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REDUCTION OF RIPPLE FOR DIRECT TORQUE CONTROLLED THREE PHASE INDUCTION MOTOR BASED ON A PREDICTIVE CONTROL TECHNIQUE

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Abstract: Direct torque control is one of the among control schemes for alternating current drives. It has simple structure, fast control, robust and has good performance. The major disadvantage of direct torque control is the inherent torque and stator flux ripples. The present paper deals with the design and simulation of direct torque controlled high power three phase induction motor based on a developed predictive control that predict current and flux several times to obtain the advanced effective voltage vectors with a three-level space vector pulse width modulation inverter. The simulation results show that the ripples in the developed torque and stator flux are reduced by 12% and6.4%, respectively.

Keywords*: Direct torque control (DTC), Predictive control (PC), Model predictive torque control (MPTC), Ripple reduction*

تقليل تموج لعزم الدوران المباشر المسيطر على محرك ثلاثي الطور والتي تعتمد على تقنية التحكم التنبؤي المسبق

الخلاصة: التحكم في عزم الدوران المباشر هو واحد من بين اليات التحكم لمحركات التيار المتناوبة .انه يمتلك بنية بسيطة، سيطرة سريعة، فعال وذو أداء الجيد .العيب الرئيسي للسيطرة على عزم الدوران المباشر هو التموج في عزم الدوران وفي فيض الجزء الثابت .وتتناول هذه الورقة تصميم ومحاكاة عزم الدوران المباشر الذي يسيطر على محرك حثي ثلاثي الطور على أساس السيطرة التنبوية المتقدمة التي تتنبأ التيار والفيض عدة مرات للحصول على ناقلات الجهد الفعال المتقدمة مع العاكس ذو ثلاثة مستويات .وتظهر نتائج المحاكاة أن التموجات في عزم الدوران والفيض قد انخفضت بنسبة 12٪ و 6.4٪ على التوالي.

1. Introduction

In the last decades, different methods have been proposed to deal with the problems of classical direct torque control(DTC), like using space vector pulse width modulation (SVPWM) [1], multilevel inverter applications [2] and model predictive control (MPC) [3]. Recently, MPC introduced an effective method to deal with classical DTC and takes allot of attention in both industrial and academic communities [4-7].In general, the MPC applications in electrical drives are classified in two types, model predictive current control (MPCC) [8,9] and model predictive torque control (MPTC) [4,7].

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The MPTC is operated in stationary frame as compared with MPCC which operated in rotary reference frame; MPTC has simple structure and achieved less torque ripples than MPCC, because the control of torque was direct in MPTC. Moreover, the MP application of direct flux vector control (DFVC) as proposed in [10], which is accumulate the features of direct torque and flux control and fast current vector control (CVC). And a direct predictive control scheme without current sensor for induction motor drives is present [11]. A universal multiple vector based on MPC (UMV-MPC) is proposed in[12], which attains the same performance with the state of the double vector based on MPC, but implements in a much more effective and global way.

In this paper, the Simulink model and simulation results are carried out using MATLAB/Simulink software for a developed MPTC to a high power 3-phase induction motor. The principles of classical DTC and with a developed MPTC based on PI controller are given. Moreover, the proposed MPTC method is explained and simulated to overcome the ripples problem in developed torque and stator flux. The results show an improvement in behavior of direct torque controlled three-phase induction motor based on predictive control theory.

2. Principles of Classical Direct Torque Control Strategy

The developed torque T_e, in a three-phase induction motor can be expressed by the following equation [1]

$$T_e = \frac{3p}{2}\frac{L_m}{\sigma L_s L_r}|\lambda_s||\lambda_r|\sin\theta_T \qquad (1)$$

where; L_m is mutual leakage inductance; L_s is stator self-inductance; L_r is rotor self-inductance, σ is leakage factor ($1-\frac{L_m^2}{L_s L_r}$); θ_T is torque angle; λ_s and λ_r are stator and rotor flux linkage respectively.

According to Eq.(1), the developed torque T_e can be directly controlled by stator flux λ_s and the angle θ_T between λ_s and λ_r.Therefore, the main variables to be controlled in the classical DTC scheme is the stator flux vector λ_s and its angle because λ_r is constant with small change in Δ_t due to the inertia of the rotor. The stator voltage equation can be expressed as follow [13,14]:

$$\frac{d}{dt}\vec{\lambda}_s=\vec{v}_s - R_s\vec{i}_s \qquad (2)$$

where; $\vec{v}_s$ is the stator voltage, $\vec{i}_s$ is the stator current and R_s is the stator resistance. It is worth to mention that, the derivative of λ_s reacts directly to changes in $\vec{V}_s$ and $\vec{V}_s$ is bigger than $R_s\,\vec{i}_s$

$$\frac{d}{dt}\vec{\lambda}_s=\vec{V}_s \qquad (3)$$

$$\text{Or,}\,\Delta\vec{\lambda}_s=\vec{V}_s\Delta_t \qquad (4)$$

In general, the classical DTC principle is how to select the appropriate vector of voltage source inverter vectors by using a switching logic table depending on the hysteresis of both torque and flux as well as the sector number. Fig.1 shows the block diagram of classical DTC. Two control loops, the outer is to introduce the reference torque by comparing the reference and actual speed, while the inner loop is used to run the two hysteresis for torque and flux control. The switching logic is used to generate the suitable voltage vectors that drive the VSI which supplies the motor windings.

