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Efficiency Improvement of IPM Synchronous Motor based on Model Predictive Direct Torque Control

Mohammad Akbari-Farmanbar*, Seyed Jafar Salehi and Jafar Siahbalaee and Seyed Mostafa Ghadami

Department of engineering, Aliabad Katoul branch, Islamic Azad university, Aliabad Katoul, Iran.

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Abstract

This paper presents a loss minimization algorithm (LMA) with model predictive control (MPC) for efficiency improvement of interior permanent magnet synchronous motor (IPMSM). The nature of the LMA strategy without MPC necessitates that the stator flux linkage amplitude is employed as the loss minimization control variable. Thus, the optimal stator flux linkage is determined in a way that the total electrical losses is minimized. In this paper in addition to improvement of the efficiency of IPMSM drive, electrical losses are command signal instead stator flux magnitude and the volume of calculations are very low. In the LMA strategy with MPC, electrical losses in step of (k+1) is reference signal instead stator flux magnitude. Hence in the proposed method, do not need to look up table, hysteresis controller and flux vector sector S(k) and control process is accomplished based to minimize of cost function. Since the efficiency is low in no load and low speed condition, a performance comparison at speed of 20rad/s is performed between the with and without MPC methods, and we are shown that the proposed method is improved the efficiency about 1.5% at low speeds. The performance of the proposed LMA based on with and without MPC of IPMSM drive is tested in experimental setup using TMS320F2812 as digital controller at different operating conditions.

Keywords: Electrical Losses, Loss minimization algorithm, Optimal flux, Direct torque control, Model predictive control, Interior permanent magnet synchronous motor.

1. Introduction

Nowadays, the permanent magnet synchronous motor (PMSM) has been widely used in a variety of applications like as railway vehicle, hybrid electric vehicle, washing machines, industrial robots, aerospace and shipping industries because it has very advantages than induction motor such as high efficiency, low inertia, higher torque to volume ratio and higher power density. On the other hand, PMSMs are applicable where fast dynamic response is required. Therefore, strategy of control for PMSM is very important duo to increase of them applications [1-3].

From all of the control strategy, direct torque control (DTC) is better than field oriented control (FOC) because it does not need any coordinate transformation, pulse width modulation (PWM) and current regulators. The DTC utilizes hysteresis band comparators for both flux and torque controls. The PWM modulator stage processing time takes almost several times longer than the DTC for responding to the actual change [4], [5]. The DTC uses flux and torque as primary control variables, which are directly obtained from the motor itself. Thus, the DTC is simpler and much faster to respond in comparing to the conventional FOC. In industrial applications, rotor speed and load torque are not always at rating values. Therefore, efficiency of PMSM motors for all conditions is not maximum [6].

In the DTC scheme, the motor actual torque and the air gap flux linkage values are compared with their corresponding reference values. The torque and flux hysteresis comparators take the corresponding error signals and generate the logic signals of the voltage vector lookup table. Therefore, for proper speed control of DTC based motor drive system an accurate reference flux estimator is mandatory. The torque reference value is obtained based on motor speed error between actual and reference values through a speed controller. Traditionally, researchers choose a constant value of air-gap flux reference based on trial and error method which may not be acceptable for high performance drives as the air-gap flux changes with various operating conditions and system disturbances [7-10]. The high performance motor drives require a fast and accurate speed response corresponding with various load torque and rotor speed. However, if the reference air-gap flux is maintained constant it is not possible to decrease the motor losses and the efficiency of the drive system cannot be optimized. Therefore, stator reference flux must be optimized in LMA due to (1) As more than 50% of the electrical energy produced in the world is consumed by electric motors, the motor control technique should be properly developed to optimize the efficiency of the motor drives for lower energy consumption and (2) Rotor speed and load torque are not always at rating values [11], [12].

Model predictive control (MPC) is a discrete–time algorithm in which the input sequence is chosen on the basis of the prediction of the future behavior of the system state that there are voltages and currents as input variables and torque and flux as output variables for IPMSM closed loop

*E-mail address: akbarifarmanbar@aliabadiau.ac.ir
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drive [13], [14]. In this paper, MPC is used for efficiency improvement by predicting of the stator voltages and currents. MPC appears to be an efficient strategy to control many applications in industry. It can efficiently control a great variety of processes, including systems with long delay times, non- minimum phase systems, unstable systems, multivariable systems, constrained systems as well as complex and hybrid systems [15]. More precisely, the controller chooses the input signal so that minimize a given cost function of the state, generally a quadratic norm. It calculates the optimal primary voltages while respecting the given constraints over the flux and current to keep them within permissible values. This optimal solution is calculated based on the current states of the system, the actual torque and electrical losses and the predicted future (k+1) voltage as output of the model and motor efficiency is optimized by minimizing the electrical losses through LMA based on MPC [16]. This paper is compared efficiency of typical IPMSM motor in three control strategies: (1) direct torque control without LMA, (2) direct torque control with LMA and (3) direct torque control with LMA based MPC. In all conditions core resistance is considered in model of IPMSM motor as core loss that it is depend on frequency and voltage of motor, but in this paper core resistance is considered in current equations as part of total loss. In [17-19] core loss was considered as function of voltage and frequency and closed loop drive is not used for minimize of losses. In [20-25] minimize of losses was accomplished and optimum flux is considered as command signal that they have complicated calculations. In this paper in addition to improvement of the efficiency of IPMSM drive, electrical losses are command signal instead stator flux magnitude and the volume of calculations are very low.

