# Efficiency Improvement in VSI-fed SPMSM Drive

Chandan Dutta [1] S. M. Tripathi [2]

**Abstract–A model-based loss minimization control strategy is presented which reduces the total power loss in a surface-mounted permanent magnet synchronous motor (SPMSM) drive without reducing its dynamic performance. A modified dynamic model of SPMSM (incorporating core loss resistance) is considered. The *d*-axis armature current is utilized to reduce the total power loss in a closed-loop field oriented controlled SPMSM drive. It is found through detailed computer simulations that efficiency of the drive is improved with model-based loss minimization algorithm as compared to the conventional zero *d*-axis current control strategy.**

**Keywords–Efficiency improvement, field-oriented control (FOC), surface-mounted permanent magnet synchronous motor (SPMSM), loss minimization algorithm (LMA).**

## NOMENCLATURE

| | |
|---|---|
| $i_d$ , $i_q$ | *d-q* axes stator current components |
| $i_{cd}$ , $i_{cq}$ | *d-q* axes iron loss current components |
| $i_{od}$ , $i_{oq}$ | *d-q* axes magnetizing current components |
| $v_d$ , $v_q$ | *d-q* axes stator voltage components |
| $L_d$ , $L_q$ | *d-q* axes stator winding inductances |
| $R_s$ , $R_c$ | Stator winding and iron loss resistances |
| $\omega_e$ | Angular electrical frequency |
| $\omega_m$ | Rotor mechanical speed |
| $J$ | Moment of inertia |
| $T_e$ | Electromagnetic torque |
| $T_m$ | Load torque |
| $\Psi$ | Flux linkage due to rotor magnets |
| $\Theta$ | Rotor electrical position |
| $P$ | Number of pole pairs |
| $F$ | Damping coefficient |
| $W_{cu}$ | Stator winding copper losses |
| $W_{fe}$ | Iron losses |
| $P_{in}$ | Input power |
| $P_{out}$ | Output power |
| $W$ | Total power losses |
| $\eta$ | Efficiency |

## I. INTRODUCTION

Roughly 58% of the total absorbed electrical energy is used in electric motors. Therefore, minimizing the losses and hence efficiency optimization is an important concern in the industry [1–3].

The widely utilized induction motors exhibit poor efficiency due to copper losses in the rotor circuit [4–6]. Therefore, nowadays permanent magnet synchronous motors (PMSM) are used in variable-speed drive systems due to its high torque-inertia ratio, high power factor, low maintenance cost and robustness.

The motor losses consist of copper losses, iron losses and mechanical losses. Copper losses and iron losses are controllable whereas mechanical losses depend on speed and are not controllable. Copper losses can be reduced by maximum torque-per ampere control (MTPA) and iron losses can be minimized by flux-weakening control [7–8]. Several control techniques have been proposed for loss minimization and efficiency enhancement. Zhou *et al.* [9] increased the efficiency of PMSM drive by incorporating MTPA with fuzzy logic for searching the optimum point. Solutions for MTPA equations were obtained by Newton's method. Lee *et al.* [10] applied Lagrangian to the loss function and numerical techniques were used to obtain the solutions of the fourth order polynomial formed. Also a look-up table was used in the current control loop which was obtained by loss minimizing current sets for given torque and speed. Cho *et al.* [11] used precise parameter estimation for maximizing efficiency of IPMSM drive. Then current phase angles were utilized to determine maximum efficiency point.

In this paper, a control method is presented which reduces the total controllable losses (both iron and copper losses) through the insertion of most optimal *d*-axis current. The results obtained are compared to those obtained with conventional zero *d*-axis current control strategy for a field-oriented controlled SPMSM drive.

## II. MODELING EQUATIONS

Conventional PMSM models found in literature do not take iron losses into account. Therefore, in order to obtain a more realistic model, an iron loss resistance $R_c$ aimed for accounting iron losses is inserted in parallel to the magnetizing branch [12–15]. The *d-q* axes stator current components ($i_d$, $i_q$) are thus divided into the iron loss current components ($i_{cd}$, $i_{cq}$) and magnetizing current components ($i_{od}$, $i_{oq}$) as shown in Fig.1.