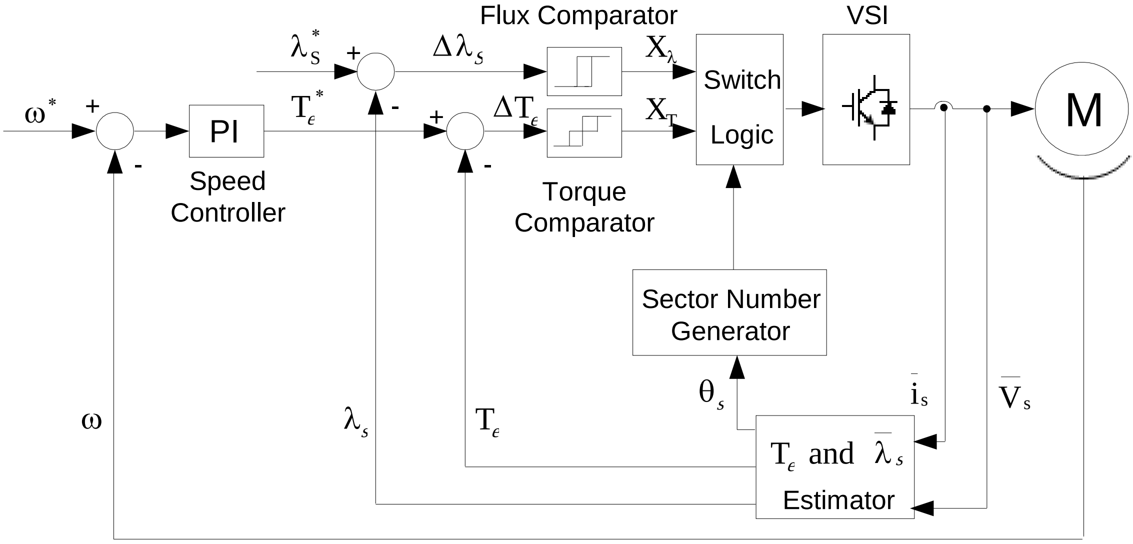


Fig. 1 classical DTC block diagram

2. MPTC Based on PI Controllers

The major idea of predictive control is to predict the future performance of the variables based on the system model. In MPTC, the hysteresis comparators of torque and flux have been replaced with a two classical PI controllers to control the error of the torque and stator flux after comparing with their references values as illustrate in Fig.2. The stator voltage equations in stationary reference frame (ω_1=0) are [5,16]

$$v_{ds}=R_s i_{ds} + L_s \frac{d}{dt} i_{ds} \qquad (5)$$

$$v_{qs}=R_s i_{qs} + L_s \frac{d}{dt} i_{qs} \qquad (6)$$

where;$v_{ds}$and$v_{qs}$are dq-axis stator voltages; $i_{ds}$and $i_{qs}$are dq-axis stator currents.

Rearranged Eqs. (5) and (6) as respect to the predictive stator current, the prediction of the stator current at a sampling time can be expressed as [5]

$$i_{ds}^{k+1}= i_{ds}^{k}+ \frac{1}{L_s}\left[-R_s i_{ds}^{k}+ v_{ds}^{k}\right]. T_s \qquad (7)$$

$$i_{qs}^{k+1}= i_{qs}^{k}+ \frac{1}{L_s}\left[-R_s i_{qs}^{k}+ v_{qs}^{k}\right]. T_s \qquad (8)$$

where; T_s is the sampling time. Meanwhile, the predictive stator flux can be given as follows

$$\lambda_{ds}^{k+1} = \lambda_{ds}^{k} + \left[v_{ds}^{k} + R_s i_{ds}^{k+1}\right].\,T_s \tag{9}$$

$$\lambda_{qs}^{k+1} = \lambda_{qs}^{k} + \left[v_{qs}^{k} + R_s i_{qs}^{k+1}\right].\,T_s \tag{10}$$

$$|\lambda_{s}^{k+1}| = \sqrt{\left(\lambda_{ds}^{k+1}\right)^2 + \left(\lambda_{qs}^{k+1}\right)^2},\ \theta_s^{k+1} = \tan^{-1}\frac{\lambda_{qs}^{k+1}}{\lambda_{ds}^{k+1}} \tag{11}$$

Therefore, the prediction of the torque can be expressed as;

$$T_e^{k+1} = \frac{3}{2}\frac{P}{2}\left[\lambda_{ds}^{k+1} i_{qs}^{k+1} - \lambda_{qs}^{k+1} i_{ds}^{k+1}\right] \tag{12}$$

The operation of MPTC can be summarized in the following steps

1. The stator current and the voltage are measured.
2. The stator current for the next step is predicted.
3. The results from step one and two are used to predict the new stator flux and the new torque.
4. The predicted torque and stator flux are compared with their reference values. After that the errors are used as input to the classical PI controllers.
5. The output of the PI controllers are used to control SVPWM inverter.

Fig.2 shows the block diagram of MPTC and illustrate the summarized steps with a two closed loop for torque and stator flux.

