

Mitigate Torque Ripple in Three Phase Induction Motor with Predictive Torque Control Strategy

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ABSTRACT: This paper proposes a novel control method of induction motors (IMs) with improved fast response in transient state and decrease the large ripple in steady-state performance by using a model-based predictive control algorithm. In this proposed technique the PTC can analyze the relation between stator flux of IM and torque. However, the conventional PTC method has a fixed reference voltage vector magnitude and thus has a large torque ripple in the steady state and slow dynamics in the transient state. The proposed PTC modeled in MATLAB\SIMULINK and verified the simulation results.

Index terms: The predictive torque control (PTC), Induction motor drives, predictive torque control, space vector modulation, torque ripple reduction.

I.INTRODUCTION: Induction motors (IMs) are not only simple structured machines relative to dc motors but also have lower cost robust characteristics, and higher reliability. In addition, with the emergence of an improved control technique, their dynamics correspond to those of dc motors, and hence, their use is expanding. There are few control methods to operate IMs. One of them is vector control,

which represents an IM stator current as two main components, one of which is aligned with rotor flux and the other aligns with torque and is perpendicular to the rotor flux. Thus, the flux and torque can be controlled independently, allowing excellent control performance of IMs to be achieved with dc motor simplicity. Despite the superiority of this method, there are some drawbacks.

First, the control performance regarding the stator currents of the IMs highly depends on proportional integral controller gain. Another drawback lies in obstacles to determine the rotating angle and flux magnitude information for the vector control. Along with the reference frame transformation and complex computations, this leads to software complexity and requires a high-performance processor.

The development of a direct torque control method (DTC) has helped overcome some disadvantages of the previous control method. The DTC techniques described in [3]–[8] made it possible to control the motor torque directly with a simple structure while eliminating the process of reference frame transformation. Another advantage of the DTC method is a very fast torque response. Constant dynamic characteristics in the case of abrupt load change or reference change have led to this method being used in many applications.

However, there are some disadvantages: the torque ripple size of the DTC depends on both the operation state of the motor and the voltage magnitude of the dc-link capacitor. It is also easy to make a large torque ripple at the start-up or during low-speed operation. The switching frequency can vary according to the IM operation frequency and load conditions. To overcome the drawbacks of classical DTC, many methods have been proposed.

Recently, active studies on model predictive control (MPC), which is intuitive and easy to understand, were conducted. The MPC method uses a control target model to obtain state variables and execute control object optimization by anticipating output states using an adequate cost function and restrictive conditions through reference values and feedback-state values. In other words, the method uses optimized states, which minimize the cost function for each control period, as a control input. Because MPC can simply include various limitations and nonlinear characteristics, it is applicable to various systems. However, as with the DTC, the MPC increases torque and stator flux ripples owing to the application of one voltage vector for one control period. For these reasons, although the number of studies on control techniques continues to increase, the procedure for dividing voltage vectors in precise control systems still requires many calculations.

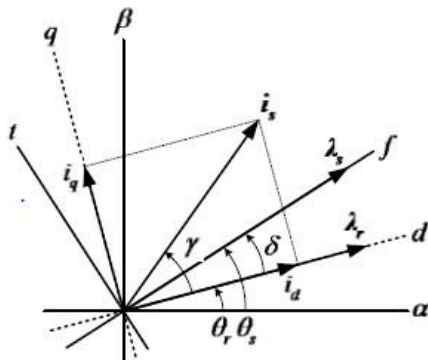


Fig. 1. Vector diagram of the IM and the different coordinate axes.

In addition, studies on generalized predictive control (GPC) method were conducted. The GPC is based on a transfer function model of both the plant and the disturbance. It is able to use for torque control as the most accurate predictive method with very low torque ripple, however, it is required to complicated computation and long operation time.

Another known and widely used predictive control algorithm for controlling IMs is predictive torque control (PTC). Unlike the conventional DTC, the PTC does not choose the voltage vector according to a lookup table but performs the control by analyzing the relationship between the electromagnetic torque and the voltage and then calculating the desired voltage vector using mathematical equations. Thus, it is possible to achieve accurate and fast control without transient torque and overshooting. Nevertheless, the drawback of the PTC algorithm is a torque ripple in a low-speed region. It is caused by a limited choice of the voltage vector of the inverter as a result of fixed time duration of the voltage vector.

II. MODEL PREDICTIVE CONTROL

Model predictive control (MPC) is a propelled technique for procedure control that has been being used in the process enterprises in chemical plants and oil refineries facilities since the 1980s. As of late it has likewise been utilized in power framework adjusting models. Model prescient controllers depend on unique models of the procedure, frequently direct exact models acquired by framework ID. The primary preferred position of MPC is the way that it permits the current timeslot to be advanced, while keeping future timeslots in record. This is accomplished by upgrading a limited time-skyline, however just actualizing the current timeslot. MPC can envision future occasions and can take control activities in like manner. PID and LQR controllers don't have this prescient capacity. MPC is almost generally executed as a

digital control, despite the fact that there is examination into accomplishing quicker reaction times with extraordinarily planned simple hardware.