This paper is organized as follows: in Section II mathematical equations of IPMSM model is provided. In Section III the flux optimized in LMA without MPC method for the drive is presented. In Section IV the LMA with MPC method is designed. Performance Evaluation of both LMA strategies is presented in Section V with its experimental results.

2. PMSM mathematical equations

The IPMSM has interior magnet in rotor and this caused the d and q axis inductances are not equal to each other. In order to analysis of minimize the losses of IPMSM, core resistance is considered in circuit equivalent. Also due to apply MPC in closed loop, all equations should be converted to discrete time for one step to future (k+1). Fig.1 and Fig.2 show the d and q equivalent circuit of IPMSM in steady state. Also Fig.3 shows the vector diagram of the IPMSM motor.

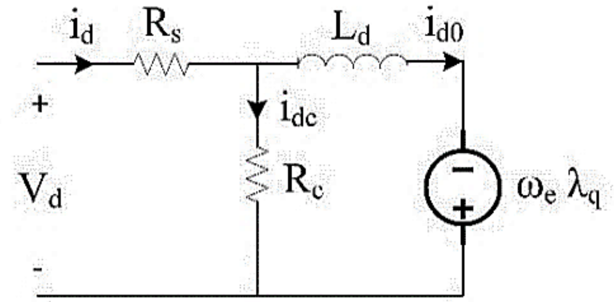

Fig. 1. Steady state equivalent circuit for d-axis of the IPMSM motor.

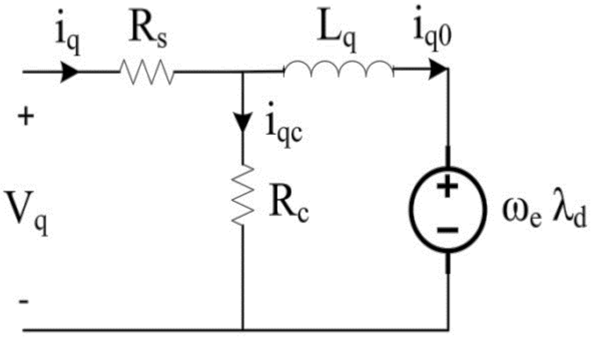

Fig. 2. Steady state equivalent circuit for q-axis of the IPMSM motor.

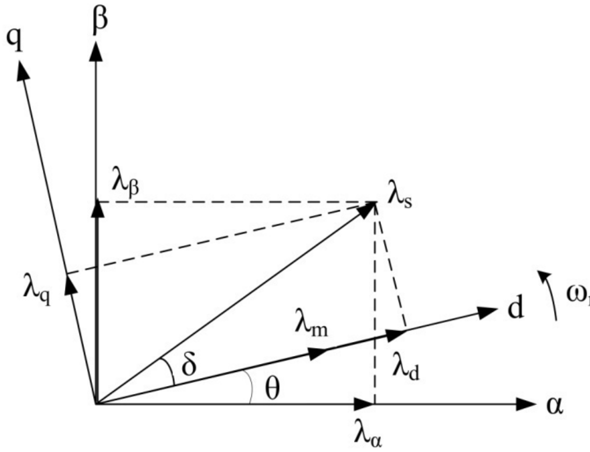

Fig. 3. The IPMSM motor vector diagram.

Relation between voltage and currents for d-axis can be expressed as [26]:

$$\begin{cases} V_d = R_s i_d + L_d \dfrac{di_{d0}}{dt} - \omega_e \lambda_q \\ i_{d0} = \dfrac{i_d (R_c + R_s) - V_d}{R_c} \\ V_d = R_s i_d + R_c i_{dc} \end{cases} \quad (1)$$

where i_d and i_q are d-q axis stator currents, i_{dc} and i_qc are d-q axis core loss armature currents, Rs and Rc are stator resistance and core resistance respectively. λq is q-axis component of stator flux that $\lambda_q = L_q i_{q0}$ and ωe is rotor electrical speed in rad/s. L_d and L_q are d-axis and q-axis components of stator inductances respectively. Also q-axis equation can be defined as:

$$\begin{cases} V_q = R_s i_q + L_q \dfrac{di_{q0}}{dt} + \omega_e \lambda_d \\ i_{q0} = \dfrac{i_q (R_c + R_s) - V_q}{R_c} \\ V_q = R_s i_q + R_c i_{qc} \end{cases} \quad (2)$$

where λ_d is d-axis component of stator flux that $\lambda_d = L_d i_{d0} + \lambda_m$ and λ_m is rotor magnetic flux. The torque equation would be as follows:

$$T_e = \frac{3p}{2} (\lambda_m i_{q0} + (L_d - L_q) i_{d0} i_{q0}) \quad (3)$$

where p is pole pair. It should be noted that i_{d0} and i_{q0} product torque because these currents pass form Back-EMF in equivalent circuit. After mathematical operation, currents equations can be obtained as:

$$\frac{di_{d0}}{dt}=a(V_d-bi_{d0}+c\omega_e i_{q0}) \quad (4)$$

$$\frac{di_{q0}}{dt}=d(V_q-bi_{q0}-e\omega_e i_{d0}-\omega_e f) \quad (5)$$

where, $a=\frac{R_c}{L_d(R_s+R_c)}$, $b=R_s$, $c=\frac{L_q(R_s+R_c)}{R_c}$, $d=\frac{R_c}{L_q(R_s+R_c)}$, $e=\frac{L_d(R_s+R_c)}{R_c}$, $f=\frac{\lambda_m(R_s+R_c)}{R_c}$.