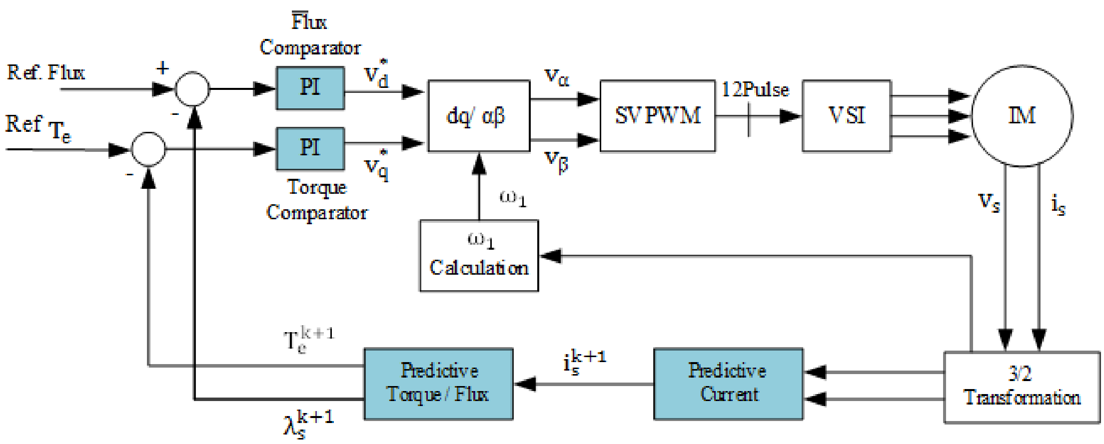


Fig. 2 MPTC block diagram

The synchronous speed ω_1 is simulated based on rotor speed and slip speed

$$\omega_1 = \omega_r + \text{slip speed} \tag{13}$$

$$\text{where; slip speed} = \frac{R_r\, i_{qs}}{L_r\, i_{ds}} \tag{14}$$

The Simulink model of the MPTC drive is shown in Fig.3. It consists of six blocks; IM model block, three-level SVPWM inverter block, arbitrary transformation block, current predictive block, stator flux predictive block and developed torque predictive block.

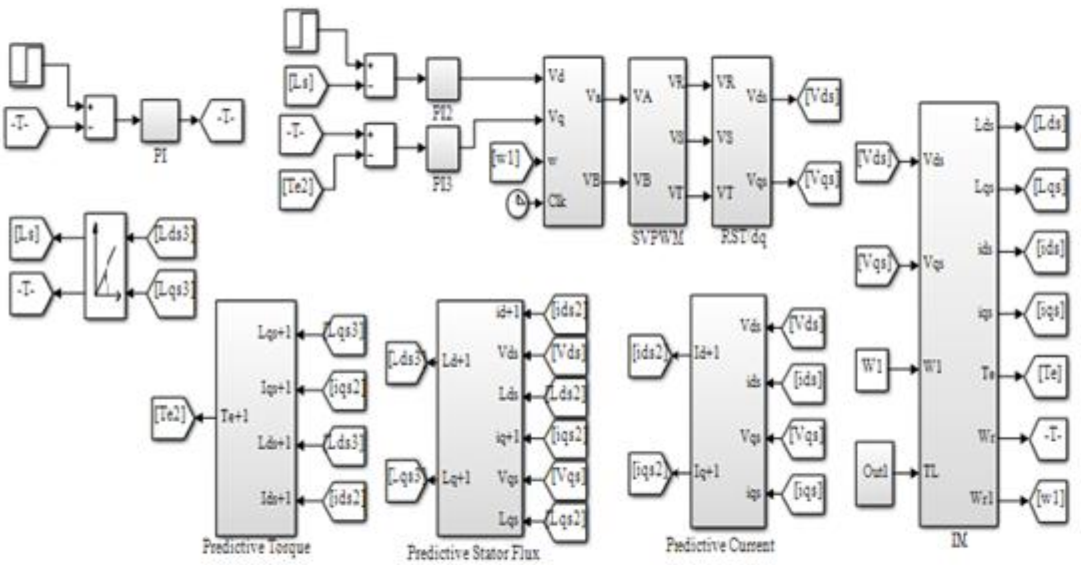


Fig. 3 Simulink model of MPTC

4. Proposed MPTC Method for Induction Motor Drive

The proposed method based on the predictive current and flux to find the next steps of the stator current i_s^{k+n} and the next steps of the stator flux λ_s^{k+n} up to get a certain tolerance ϵ[15].

$$\epsilon_{is} = \vec{i}_s^{k+n} - \vec{i}_s^{k+(n\text{-}1)} \tag{15}$$

$$\epsilon_{\lambda s} = \vec{\lambda}_s^{k+n} - \vec{\lambda}_s^{k+(n\text{-}1)} \tag{16}$$

If ϵ_{is} and $\epsilon_{\lambda s}$ are satisfied, the stator voltage is generated by the same previous method used in section 3, then the developed torque is calculated. The predictive stator flux can be obtained depending on its predictive angle as[7]

$$\overrightarrow{\lambda_s^{k+1}} = \lambda_s^* e^{i\theta_s^{k+1}} \tag{17}$$

The graphical representation of induction motor magnetic flux vectors is shown in Fig.4. It is illustrate the position of the stator flux in the next step (k+1) depending on the position of the rotor flux angle and the change in the rotor flux angle with one step, it can be represented in Eq.(18) [7].