The steady-state modeling equations of the SPMSM in synchronous reference frame taking into account the iron losses are given by

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_s \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1 + \frac{R_s}{R_c}\right) \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega_e L_d \\ \omega_e L_d & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \psi \end{bmatrix} \tag{2}$$

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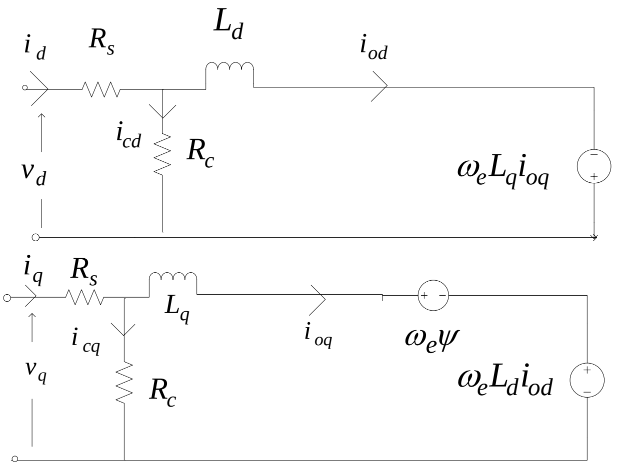



Fig.1. *d-q* axes equivalent circuits for SPMSM model taking iron losses into account under steady-state.

$$i_{cd} = -\frac{\omega_e i_{oq} L_q}{R_c} \quad ; \quad i_{cq} = \frac{\omega_e (\psi + i_{od} L_d)}{R_c} \tag{3}$$

$$i_{od} = i_d - i_{cd} \quad ; \quad i_{oq} = i_q - i_{cq} \tag{4}$$

$$J \frac{d\omega_m}{dt} = T_e - T_m - F\omega_m \tag{5}$$

The electromagnetic torque is given by

$$T_e = 1.5\, P\, [\psi\, i_{oq} + (L_d - L_q) i_{oq}\, i_{od}] \tag{6}$$

For a surface mounted PMSM: $L_d \approx L_q$, so the torque equation becomes

$$T_e = 1.5 P\, \psi i_{oq} \tag{7}$$

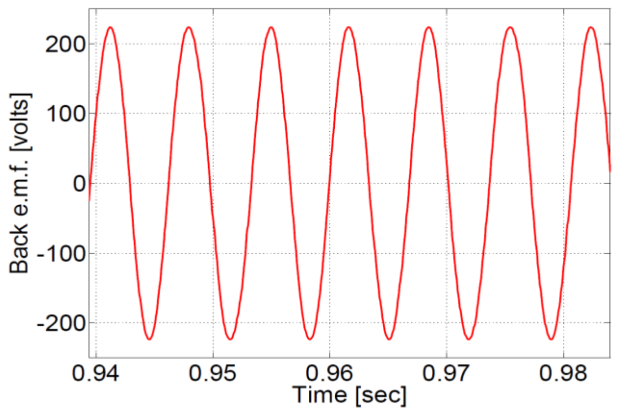



Fig.2. Sinusoidal back e.m.f. waveform of SPMSM.

The back e.m.f. waveform of a SPMSM is induced by the flux coupled with the stator winding and depends on the distribution of the stator winding. The SPMSM block in motoring mode with a closed-loop control system is modeled in MATLAB / Simulink platform which assumes that the stator winding is distributed in a manner that the flux established by the permanent magnets in the stator is sinusoidal and hence, induction of the sinusoidal back e.m.f. as can be seen in Fig.2.

