running of the motor. Obviously, key issues in this case are the knowledge of a precise system model, an accurate identification of its parameters, and also the variation of the parameters with the temperature, current, etc. By expressing the losses as a function of the control variables of the drive, then it is possible to impose an operating condition to obtain a maximum of the efficiency [1].

The "search control" algorithm, on the contrary, is not based on a model rather on an adaptive routine. The approach mainly consists on changing step by step the value of a control variable, then measuring for each operating point the active power flowing into the motor. Finally, by comparing the measurement result with the previous one at fixed operating conditions, the minimum power consumption of the drive is searched. To this aim, recent works have experimentally demonstrated that the searching procedure successful can individuate a maximum efficiency point [2]. The "search control" algorithm has the advantage that there is no need to know the model of the motor and its parameters. A drawback is that such a technique can originate system oscillation phenomena, thus making unstable the drive. As far as this technique is adopted, a requirement of an additional stabilization network may arise [5].

PMSM DYNAMIC MODEL WITH IRON LOSSES

The basic hypotheses, which have been used in order to define the proposed dynamic model of a PMSM, are that the spatial distribution of the magnetic flux in the air gap is sinusoidal and the magnetic circuit is linear. Moreover, a dedicated parameter has been considered aiming to account for the loss of the stator iron. In particular, the iron loss is modeled by a resistance R_c, which is inserted in the traditional equivalent circuits of a synchronous machine so that the loss depends on the air-gap linkage flux. According, by considering the two-axes theory of Park and introducing the change in the model as above defined to account for the iron losses, the dynamic d- and q-axis equivalent circuits of the PMSM can be drawn,



as it is shown in Fig. 1. With reference to Fig. 1, the state equations of the dynamic model of a PMSM, taking into account also the iron losses, are:

Fig. 1. Dynamic equivalent circuits along the d- and q-axis of a PMSM.

$$\frac{di_d}{dt}=\frac{1}{L_{ld}}\left(v_d-Ri_d-L_{md}\frac{di_{od}}{dt}+L_q P\omega_r i_{oq}\right) \tag{1}$$

$$\frac{di_q}{dt}=\frac{1}{L_q}\left(v_q-Ri_q-L_{mq}\frac{di_{oq}}{dt}-L_d P\omega_r i_{od}-\lambda_{PM}P\omega_r\right) \tag{2}$$

$$\frac{d\omega_r}{dt}=\frac{1}{J}\left[T_e-C\ Sign\left(\omega_r\right)-F\omega_r-T_m\right] \tag{3}$$

$$\frac{d\theta_r}{dt}=\omega_r \tag{4}$$

where

$$i_{od}=i_d-i_{cd}\ ,\ i_{oq}=i_q-i_{cq} \tag{5}$$

$$i_{cd}=\frac{-\omega P L_d i_{oq}+L_{md}\frac{di_{od}}{dt}}{R_c}\ ,$$

$$i_{cq}=\frac{\omega\left(\lambda_{PM}+L_d i_{od}\right)+L_{mq}\frac{di_{oq}}{dt}}{R_c} \tag{6}$$

$$T_e=\frac{3}{2}P\left[\lambda_{PM}i_{oq}+\left(L_{md}-L_{mq}\right)i_{od}i_{oq}\right] \tag{7}$$

LOSS MINIMIZATION ALGORITHM

The power losses in a PMSM are copper and iron losses in the stator, mechanical losses, and additional copper and iron losses. The considered losses can be separated into two categories, namely, controllable and uncontrollable losses. The copper losses, which are caused by the fundamental harmonic component of the stator current, and the iron losses, which are caused by the fundamental harmonic components of the air-gap linkage flux, belong to the first type (in turn, these losses depend on the controllable variables of the motor). Unlike the above quantities, copper and iron losses, which are caused by the higher harmonic components, together with the mechanical losses belong to the uncontrollable ones. For this reason, the mechanical and additional losses are here not considered.