Equations (4) and (5) should be converted to discrete time for step of (k+1) in MPC control method. Thus are can be written:

$$i_{d0}(k+1)=i_{d0}(k)+aT_s[V_d(k)-bi_{d0}(k)+c\omega_e i_{q0}(k)] \quad (6)$$

$$i_{q0}(k+1)=i_{q0}(k)+dT_s[V_q(k)-bi_{q0}(k)-e\omega_e(k)i_{d0}(k)-\omega_e(k)f] \quad (7)$$

where T_s is sample period.

3. The LMA strategy without MPC

In LMA strategy without MPC, stator flux is command signal, but it is not constant and obtained using to minimize of electrical losses and depended on frequency and load torque. The steady state electrical losses can be expressed as [27]:

$$P_{loss}=\frac{3}{2}R_c\left(i_{dc}^2+i_{qc}^2\right)+\frac{3}{2}R_s\left(i_d^2+i_q^2\right) \quad (8)$$

In (8), $i_d=i_{dc}+i_{d0}$ and $i_q=i_{qc}+i_{q0}$. Also, i_{dc}, i_{qc}, i_{d0} and i_{q0} currents are depended on stator flux, and they can be given as:

$$i_{dc}=-\frac{\omega_e\lambda_q}{R_c}=-\frac{\omega_e\lambda_s\sin(\delta)}{R_c} \quad (9)$$

$$i_{qc}=\frac{\omega_e\lambda_d}{R_c}=\frac{\omega_e\lambda_s\cos(\delta)}{R_c} \quad (10)$$

$$i_{d0}=\frac{\lambda_d-\lambda_m}{L_d}=\frac{\lambda_s\cos(\delta)-\lambda_m}{L_d} \quad (11)$$

$$i_{q0}=\frac{\lambda_q}{L_q}=\frac{\lambda_s\sin(\delta)}{L_q} \quad (12)$$

where λ_s is the stator flux magnitude. Substituting (9)-(12) into (8), and along with some mathematical simplification a function for electrical losses can be derived as:

$$P_{loss}(\lambda_s)=\frac{3}{2}R_c\left[A\lambda_s^2+B\lambda_s^2\right]+\frac{3}{2}R_s[(C\lambda_s-D-E\lambda_s)^2+(F\lambda_s+G\lambda_s)^2] \quad (13)$$

Coefficients of (13) are demonstrated in table 1. Also δ is torque angle according to figure 3. Equation (13) expresses the steady state electrical losses as a function of stator flux amplitude. Therefore, for a given δ and ω_e in the magnetic flux plane, the circle $|\lambda_s|$ gives the locus of constant electrical losses. For the given operating conditions, figures 4 and 5 demonstrate the electrical losses as a function of stator flux amplitude variations. The minimum of electrical losses is obtained by differentiating the loss function with respect to λ_s:

$$\frac{dp_{loss}(\lambda_s)}{d\lambda_s}=0 \quad (14)$$

By solving (14), the optimum flux is reached:

$$\lambda_{s\text{-}opt}=\frac{D(C-E)}{A+B+C(C-E)-E(C-E)+(F+G)^2} \quad (15)$$

where $\lambda_{s\text{-}opt}$ is the optimum stator flux. It should be noted that equation (15) is applied in LMA strategy without MPC and optimum stator flux is command signal and depend on A-G coefficients of table1.

Table 1. Coefficients of equation (13).

Coefficients of Equ.13	Definition
A	$\left(\frac{\omega_e\sin(\delta)}{R_c}\right)^2$
B	$\left(\frac{\omega_e\cos(\delta)}{R_c}\right)^2$
C	$\frac{\cos(\delta)}{L_d}$
D	$\frac{\lambda_m}{L_d}$
E	$\frac{\omega_e\sin(\delta)}{R_c}$
F	$\frac{\sin(\delta)}{L_q}$
G	$\frac{\omega_e\cos(\delta)}{R_c}$

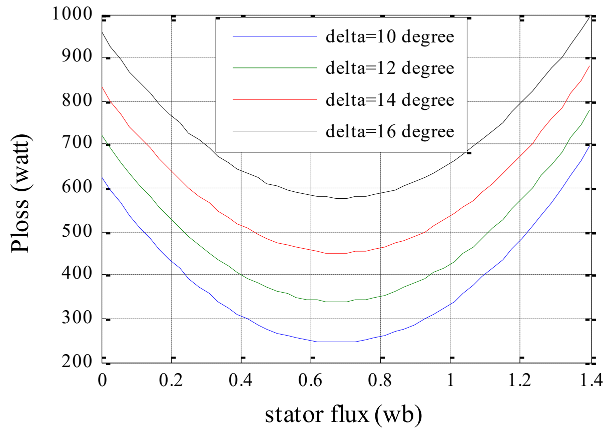

Fig. 4. The effect of stator flux variations on electrical losses at nominal speed.