## III. Field-Oriented Controlled SPMSM Drive

The proposed schematic is shown in Fig.3. Practically, the actual rotor speed of the SPMSM is measured using a shaft encoder or a resolver and is then compared with the reference rotor speed. The speed error is passed through a speed PI controller to generate the reference stator *q*-axis current. Reference stator *d*-axis current is first set to zero and secondly, it is obtained through model-based loss minimization algorithm. Using inverse Park's transformation, the reference stator *d-q* axes currents are transformed into reference stator *a-b-c* currents. The errors between reference stator *a-b-c* currents and actual stator *a-b-c* currents are regulated through the hysteresis current controllers so as to generate the control signals for the voltage source inverter (VSI) feeding the SPMSM.

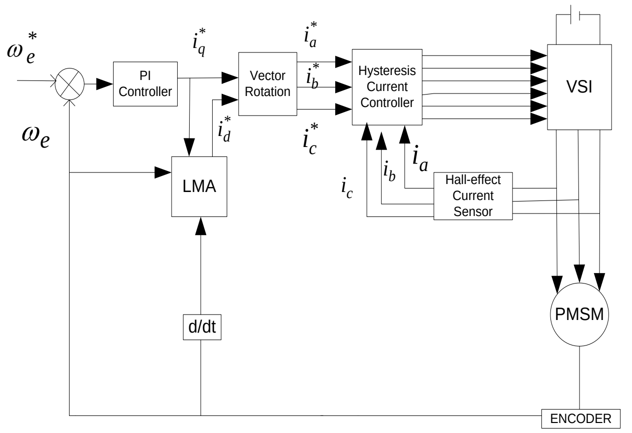



Fig.3. Block-diagram of proposed LMA based SPMSM drive

The values of $K_p$ and $K_i$ are chosen as per the symmetric optimum PI tuning criterion (thoroughly discussed in [16]) and are listed in Appendix.

## IV. Model-Based Loss Minimization Algorithm

Based on (1)–(4), the controllable copper losses can be expressed as

$$W_{cu} = \frac{3}{2} R_s \left(i_d^2 + i_q^2\right) \tag{8}$$

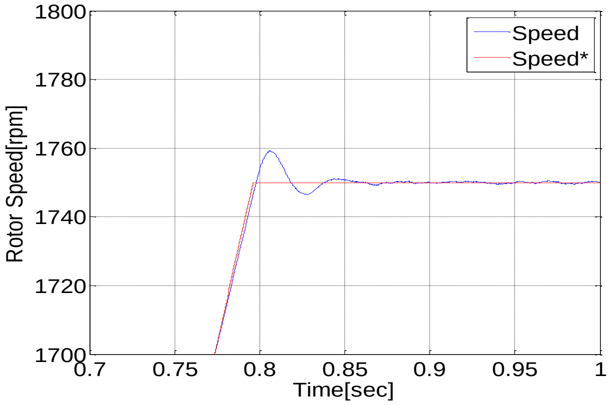
$$W_{cu} = \frac{3}{2} \left\{ \left( i_{od} - \frac{\omega_e L_q i_{oq}}{R_c} \right)^2 + \left( i_{oq} + \frac{\omega_e (\psi + i_{od} L_d)}{R_c} \right)^2 \right\} \tag{9}$$

$$W_{fe} = \frac{3}{2} R_c \left(i_{cd}^2 + i_{cq}^2\right) \tag{10}$$

$$W_{fe} = \frac{3}{2} \left\{ \frac{(\omega_e L_q i_{oq})^2}{R_c} + \frac{(\omega_e \psi + \omega_e i_{od} L_d)^2}{R_c} \right\} \tag{11}$$

The total electrical losses are

$$W(i_{od}, i_{oq}, \omega_e) = W_{cu}(i_{od}, i_{oq}, \omega_e) + W_{fe}(i_{od}, i_{oq}, \omega_e) \tag{12}$$

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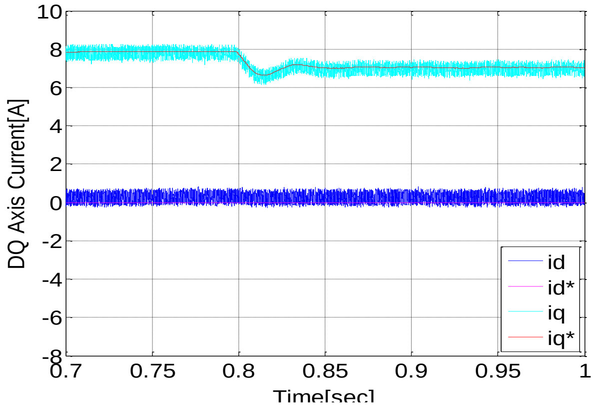