The dynamic model described by relations (1-7) has been prepared aiming to perform both the steady state and transient simulations of a PMSM drive. However, the optimization of the power loss consumption is done by considering an algorithm (see [1]) which refers to a steady-state model. By setting to zero the time derivatives of the d- and q-axis current components in (1), and (2), and also of the rotor angular speed in (3), the steady state model is obtained. Hence, the power losses caused by the fundamental harmonic of the current in the windings (W_{Cu}), and the power losses caused by the fundamental harmonic of the air-gap flux linkage in the iron stack (W_{Fe}), can be expressed as a function of the i_{od} and i_{oq} current components and of the electrical speed, $\omega = P\omega_r$.

$$W_{Cu}\left(i_{od}, i_{oq}, \omega\right) = \frac{3}{2} R \left(i_d^2 + i_q^2\right) = \frac{3}{2} R \left\{ \left(i_{od} - \frac{\omega k L_d i_{oq}}{R_c}\right)^2 + \left(i_{oq} + \frac{\omega\left(\lambda_{PM} + L_d i_{od}\right)}{R_c}\right)^2 \right\} \tag{8}$$

$$W_{Fe}\left(i_{od}, i_{oq}, \omega\right) = \frac{3}{2} R_c \left(i_{cd}^2 + i_{cq}^2\right) = \frac{3}{2} \frac{\omega^2 \left(k L_d i_{oq}\right)^2}{R_c} + \frac{3}{2} \frac{\omega^2 \left(\lambda_{PM} + L_d i_{od}\right)^2}{R_c} \tag{9}$$

By adding relations (8-9) the total electrical losses are calculated:

$$W_C\left(i_{od}, i_{oq}, \omega\right) = W_{Cu} + W_{Fe} \tag{10}$$

By combining relations (7) and (10), a relation that expresses the power losses of the motor as function of the electromagnetic torque T_e, the direct axis current component i_{od}, and the angular speed ω_r is obtained:

$$W_C\left(i_{od}, T_e, \omega\right) = W_{Cu}\left(i_{od}, T_e, \omega\right) + W_{Fe}\left(i_{od}, T_e, \omega\right) \tag{11}$$

Based on inspection of relation (11), a simple consideration can be carried out: at fixed values of both T_e and ω, the total controllable losses depend only on the i_{od} value, then can be minimized by controlling the current space vector. In reference [1] the value of i_{od} that minimizes the electrical losses has been analytically calculated by differentiating expression (11), with respect to the i_{od} variable, and successively equating the resulting expression to zero. The following relations summarize the main results of such a procedure, being the "heart" of a new technique of implementation and solution of the algorithm of the minimum loss condition:

$$AB = T_e^2 C \tag{12}$$

where

$$A = P^2\left[R R_c^2 i_{od} + \omega^2 L_d \left(R + R_c\right)\left(L_d i_{od} + \lambda_{PM}\right)\right]$$

$$B = \left[\lambda_{PM} + (1-k) L_d i_{od}\right]^3 ,$$

$$C = \left[R R_c^2 + \left(R + R_c\right)\left(\omega\, k\, L_d\right)^2\right] (1-k) L_d$$

In the case of machines with isotropic rotor structure the parameter of saliency is k=1, and condition (12) simplifies. According, the optimal current i_{od}* can be easily expressed as analytical function [1]. However, for a more general structure of the motor rotor, the problem cannot be easily solved, and a closed solution i_{od}* is not obtainable, because of the non-linear relationship nature of (12). For this reason, in reference [1] the value of i_{od}* which minimizes the losses has been calculated by using an approximate procedure. By the use of a polynomial expression, which is a function of i_{oq}, the solution of the optimal d-axis current is “on line" calculated through the use of an implemented "off line" look-up table previously calculated. This method has the burden relative to the recalculation of a lot of coefficients, in order to update the look-up table, aiming to account for the new parameters in case the motor is changed.

In this paper an alternative solution is proposed. By the use of a subroutine implemented in the simulation tool MATLAB-Simulink expression (12) has been solved. The timing of the procedure is roughly the following. The current i_{oq} is determined by substituting both the calculated optimal current i_{od}* and the desired torque T_e in relation (7). The d- and q-axis components of the current i_d and i_q are then determined based on relations (5-6). The main difference in respect of the procedure used in [1] is the "on line" calculation of the i_d and i_q current components that minimize the power losses. Moreover, any change of the used motor needs the simple introduction of the major motor parameters, thus avoiding the "off line" calculation of many data and the implementation in the look up table.