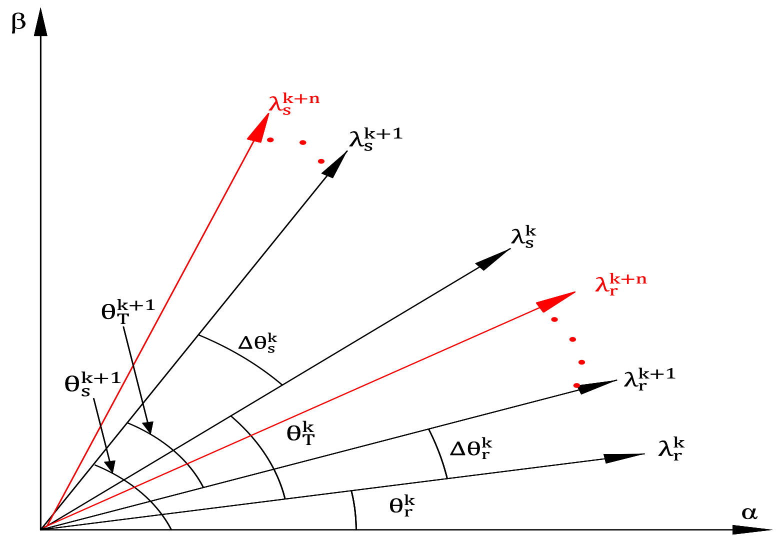


Fig.4 Magnetic flux vectors of IM proposed MPTC

$$\theta_s^{k+1} = \theta_r^k + \Delta\theta_r^k + \theta_T^{k+1} \qquad (18)$$

where; θ_r^k is the rotor flux angle and $\Delta\theta_r^k$ is the change in the rotor flux angle with one step. The rotor flux angle can be found as;

$$\theta_r^k = \tan^{-1}\frac{\lambda_{qr}^k}{\lambda_{dr}^k} \qquad (19)$$

where; λ_{dr}^k and λ_{qr}^k are the (d-q) rotor flux of the induction motor which they depending on the (d-q) stator flux and can be found as;

$$\vec{\lambda}_{dr}^k = \frac{L_r}{L_m}\left(\vec{\lambda}_{ds}^k - \sigma L_s \vec{i}_{ds}\right) \qquad (20)$$

$$\vec{\lambda}_{qr}^k = \frac{L_r}{L_m}\left(\vec{\lambda}_{qs}^k - \sigma L_s \vec{i}_{qs}\right) \qquad (21)$$

So, the magnitude of the rotor flux can be expressed as;

$$|\lambda_s^k| = \sqrt{(\lambda_{ds}^k)^2 + (\lambda_{qs}^k)^2} \qquad (22)$$

And the change of rotor flux vector with one step can be found as;

$$\Delta\theta_r^k = \left[\omega_r^k + \frac{R_r T_e^k}{P\,|\lambda_r^k|^2}\right] * T_s \qquad (23)$$

where R_r is the rotor resistance and ω_r^k is the rotor angular speed.

Finally, the torque angle θ_T^{k+1} can be found by rearranged Eq. (1) as

$$\theta_T^{k+1} = \sin^{-1}\left[-\frac{2\,T_e^{*}\,\sigma\,L_s L_r}{3P\,L_m\left|\lambda_s^{*}\right|\left|\lambda_r^{k}\right|}\right] \qquad (24)$$

Now, all the variables of Eq. (18) have been measured. The predicted value of current and stator flux will be used to obtain the next two step of the stator flux in Eqs.(25) and (26)

$$\lambda_{ds}^{k+2} = \lambda_{ds}^{k+1} + \left[v_{ds}^{k} + R_s i_{ds}^{k+1}\right].\,T_s \qquad (25)$$

$$\lambda_{qs}^{k+2} = \lambda_{qs}^{k+1} + \left[v_{qs}^{k} + R_s i_{qs}^{k+1}\right].\,T_s \qquad (26)$$

The same procedure is used to calculate the next step of calculation to find i_s^{k+2}, λ_s^{k+3}. The calculation of k+2 step require v_s^k and this value of voltage is estimated by

$$\vec{v}_s^{\,k+n} = \frac{\left[\vec{\lambda}_s^{\,k+n} - \vec{\lambda}_s^{\,k}\right]}{T_s} + R_s \vec{i}_s^{\,k} \qquad (27)$$

After calculate k+n step which satisfy the tolerance in current and flux, the developed torque T_e^{k+n} is calculated as follows

$$T_e^{k+n} = \frac{3\,P}{2}\left[\lambda_{ds}^{k+n} i_{qs}^{k+(n-1)} - \lambda_{qs}^{k+n} i_{ds}^{k+(n-1)}\right] \qquad (28)$$

Fig.5 shows the schematic diagram of the proposed MPTC strategy, the predictive value of k+n step of torque and stator flux have been compared with their reference values.

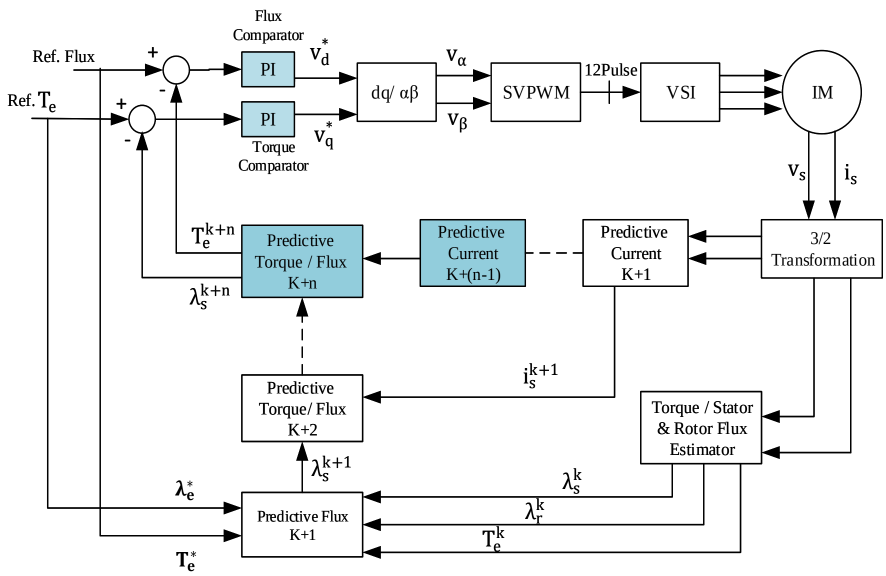


Fig.5 Schematic diagram of the proposed MPTC strategy.