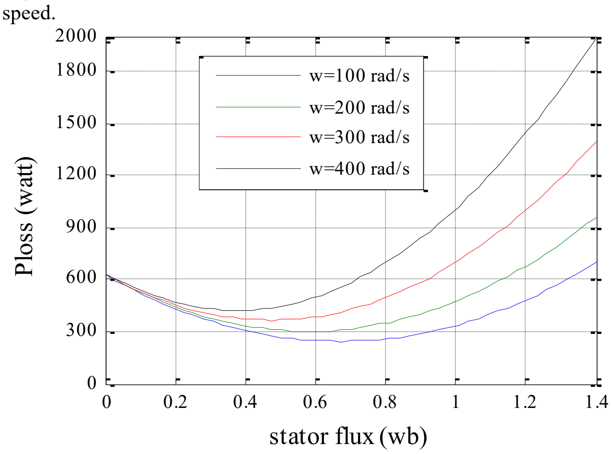

Fig. 5. The effect of stator flux variations on electrical losses at nominal torque.

In addition to equation (3), torque can be expressed as:

$$T_e=\frac{3p\lambda_s}{4L_dL_q}\left[2\lambda_m L_q\sin(\delta)+\lambda_s\left(L_d-L_q\right)\sin(2\delta)\right] \quad (16)$$

For simplicity, second term in (16) is neglected and it can be rewritten as:

$$T_e=\frac{3p\lambda_s\lambda_m}{2L_d}\sin(\delta) \quad (17)$$

Therefore

$$\delta=\sin^{-1}\left(\frac{2T_eL_d}{3p\lambda_s\lambda_m}\right) \quad (18)$$

Equations (1), (2), (3) and (18) are applied to the LMA algorithm. Block diagram of the proposed LMA strategy is shown in Fig.6.

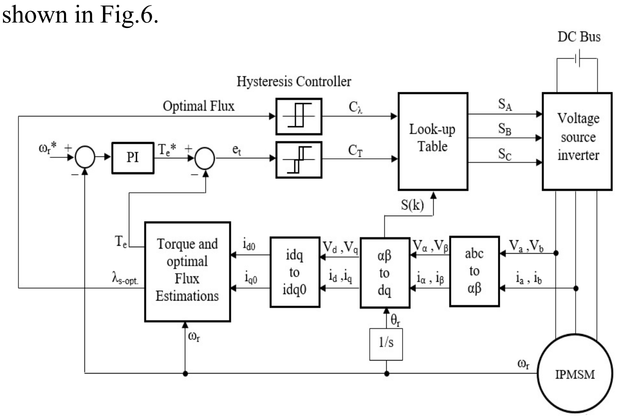

Fig. 6. The LMA strategy without MPC for the IPMSM under DTC.

4. Proposed LMA Strategy with MPC

In LMA strategy with MPC, stator flux magnitude is variable and depended on frequency and load torque, but it is not reference signal and electrical losses is reference signal in step of (k+1). In MPC, measuring the machine currents ($i_{d0}(k+1)$, $i_{q0}(k+1)$), the stator linkage flux ($\lambda_s(k+1)$) and the electromagnetic torque ($T_e(k+1)$) are accomplished for step (k+1). Therefore, torque and stator flux equations would be as follows:

$$T_e(k+1)=\frac{3p}{2}\left[\lambda_m i_{q0}(k+1)+(L_d-L_q)i_{d0}(k+1)i_{q0}(k+1)\right] \quad (19)$$

$$\lambda_s(k+1)=\sqrt{(L_d i_{d0}(k+1)+\lambda_m)^2+\left(L_q i_{q0}(k+1)\right)^2} \quad (20)$$

Steady state electrical losses at (k+1) instance can be expressed as:

$$P_{loss}(k+1)=\frac{3}{2}R_c\left(i_{dc}^2(k+1)+i_{qc}^2(k+1)\right)+\frac{3}{2}R_s\left(i_d^2(k+1)+i_q^2(k+1)\right) \quad (21)$$

In (21), first term is iron loss and second term is copper loss at (k+1) instance. According to Equ.9 and Equ.10, i_{dc} and i_{qc} are equal to:

$$i_{dc}(k+1)=-\frac{\omega_e(k+1)\lambda_q(k+1)}{R_c} \quad (22)$$

$$i_{qc}(k+1)=\frac{\omega_e(k+1)\lambda_d(k+1)}{R_c} \quad (23)$$

Therefore:

$$i_{dc}^2(k+1)+i_{qc}^2(k+1)=\frac{[\lambda_s(k+1)\omega_e(k+1)]^2}{R_c^2} \quad (24)$$

$$i_d(k+1)=i_{dc}(k+1)+i_{d0}(k+1) \quad (25)$$

$$i_q(k+1)=i_{qc}(k+1)+i_{q0}(k+1) \quad (26)$$

where $i_{d0}(k+1)$ and $i_{q0}(k+1)$ can be defined as equations (6) and (7) respectively. Also $i_{dc}(k+1)$ and $i_{qc}(k+1)$ are obtained as equations (22) and (23) where d-q axis stator fluxes can be obtained as:

$$\lambda_d(k+1)=L_d i_{d0}(k+1)+\lambda_m \quad (27)$$

$$\lambda_q(k+1)=L_d i_{q0}(k+1) \quad (28)$$

Substituting (24) into (21), gives electrical losses independent of core loss armature currents. Also with considering (25) and (26), electrical losses at (k+1) instance can be expressed as:

$$P_{loss}(k+1)=\frac{3}{2}\frac{[\lambda_s(k+1)\omega_e(k+1)]^2}{R_C}+\frac{3}{2}R_s\left((i_{dc}(k+1)+i_{d0}(k+1))^2+(i_{qc}(k+1)+i_{q0}(k+1))^2\right) \quad (29)$$

Equations (19) and (29) only depend on id_0 and i_q0 currents and rotor angular speed and they are applied to LMA strategy with MPC for improving of IPMSM motor efficiency. The block diagram of the proposed LMA strategy with MPC has been shown in Fig. 7. As shown in this figure, unlike LMA strategy without MPC this control method doesn't need hysteresis controller and switching table. In fact, the proper switching state in each time interval is selected according to flowchart that has been shown in Fig. 8.