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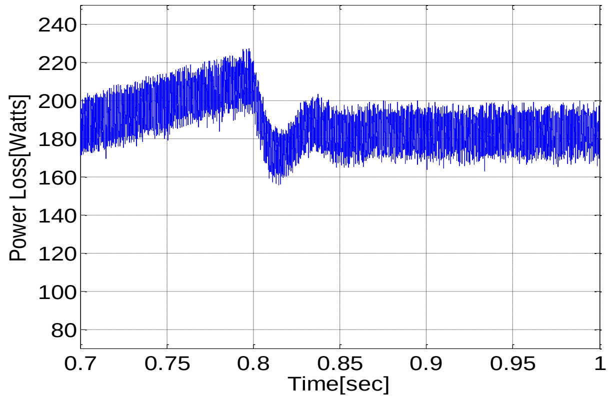


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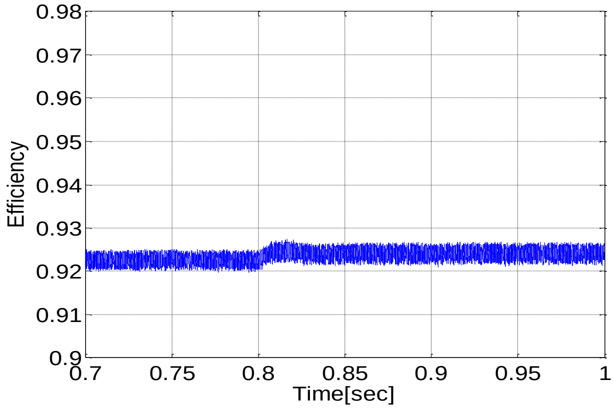
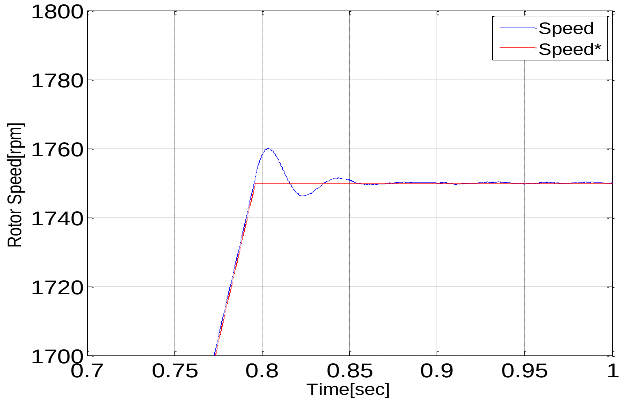



(d)

Fig.4. Different responses when rotor accelerates from 0 to 1750 rpm at constant load torque of 12 N-m with conventional $i_d = 0$ approach—(a) rotor speed (b) stator *d-q* axes currents (c) Power loss (d) efficiency.

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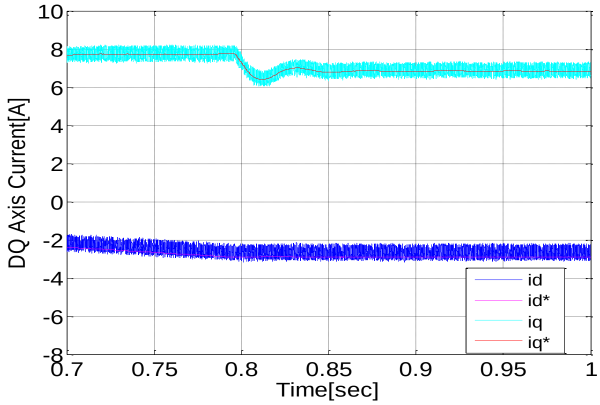