Overview

The models utilized in MPC are commonly expected to speak to the conduct of complex dynamical frameworks. The extra multifaceted nature of the MPC control calculation isn't commonly expected to give satisfactory control of straightforward frameworks, which are frequently controlled well by conventional PID controllers. Basic unique attributes that are hard for PID controllers incorporate enormous time deferrals and high-request elements.

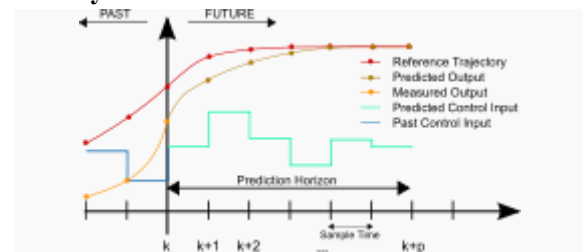
MPC models anticipate the adjustment in the needy factors of the demonstrated framework that will be brought about by changes in the free factors. In a synthetic procedure, free factors that can be balanced by the controller are frequently either the set purposes of administrative PID controllers (pressure, flow, temperature, and so on.) or the last control component (valves, dampers, and so on.). Free factors that can't be balanced by the controller are utilized as unsettling influences. Subordinate factors in these procedures are different estimations that speak to either control destinations or procedure imperatives.

MPC uses the current plant measurements, the current dynamic state of the process, the MPC models, and the process variable targets and limits to calculate future changes in the dependent variables. These changes are calculated to hold the dependent variables close to target while honoring constraints on both independent and dependent variables. The MPC typically sends out only the first change in each independent variable to be implemented, and repeats the calculation when the next change is required.

When linear models are not sufficiently accurate to represent the real process nonlinearities, several approaches can be used. In some cases, the process variables can be transformed before and/or after the linear MPC model to reduce the nonlinearity. The process can be controlled with nonlinear MPC that uses a nonlinear model directly in the control application. The nonlinear model may be in the form of an empirical data fit (e.g. artificial neural networks) or a high-fidelity dynamic model based on fundamental mass and energy balances. The nonlinear model may be linearized to derive a Kalman filter or specify a model for linear MPC.

An algorithmic study by El-Gherwi, Budman, and El Kamel shows that utilizing a dual-mode approach can provide significant reduction in online computations while maintaining comparative performance to a non-altered implementation. The proposed algorithm solves N convex optimization problems in parallel based on exchange of information among controllers.

Theory behind MPC



A discrete MPC scheme.

III. PROPOSED METHOD: To simplify the control structure of the conventional PTC [18], it is necessary to limit the active voltage vector magnitude $uk (= kus)$ by the coefficient k ($0 < k \leq 1$). Increasing k leads to a dynamics improvement along with the torque ripple increase. In contrast, with decreasing k , the torque ripple will also decrease, and the dynamics will slow down. To overcome this disadvantage, the method proposed in this paper does not fix the value of k but, through a simple calculation, obtains the value of the active

voltage vector, which leads to error minimization in the torque T_e and flux λ_s . In other words, the coefficient k has large value during transient state of the torque in order to improve the dynamics and it has small value during the steady state in order to reduce the torque ripple. The proposed method selects the most relevant reference voltage vector through a simple mathematical calculation. This voltage includes both the electromagnetic torque error and the stator-flux error and is accurately applied to the motor torque and stator-flux control. Therefore, the advantage of this method is reduced torque ripple and improved system dynamics

3.2 Minimum torque ripple strategy

The proposed torque ripple reduction method for the proposed PTC has a two-step design. The first step is to determine the magnitude of the reference voltage in the d-axis u^*_d , which is the rotating frame synchronized with the rotor, by using stator flux error $\Delta\lambda_s$ and apply the nonzero voltage vector uk as required by the stator-flux control, as shown in Fig. 3. The second step is to modify the reference voltage vector u^*_{mod} , which was previously determined by predictive u^*_s by calculating the angle and the magnitude of u^*_s with the same torque change rate ΔT_e within the magnitude of u^*_d . The predictive algorithm computes ΔT_e by applying each vector and selecting the one that contributes to the minimum error.