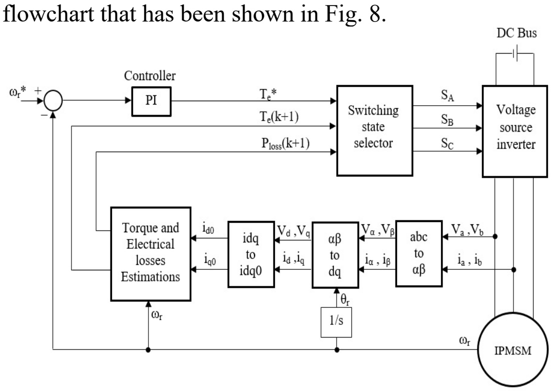

Fig. 7. The proposed LMA strategy with MPC for IPMSM under DTC.

The first step is to predict the machine states in k^{th} control period according to the prediction model and current-voltage vector applied to the machine. Then, the possible future machine states within prediction horizon N are computed while all admissible voltage vectors are considered with calculation of torque and electrical losses. Finally, the prediction results are evaluated against a cost function and the voltage vectors (v1, v2, v3, v4, v5, v6, v7, v8) with lowest cost would be applied to the machine during kth control period. In the next control interval, the same procedure is repeated with updated measurements. The cost function for conventional MPC can be expressed as:

$$QF(j)=\mu_1|T^*_e-T_e|+\mu_2|\lambda^*_s-\lambda_s| \quad (30)$$

where μ1 and μ2 are weight coefficients. It should be noted that in LMA strategy with MPC, it is not necessary to reference flux and instead electrical losses is command signal for switching state selector. Therefore, the cost function is must be corrected and it can be expressed as:

$$QF(j)=\mu_1|T^*_e-T_e|+\mu_2 P_{loss} \quad (31)$$

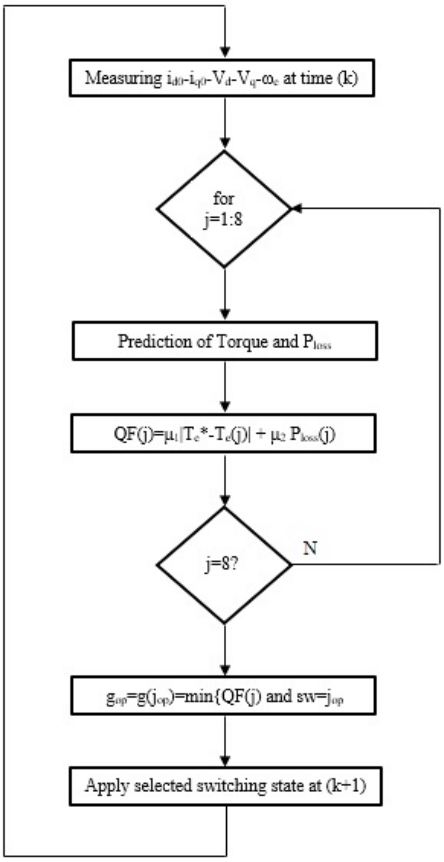

Fig 8. Flowchart of the proposed LMA strategy with MPC.

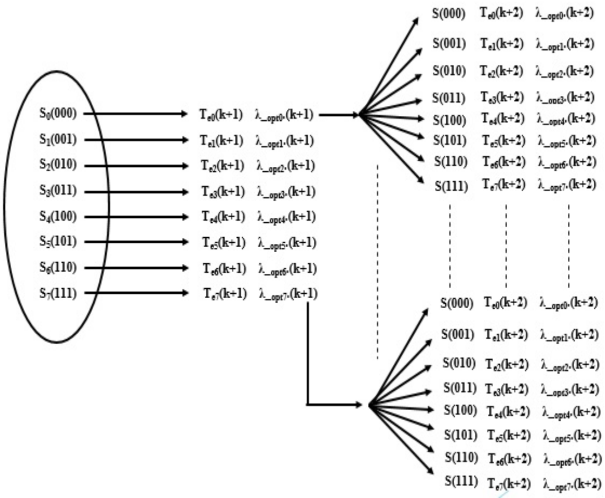

Fig 9. Switching state selection rules at k, k+1 and k+2 moments in model predictive direct torque control.

According to Fig.9, at (k+1) step, every switching vector is divided to eight vector and for (k+2) step there are 64 vectors to apply on switching state selector and it decided which vector of switching states of voltage source inverter (S1, S2, S3, S4, S5, S6, S7, S8) purposing to minimize of cost function is active.