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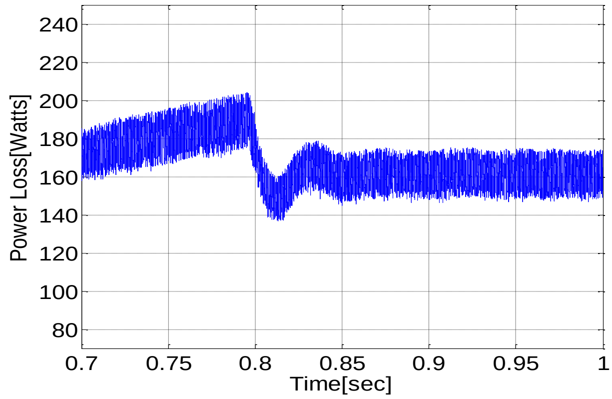


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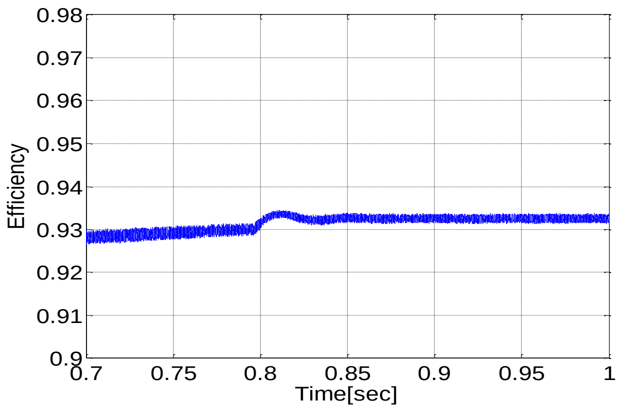


(d)

Fig.5. Different responses when rotor accelerates from 0 to 1750 rpm at constant load torque of 12 N-m with proposed model-based LMA—(a) rotor speed (b) stator *d-q* axes currents (c) Power loss (d) efficiency.