The Simulink model of the developed MPTC drive is shown in Fig.6. It consists of six blocks; IM model block, three-level SVPWM inverter block, arbitrary transformation block, stator flux predictive block(k+1) current predictive block, stator flux predictive block(k+2) and developed torque predictive block(k+2). The model presents the prediction up to k+2 step, therefore results of k, k+1 and k+2 can be obtained.

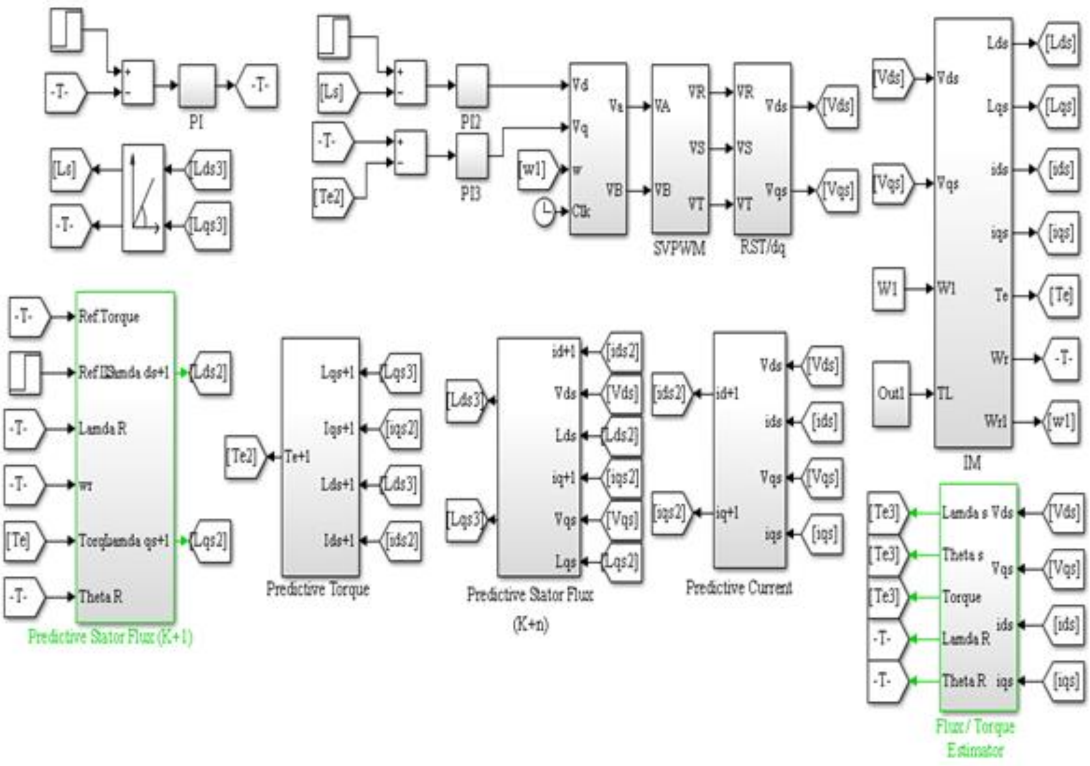
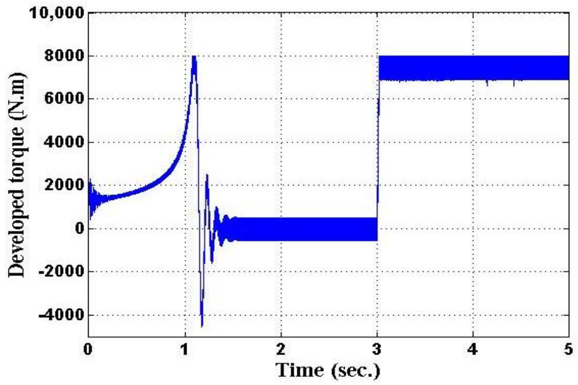
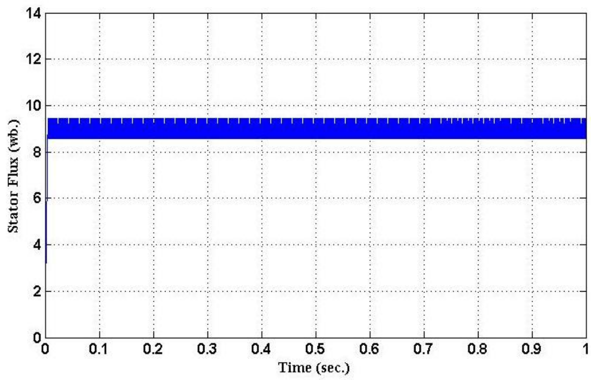