Table2 shows comparative of three control strategies. For the IPMSM motor based on DTC. According to table2, LMA strategy with MPC, do not need to look up table, hysteresis controller and sector S(k) and control process is accomplished based on minimizing of the cost function.

Table 2. Comparative of three control strategies for IPMSM motor under DTC.

Control strategies	Hysteresis controller	Look-up table	References for switch selector	Sector S(k)
Conventional DTC	Necessary	Necessary	Stator flux and Torque	Necessary
LMA without MPC	Necessary	Necessary	Only Torque	Necessary
LMA with MPC	Not necessary	Not necessary	Only Torque	Not necessary

4. Experimental results and discussions

In order to test the performance in real-time the mentioned algorithms are experimentally implemented using the TMS320F2812 DSP for a laboratory 400w motor. The snapshot of the experimental setup is shown in figure (10). This setup is equipped with several interface boards such as current and voltage sensors, gate driver and isolation circuit. The inputs and outputs of the DSP board are the analog current-voltage (on the analog to digital channels) and PWM logic signals respectively. The parameters of the PMSM are Rs=2.2 Ω, Ls=3.8 mH and 4 pole pairs. The input voltage, rating current, rating torque and rating speed of the PMSM are 200V, 2.9A, 1.2N.m and 3000RPM, respectively. The sampling frequency in position, speed and current control loops are designed with 1.8kHz, 1.8kHz and 18kHz, respectively.

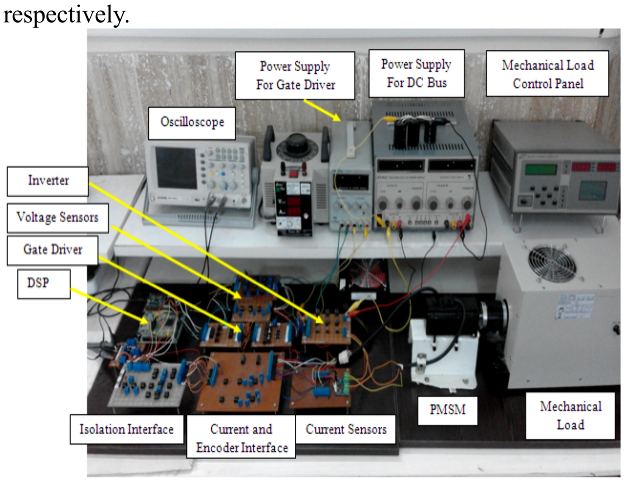

Fig 10. Experimental setup of the loss minimization algorithms based PMSM drive.

Experimental Results are compared the efficiency of typical IPMSM motor in three control strategies: (1) direct torque control without LMA, (2) direct torque control with LMA and (3) direct torque control with LMA based MPC. The performance of three control strategies is tested in experimental at different operating conditions. Experimental time and sample period are regulated at 2.5s and 25μs respectively. Figures (11), (12) and (13) are shown condition that load torque is considered on 3Nm as rated value and reference speed is variable from 20rad/s to 100rad/s at t=1s and they are result of conventional DTC, LMA without MPC and LMA with MPC respectively. Comparison between figures (11), (12) and (13) is proven that in low speed (20rad/s), efficiency in DTC and LMA without MPC, very same together and it is 83%. But efficiency in LMA strategy with MPC in low speed more than another control methods and it is 84.5%. In rated speed (100rad/s) and LMA without MPC, efficiency has increased one percent compared to conventional DTC and in LMA strategy with MPC, it has increased 2%.

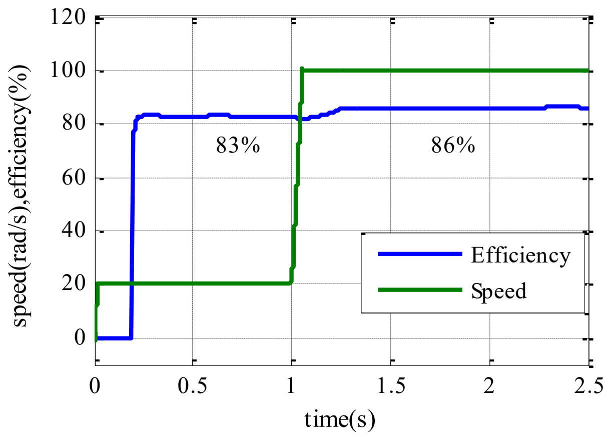

Fig 11. Efficiency and speed signals in conventional DTC under rated torque and variable speed.

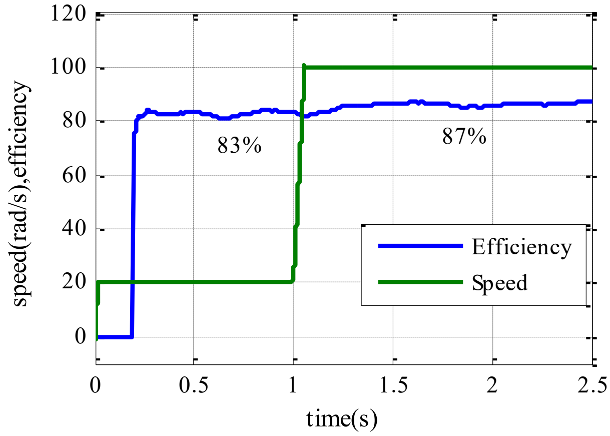

Fig 12. Efficiency and speed signals in LMA without MPC under rated torque and variable speed.