According to (3), λ_s can be processed as an integration of voltages. Neglecting the voltage drop in R_s , the magnitude of the voltage vector required for the stator-flux control can be obtained as

$$u^*_{ds} \approx \Delta\lambda_s T_s^{-1}. \quad (22)$$

The u^*_{ds} has to be modified by applying the nonzero voltage vector uk as required by the stator-flux control. Therefore, the magnitude of the modified reference voltage vector u^*_{mod} in

d-axis is determined to $\Delta\lambda_s Tk-1$, where Tk is obtained by multiplying T_s and the coefficient k ($0 < k \leq 1$) as shown in Fig. 3. The acquired magnitude of the voltage vector is set by the magnitude of u^*_{ds} and u^*_{qs} . By using the previously obtained u^*_s and $\Delta\lambda_s$, the magnitude and angle of u^*_{mod} that produces the same variation in torque can be obtained by using the following trigonometric equation:

$$|u^*_{mod}| = \sqrt{(u^*_{ds})^2 + (u^*_{qs})^2} = \sqrt{(\Delta\lambda_s Tk)^2 + (u^*_s \sin \theta^*)^2} \quad (23)$$

From the above equation, when the angle is obtained that has the same change rate ΔT_e as u^*_{mod} , it is equivalent to the following equations

$$\theta^*_{mod} = \arcsin\left(\frac{1}{k} \sin \theta^*\right) = \arcsin\left(\frac{|u^*_s|}{|u^*_{mod}|} \sin \theta^*\right) \quad (24)$$

The angle determines the direction of u^*_{mod} to obtain zero torque error. Moreover, it ensures accurate torque control of the motor and minimum torque ripple. As a result, the coefficient k has to be changed by the proposed PTC method during the drive operation in order to improve dynamics and minimize torque ripple.

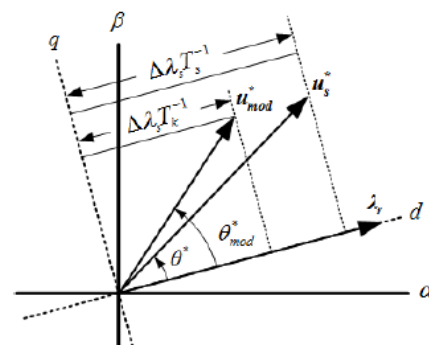


Fig. 3. Proposed PTC strategy.

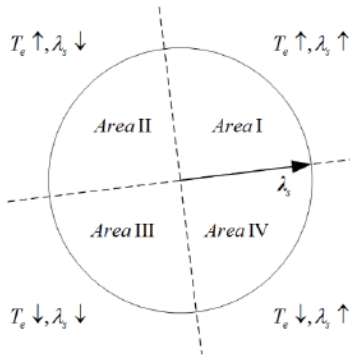


Fig. 4. Phase plane division for control of electromagnetic torque and stator flux.

 TABLE I
AREA VOLTAGE VECTOR

Stator flux	Torque	Selected areas
$\lambda_s \uparrow$	$T_e \uparrow$	Area I
$\lambda_s \downarrow$	$T_e \uparrow$	Area II
$\lambda_s \downarrow$	$T_e \downarrow$	Area III
$\lambda_s \uparrow$	$T_e \downarrow$	Area IV

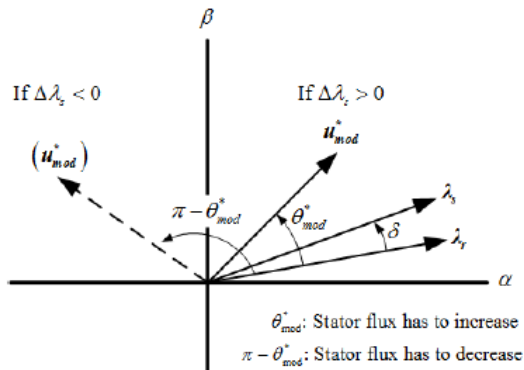


Fig. 5. Control of the stator flux.

3.3 Control of the stator flux

The λ_s synchronized to the f - t reference frame is shown in Fig. 1. The f -axis represents λ_s , and the t -axis represents T_e . These two dotted lines split the f - t reference frame into four quadrants, as shown in Fig. 4. Each zone is characterized by the sign of T_e and λ_s , as listed in Table I. When u_s is located inside one of them, T_e and λ_s can be increased or decreased depending on the selected areas. For example, when both T_e and λ_s must be increased, the selected voltage vector is located in area I. Fig. 5 shows the relationship among u^{*mod} , λ_r , and λ_s . When T_e increases, λ_s leads λ_r by angle δ . In contrast, when T_e decreases, λ_s lags λ_r by angle δ . In addition, if the phase difference between

u^{*mod} and λ_s is within $\pm 90^\circ$, the magnitude of the stator flux increases; otherwise, it decreases. Hence, the angle of u^{*mod} to control λ_s can be determined in the following manner:

- The magnitude of λ_s must increase, $\Delta\theta^* = \theta^{*mod}$
- The magnitude of λ_s must decrease, $\Delta\theta^* = \pi - \theta^{*mod}$