Fig.6 Simulink model of the proposed MPTC

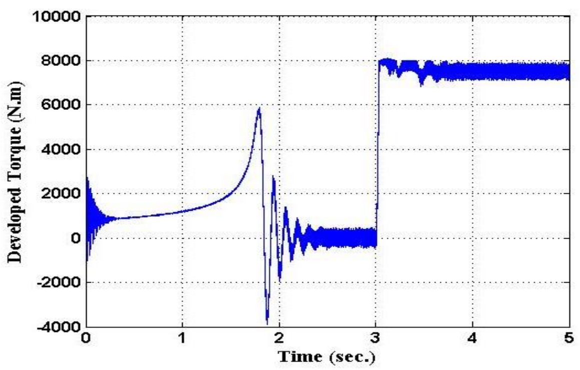
5. Simulation Results

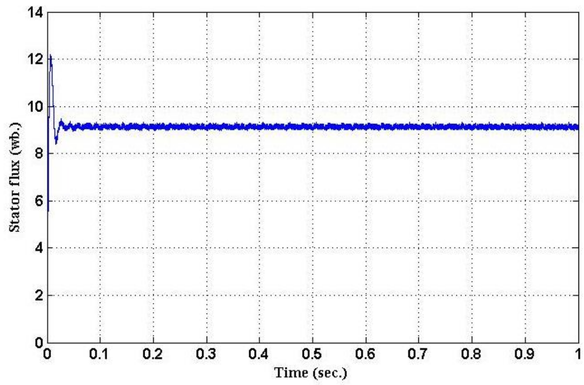
The simulation results are carried out on a high power induction motor. Its rating are 1250 hp, 4160 V, 7490 N.m, 150A, 1189rpm, 60Hz squirrel cage induction motor. Figs.7 and 8 represent the developed torque, the stator flux respectively. The developed torque in the classical DTC is changed directly with the demanded torque and the ripple equal to 15.2% as shown in Fig.7(a), this value is reduced to 5% after using the predictive control for one step K+1 as shown in Fig.7(b). Moreover, its reduced to 3.2% after using the predictive control for two steps K+2 as shown in Fig.7(c). the ripple in the stator flux equal to 9.67% as shown in Fig.8(a), this value is reduced to 3.56% after using the predictive control for one step K+1 as shown in Fig.8(b). Moreover, its reduced to 3.27% after using the predictive control for two steps K+2 as shown in Fig.8(c). Figs. 9 and 10 represent the d-q trajectory of the stator flux and the stator current respectively. The starting current is reduced by 1.25% as well as the trajectory of stator flux is modified and be better. The results obtained by classical DTC are closed to the results given in [11], which is use the same motor parameter. The results using the developed MPTC method shows a reduction in torque and stator flux ripples. Figs.11-13 represent (k) values of the phase voltage, phase current and angle of stator flux with their predictive values (k+1) and (k+2).It is clear that the new step of voltage leads the previous voltage, and this advance will not exceed one cycle of voltage. Moreover, phase current become better and close to sine wave.



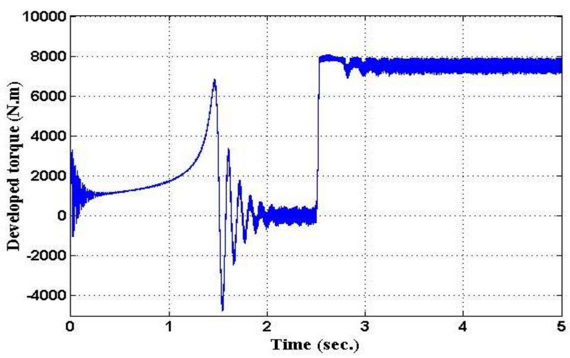


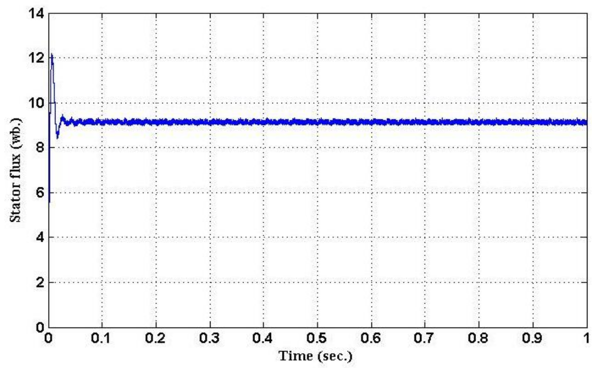
(a)





(b)