SIMULATION RESULTS

Extensive simulation runs have been carried out by implementing the PMSM electrical drive on MATLAB-Simulink environment. Some of the main results are presented in this section. Firstly, a comparison has been made between two different approaches: the loss minimization algorithm (LMA) discussed in the preceding section, and a traditional i_d=0 control. The i_d=0 condition has been reached through a speed-dependant compensation of the rotor instantaneous position. The parameters of the simulated PMSM are listed in Table I.

The efficiency curves, as a function of the mechanical speed, in the case of LMA (conts. curve) and of i_d=0 control (dotted curve) at the rated load of 1.67Nm, are shown in Fig. 2 a). The efficiency of the brushless motor, thanks to the new approach, can increase up to 5% in the high-speed range. The d- and q-axis current components as a function of the speed, at rated load conditions, are shown in Fig. 2 b). From such a figure, we can see that at high speed the flux weakening significantly reduces the iron losses. The efficiency curves as a function of the load torque, in the case of LMA (conts. curve) and of i_d=0 control (dotted curve) at the rated speed of 2000 rpm, are traced in Fig. 3 a). The d- and q-axis current components, as a function of the load torque at the rated speed (2000 rpm), are shown in Fig. 3 b). As shown in Fig. 3 a) the effectiveness of the LMA grows at increasing load and becomes more significant in proximity of the rated one.

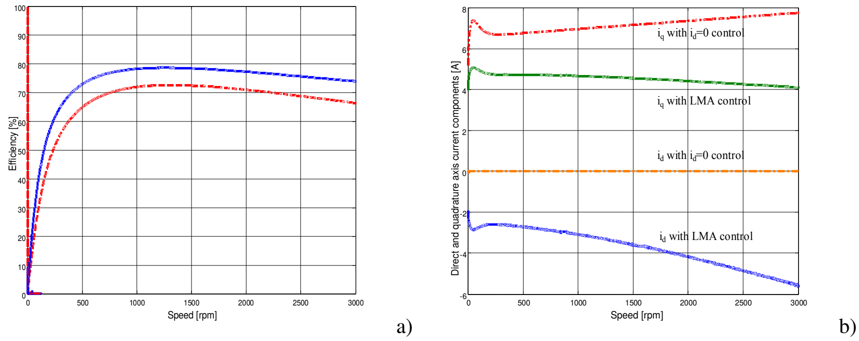


Fig. 2. a) Efficiencies vs. speed with LMA (conts. line) and i_d=0 control (dotted line) at rated load. b) d- and q-axis current components versus speed in the same conditions.

Table 1. Nameplate data and per phase parameters values of a PMSM.

Rated speed [rpm]	2000
Rated current (rms) [A]	5
Rated torque [Nm]	1.67
Number of poles	4
Armature resistance R [Ω]	0.57
Equivalent resistance of the iron losses R_c [Ω]	240
Direct axis inductance [mH]	8.72
Quadrature axis inductance [mH]	22.78
Permanent magnet flux [Wb]	0.088
Mechanical losses (torque) [Nm]	0.058

Finally, in Figs. 4 a) and b) the simulated dynamic response of the PMSM electrical drive to a sudden load change, both with i_d=0 control and LMA at 2000 rpm, is presented. The drive is running at no load condition, then at t=0.5s the rated load is applied (1.67 Nm) on the shaft. From inspection of such Figs. 4 a) and b) we can observe that there is not evidence of appreciable difference in the dynamic response of the speed (Fig. 4 a)), nor in the dynamic of the direct and quadrature current components (Fig. 4 b)), between the traditional control algorithm and the loss minimization one. On the contrary, a great difference is present in the values of the d- and q-axis current components, as it is shown in Fig. 4 b). This figure demonstrates the effectiveness and rapid convergence of the proposed control technique, capable to improve the efficiency subsequently to a transient, without appreciable delay or oscillations, while maintaining the dynamic of the current components. In order to experimentally verify the LMA, an early stage of a PMSM drive has been realized, and actually it is in progress. Preliminary experimental results, during the set up of the drive, encourage more developments in order to implement the proposed algorithm in a commercial DSP.