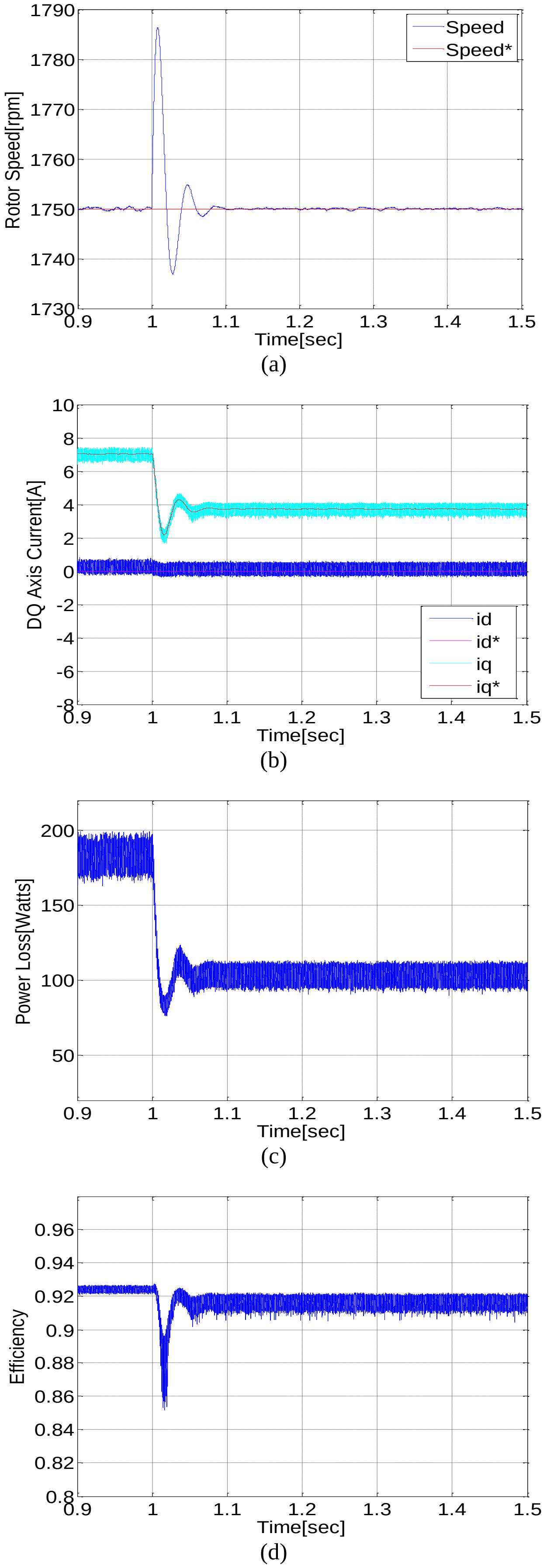


Fig.6. Different responses when load torque is reduced from 12 to 6 N-m at constant rotor speed of 1750 rpm with conventional $i_d = 0$ approach—(a) rotor speed (b) stator *d*-*q* axes currents (c) Power loss (d) efficiency.

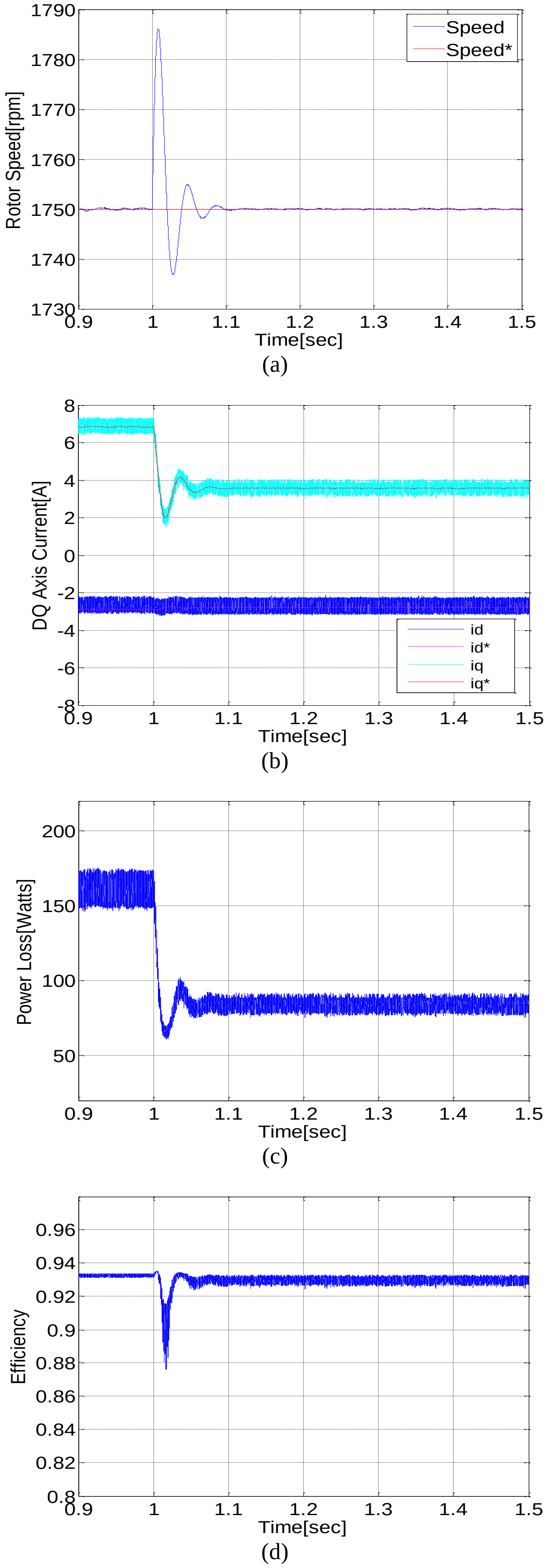


Fig.7. Different responses when load torque is reduced from 12 to 6 N-m at constant rotor speed of 1750 rpm with proposed model-based LMA—(a) rotor speed (b) stator *d*-*q* axes currents (c) Power loss (d) efficiency.