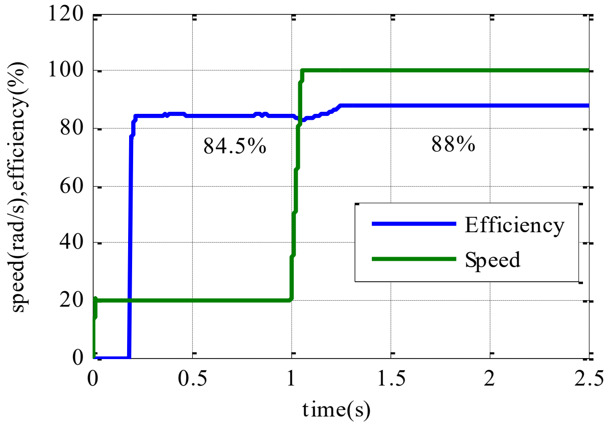

Fig 13. Efficiency and speed signals in LMA with MPC under rated torque and variable speed.

Figures (14), (15) and (16) show condition that speed is considered on 100rad/s as rated value and reference torque is variable from no load (0-0.7s) to 1.5Nm (0.7-1.4s) and 3Nm (1.4-2.5s) and they are results of conventional DTC, LMA without MPC and LMA with MPC respectively. One of important results of comparative between (14), (15) and (16) is that LMA strategy both in the without MPC and with MPC causes efficiency has been kept in maximum value at no load intervals (0-0.7s) according to figures (15) and (16) and it is unlike conventional DTC according to figure (13). Also seems that in half of the rated torque (1.5Nm applied at 0.7-1.4s), the most of efficiency belongs to the LMA strategy with MPC that is more than 3.6 percent compared to LMA strategy without MPC. In rated load (3Nm applied at 1.4-2.5s), the results are similar to rated speed and rated load conditions according to figures (11), (12) and (13).

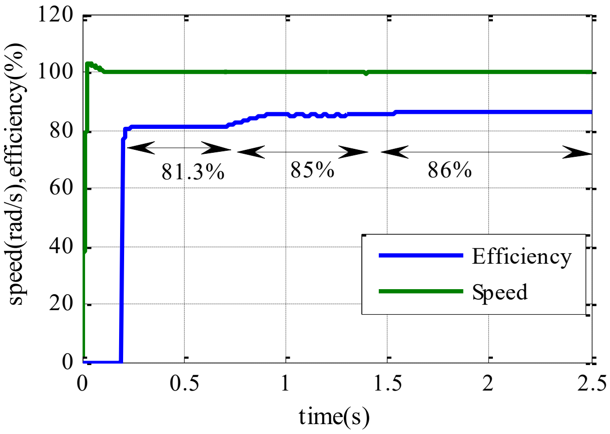

Fig. 14. Efficiency and speed signals in conventional DTC under rated speed and variable torque.

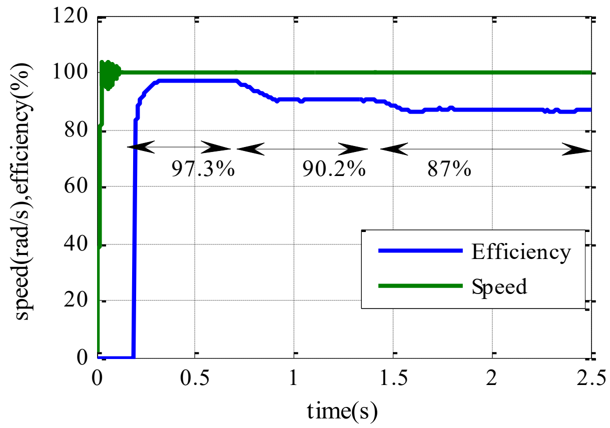

Fig. 15. Efficiency and speed signals in LMA without MPC under rated speed and variable torque

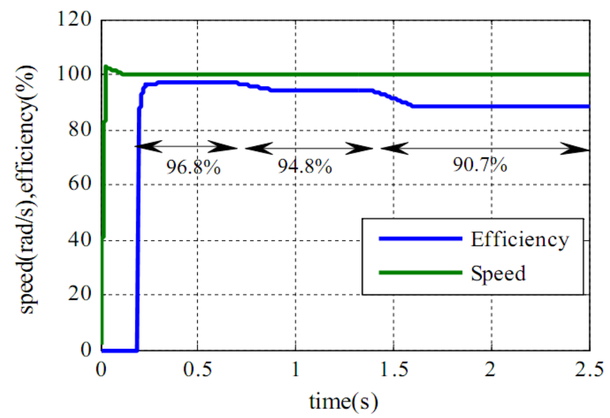

Fig. 16. Efficiency and speed signals in LMA with MPC under rated speed and variable torque.

Figures (17), (18) and (19) show the relationship between efficiency in term of torque changes under ωr=100 rad/s that load torque is selected as ramp function with slope 1. Comparing this figures, it seems that, in conventional DTC, the IPMSM motor at torque of 0.3 N.m has 82% efficiency. But, in the loss minimization algorithms (with and without MPC), the efficiency is approximately 97%. It means that, at low torque, the loss minimization algorithms (with and without MPC) can be increased the efficiency. It also seems that, in conventional DTC, the IPMSM motor at nominal torque (3 N.m) has approximately 86% efficiency that this value for LMA without MPC and with MPC is 87% and 90.5% respectively. Figures (17) and (18) show that when the torque approaches to nominal value, the efficiency is approximately equal to a constant. If the efficiency to be constant, any increase at load torque will increase input power. Hence, in conventional DTC and the LMA method without MPC, any overload in rotor shaft increases electrical energy consumption. But in LMA with MPC that it is proposed method, in various load torque, slope of efficiency is approximately monotonic and it is not constant at high torque. It means that, compared to LMA without MPC algorithm, the IPMSM in LMA with MPC algorithm consumes less electrical energy when an overload occurs in rotor shaft.