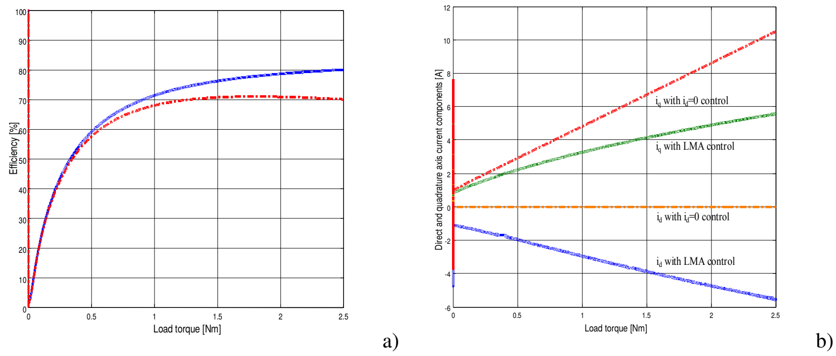


Fig. 3. a) Efficiencies vs. load torque with LMA (conts. line) and i_d=0 control (dotted line) at rated speed. b) d- and q-axis current components vs. load torque in the same conditions.

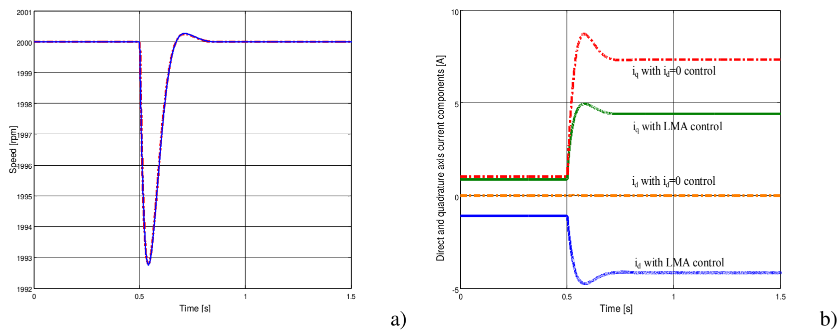


Fig. 4. a) Speed responses of the drive with LMA (cont. line) and i_d=0 control (dotted line). b) d- and q- axis current components with LMA (cont. lines) and i_d=0 control (dotted lines).

CONCLUSIONS

In this paper both a new dynamic model of the PMSM, which takes into account the iron losses, and a modified "loss-model" control strategy have been presented. In particular, it has been verified by simulation runs that controlling the stator current space vector can minimize the controllable electrical losses occurring in a brushless motor drive, consisting of the fundamental copper and iron losses. Such a control strategy, accounting for both the instantaneous speed values and the load torque condition, uses the combined effects of the field weakening and the exploitation of the reluctance torque. The loss minimization technique here reported is very flexible and simple to implement because only requires the knowledge of the common motor parameters. The main results of the simulations carried out demonstrated how, in comparison with more traditional control methods, the loss minimization algorithm increments in a significant way the efficiency of a PMSM drive without any reduction on the dynamic performances.

LIST OF SYMBOLS

i_d, i_q	*d- and q-axis current components;*	P	*motor pole pairs;*
i_{cd}, i_{cq}	*d- and q-axis iron loss current components;*	ω	*electrical angular speed;*
v_d, v_q	*d- and q-axis voltage components;*	ω_r	*rotor mechanical angular speed;*
L_{md}, L_{mq}	*d- and q-axis mutual inductances;*	T_e	*electromagnetic torque;*
L_{ld}, L_{lq}	*d- and q-axis leakage inductances;*	T_m	*load torque;*
k	*saliency ratio ($k=L_q/L_d$);*	J	*rotor inertia;*
R	*stator resistance;*	C	*Coulomb friction factor;*
R_c	*transversal resistance;*	F	*viscous friction factor;*
λ_{PM}	*permanent magnet rotor flux;*	θ_r	*instantaneous rotor position.*

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