By differentiating (12) with respect to $i_{od}$ and equating it to zero, we get the optimum $d$-axis current for which losses are minimum *i.e.* $\frac{\partial W}{\partial i_{od}} = 0$ (assuming $T_e$ and $\omega_e$ constant).

$$i_{od}^{*} = -\frac{\psi L_d \omega_e^2 (R_s + R_c)}{R_s R_c^2 + \omega_e^2 L_d^2 (R_s + R_c)} \tag{13}$$

The output power $P_{out}$ and efficiency of the motor $\eta$ is expressed as follows:

$$P_{out} = \omega_e T_e \tag{14}$$

$$\eta = \frac{P_{out}}{P_{out} + W} \tag{15}$$

## V. Performance Comparison

The drive is simulated using MATLAB / Simulink platform. The drive performance for efficiency enhancement is tested for various transient conditions. However, keeping in view the page constraint, only two transient cases *viz*. (a) start-up at rated load and (b) reduction in load torque are included in this paper so as to provide a glimpse of the effectiveness of the proposed approach for efficiency improvement in the SPMSM drive.

At first, the motor is at standstill. A speed command of rated value (1750 rpm) at rated load (12 N-m) is given. The speed of the rotor sets in 0.858 seconds with conventional control approach ($i_d$ = 0) and efficiency is recorded as 92.40%, while 0.854 seconds with model-based LMA and efficiency is recorded as 93.25%. From the curves of Figs. 4–5, it is seen that total loss is minimized and the efficiency is improved.

**Table 1: Summary of different transient cases presented**

| Performance parameters | Conventional $i_d$=0 approach | Model-based LMA |
|---|---|---|
| ***Case 1*- Speed: 0 rpm to 1750 rpm at Load Torque: 12 N-m** | | |
| **Maximum overshoot (%)** | 0.510 | 0.570 |
| **Drive settling time (s)** | 0.858 | 0.854 |
| **Efficiency (%)** | 92.40 | 93.25 |
| ***Case 2*- Load Torque: 12 N-m to 6 N-m at Speed: 1750 rpm** | | |
| **Maximum overshoot (%)** | 2.070 | 2.060 |
| **Drive settling time (s)** | 0.098 | 0.096 |
| **Efficiency (%)** | 91.60 | 92.95 |

Further, the load torque on the motor running at 1750 rpm is decreased from 12 N-m to 6 N-m at time $t$ = 1 sec. As a result, the rotor speed tends to increase however, it again settles to 1750 rpm in 0.098 seconds with conventional control approach and efficiency is recorded 91.60% while 0.096 sec. with model-based LMA and efficiency is noted as 92.95%. From the curves of Fig.6 and Fig.7 it is seen that losses are minimized and efficiency is improved for this case also.

From Table–1, it can be seen that the drive settling time and maximum overshoot is nearly the same for both control strategies. From this a conclusion can be made that the dynamic performance of the drive is not affected and still the efficiency is improved.

## VI. Conclusions

A model-based LMA scheme for SPMSM drive was presented. The $d$-axis armature current was utilized and optimally controlled for loss minimization and hence maximizing the efficiency. To compare the performance of the drive, field-oriented control strategy, firstly with conventional zero $d$-axis current control and secondly with model-based loss minimization algorithm was adopted. Results of simulation show that the dynamic performance of the drive is not affected and efficiency of the drive is improved with model-based loss minimization algorithm.

## Appendix

Parameters of the SPMSM used in simulation model are as follows: Power $P_o$ = 2.2 kW; Number of pole pairs $P$ = 5; $J$ = 0.007 Kg-m$^2$; $R_s$ = 1.72 Ω; $R_c$ = 700 Ω; $\psi$ = 0.244 Wb; $L_d$ = 20.5 mH; $L_q$ = 20.5 mH; PI Controller parameters: $K_p$ = 0.7876; $K_i$ = 271.5862

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## BIOGRAPHIES

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