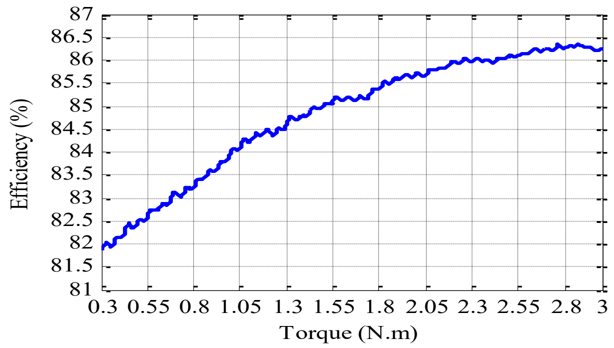

Fig. 17. Efficiency-Torque curve in conventional DTC.

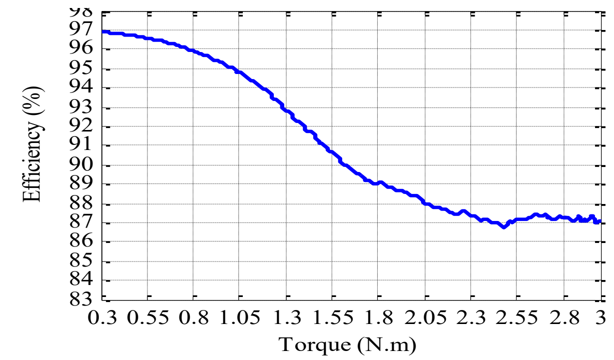

Fig. 18. Efficiency-Torque curve in LMA strategy without MPC.

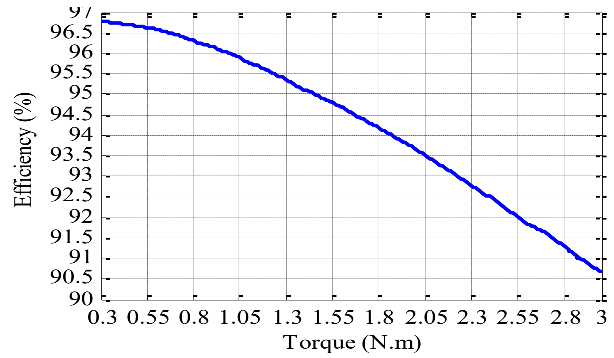

Fig. 19. Efficiency-Torque curve in LMA strategy with MPC.

Table 3 is presented a comparison between the motor efficiency at different conditions of torque and speed. According to this table, at no load condition, the LMA without MPC method has the highest efficiency of 97.3%. But by applying the torque load of 1.5N.m and 3N.m, the proposed method has maximum efficiency of 94.8% and 90.7% respectively.

Also, at rated torque (3N.m) the proposed scheme provides the highest efficiency at low speeds and at high speeds (84.5% and 88% for 20rad/s and 100rad/s respectively).

Table 3. Comparison of efficiency between the three studied methods under different conditions of speed and torque.

	Efficiency (%)				
	Rated speed and variable torque			**Rated torque and variable speed**	
	0 N.m	1.5 N.m	3 N.m	20 rad/s	100 rad/s
Conventional DTC	**81.3%**	85%	86%	83%	86%
LMA without MPC	**97.3%**	90.2%	87%	83%	87%
LMA with MPC	**96.8%**	94.8%	90.7%	84.5%	88%

Appendix: IPMSM Parameters

Rated voltage (V)	200 V – 3 phase
Rated current (A)	3.5
Rated torque (Nm)	3
Rated speed (rad/s)	100
p, No of pole pairs	2
Rs, Rc (Ω)	1.93, 330
Ld, Lq (mH)	42.44, 79.57
λm (wb)	0.314
j, Rotor inertia constant (kg.m3)	0.003
B, Friction coefficient (Nm/rad/s)	0.0008

5. Conclusion

Two loss minimization algorithms (LMA) with and without model predictive control (MPC) of the IPMSM drive based direct torque control (DTC) for improvement of efficiency has been presented in this paper. In LMA without MPC, an optimal stator flux was obtained for minimize of electrical losses as flux reference and in LMA with MPC, electrical losses at (k+1) instant, was applied to switching state selector instead to consider of stator flux. LMA with MPC do not need to look-up table and hysteresis controller and switching vectors of inverter are selected based minimize of cost function. During the full load condition and the nominal speed, the proposed method has been able to improve efficiency about 3% in comparison to LMA without MPC. Although at no load condition, it has not been improved the efficiency, but at low speeds, which efficiency is low, the proposed method has improved the efficiency about 1.5%. Also in no load condition, LMA strategy without and with MPC causes efficiency has been kept in maximum value unlike conventional DTC. Thus, the proposed LMA with MPC could be used to optimize the efficiency of the drive.

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