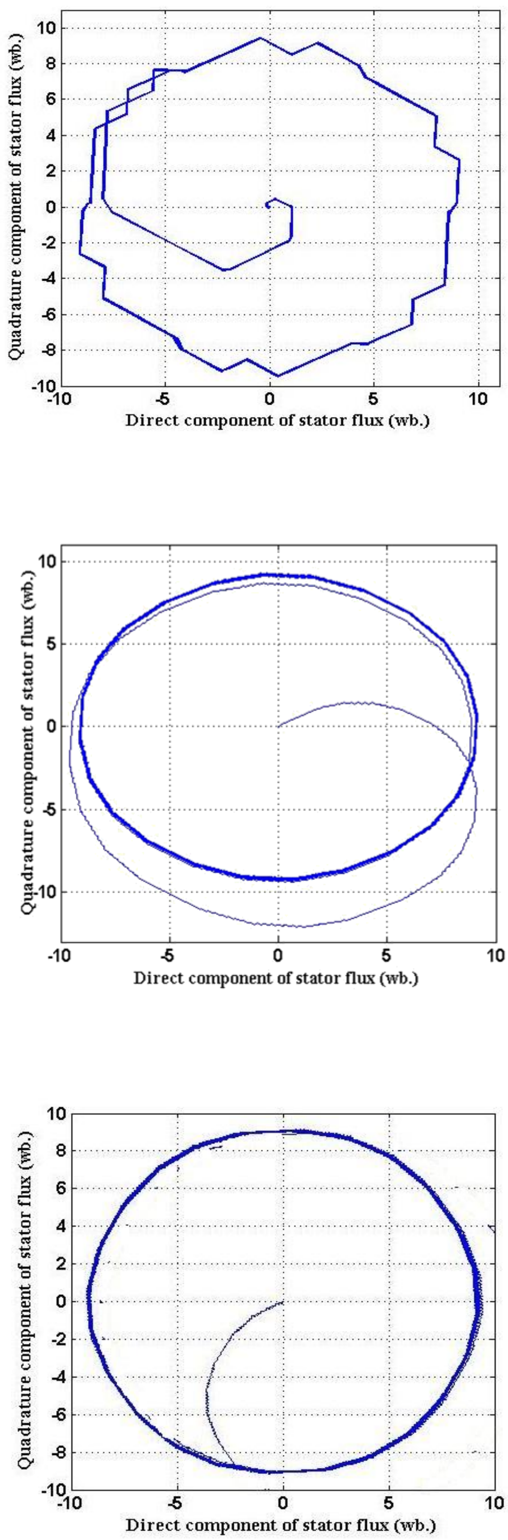




(c)

Fig.7 Developed torque
(a)Classical DTC strategy,(b)MPTC strategy, and (c)Proposed MPTC strategy

Fig. 8 Stator flux
(a)Classical DTC strategy,(b)MPTC strategy, and (c)Proposed MPTC strategy



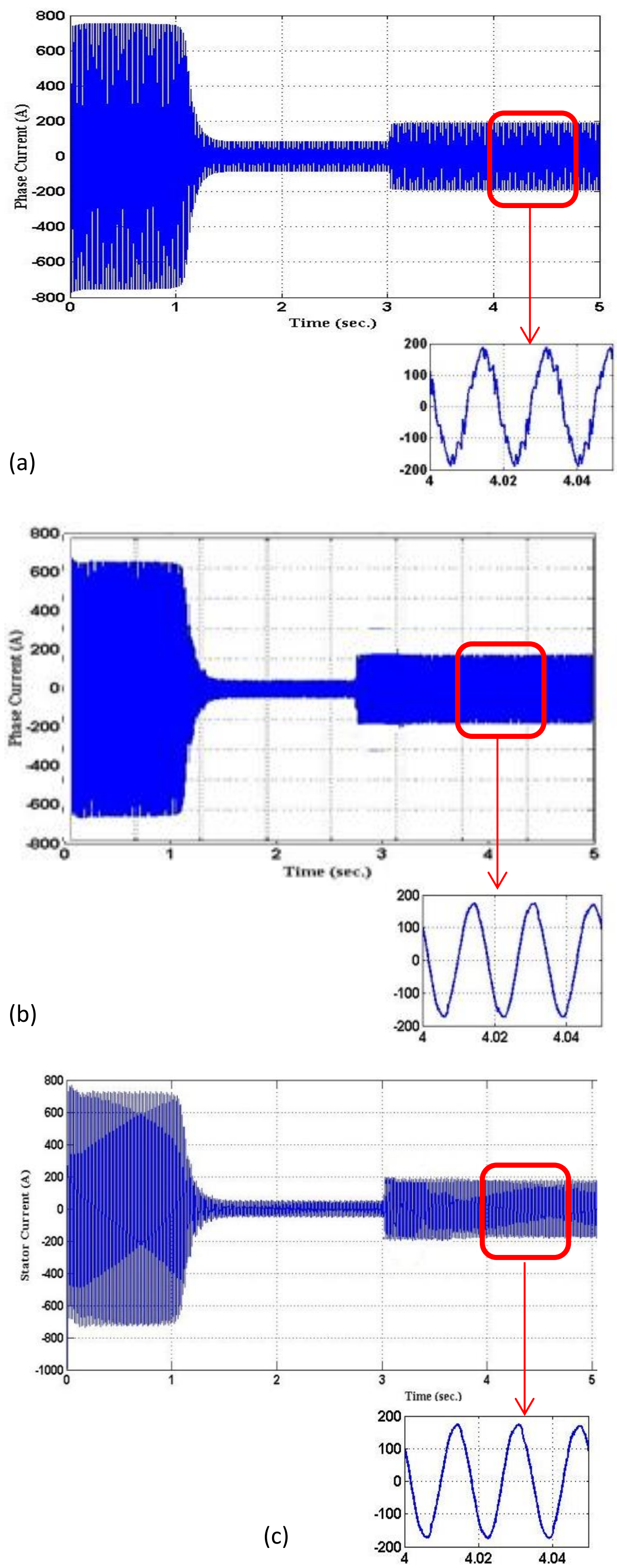


Fig.9 Trajectory of the Stator flux
(a)Classical DTC strategy,(b)MPTC strategy, and
(c)Proposed MPTC strategy

Fig.10 Phase current
(a)Classical DTC strategy,(b)MPTC strategy,
and (c)Proposed MPTC strategy

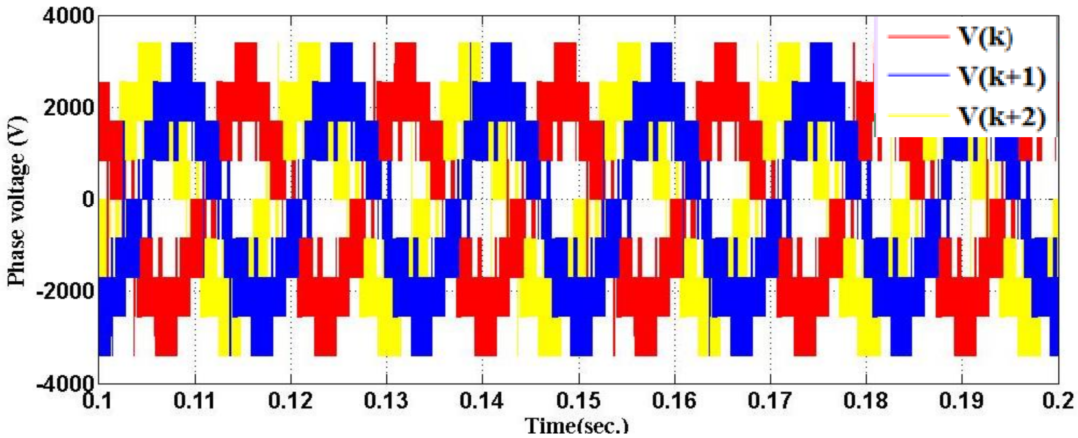


Fig.11 Phase voltage of k, k+1 and k+2 steps

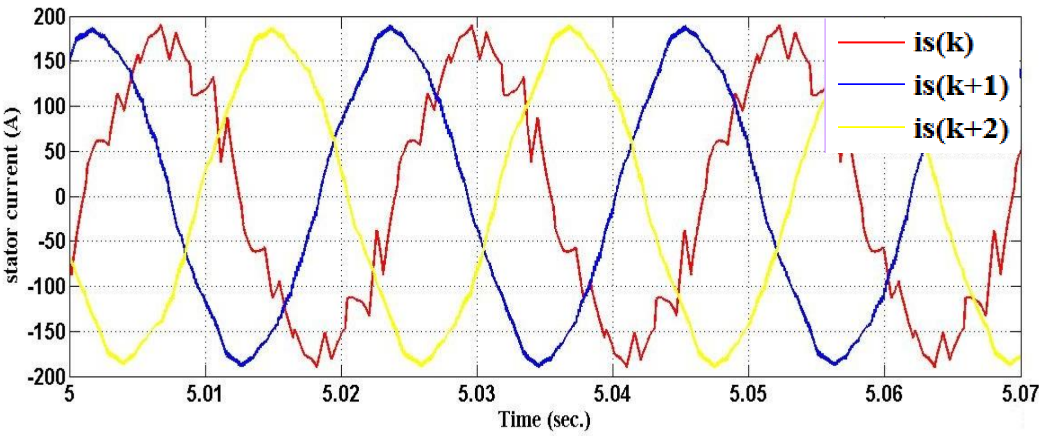


Fig.12 Phase current of k, k+1 and k+2 steps

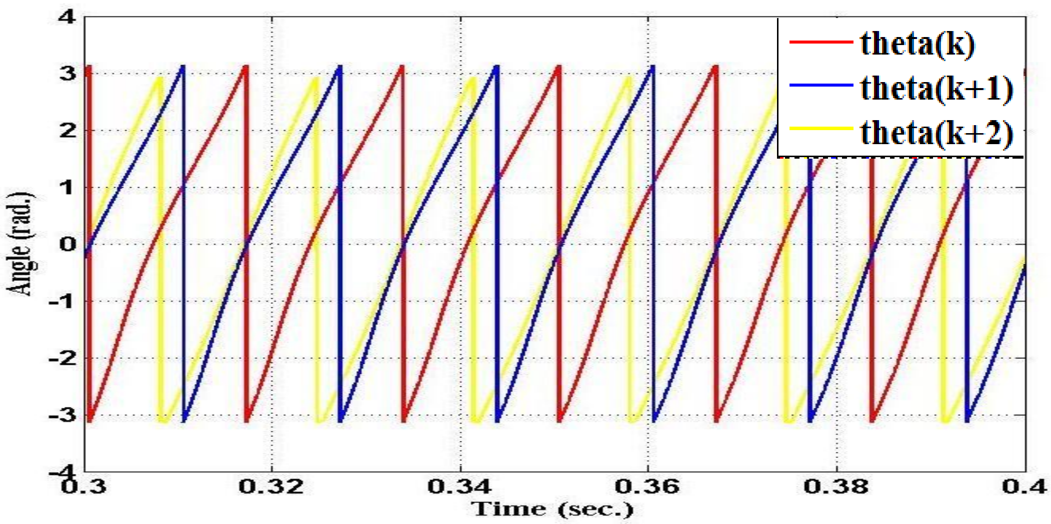


Fig.13 angle of stator flux of k, k+1 and k+2 steps

6. Conclusions

A proposed MPTC with SVPWM technique has been presented in this paper. The results showed that by using this technique made an improvement in performance of classical DTC strategy. This improvement showed a reduction in ripples of torque and stator flux compared to the classical DTC, where the torque and stator flux ripple respectively equal to 15.2% and 9.67% in the classical DTC. While it's reduced to5% and 3.56% after using MPTC with three-level SVPWM. And after comparing the results of the proposed method MPTC with the conventional MPTC, it was clear that the proposed method improved the performance of the conventional MPTC and reduced the ripple in torque and stator flux to 3.2% and 3.27% respectively. This improvement of the induction machine presents by the reduction of ripples for torque and stator flux after using the proposed predictive control for two steps, and shows clearly in the d-q trajectory of the stator flux which is be better than the classical DTC and so smooth.

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