The u^{*mod} angle of the proposed PTC becomes $\Delta\theta^*$. Therefore, after obtaining the angle increment, the amplitude of the output reference voltage vector V^* can be expressed in the following equation in polar coordinates as

$$V^* = |u_{mod}^*| \cdot e^{j(\theta_r + \Delta\theta^*)} \quad (25)$$

3.4 Predictive torque control block scheme

The actualization process of the PTC of the IM with decreased torque ripple is shown in Fig. 6. First, the output current is determined to calculate i_s in the stationary reference frame. In the flux and torque estimation block, T_e and λ_s are then estimated by using (5) and (20), respectively. The process of the λ_s calculation is clearly explained in Fig. 2. In the predictive control block, the angle of u^* s that sets ΔT_e to zero is calculated, where the maximum duty is obtained by placing T_e^* , T_e , λ_s , λ_r and ΔT_e into (15). This angle is the phase difference between u^* s and λ_r . From the ripple minimization control, the magnitude of the modified reference voltage vector in the d -axis is determined by $\Delta\lambda_s$ using (22), and u^* s is corrected by recalculating the magnitude and angle of u^{*mod} using (23) and (24). The stator flux controller creates the final V^* using the hysteresis control technique with the calculated u^{*mod} , θ_r , and $\Delta\lambda_s$. In other words, the final V^* is selected by the magnitude of $\Delta\lambda_s$ as in Fig. 5 and Fig. 6. If the $\Delta\lambda_s$ is larger than zero, the final V^* is selected by the $|u^{*mod}|$ using θ^{*mod} and if the $\Delta\lambda_s$ is smaller than zero, the final V^* is selected by the $|u^{*mod}|$ using $\pi -$

θ^*_{mod} . Finally, the recreated V^* is used to control the inverter switching using the SVM method using the reverse $d-q$ coordinate transformation.

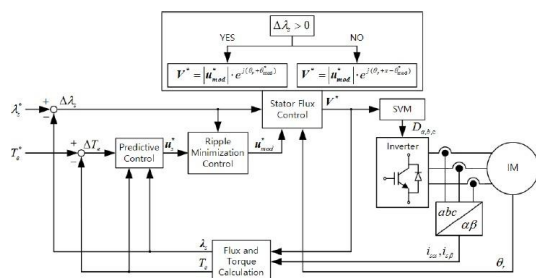


Fig. 6. Block diagram of the IM based on PTC.

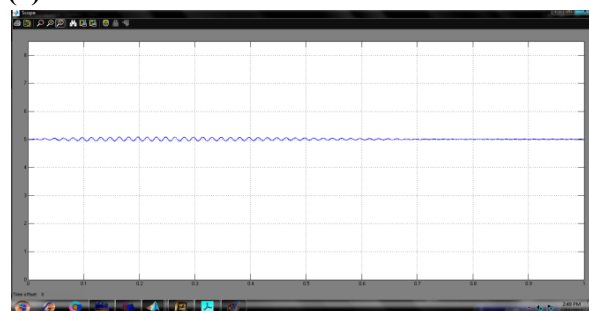
TABLE II
SIMULATION PARAMETERS

Motor parameters	Value
Rated power [kW]	3.7
Rated current [A]	8.28
Rated speed [r/min]	1750
Rated torque [Nm]	20.36
Stator resistance [Ω]	0.9335
Rotor resistance [Ω]	1.2252
Stator inductance [mH]	146.213
Rotor inductance [mH]	146.213
Magnetization inductance [mH]	139.516
Number of pole pairs	4

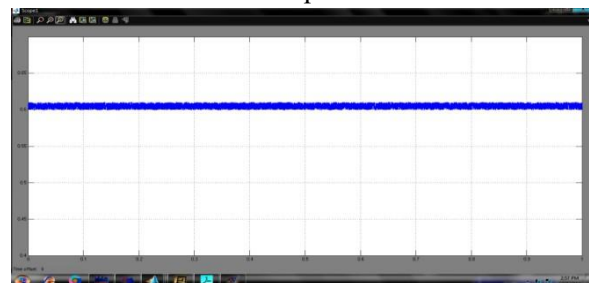
IV. SIMULATION RESULTS:

Simulation result of the motor torque and stator flux with load at 300 r/min.

(a) Conventional PTC.

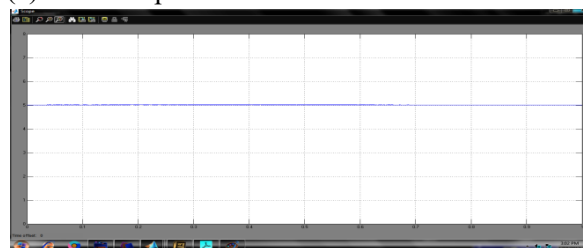


torque

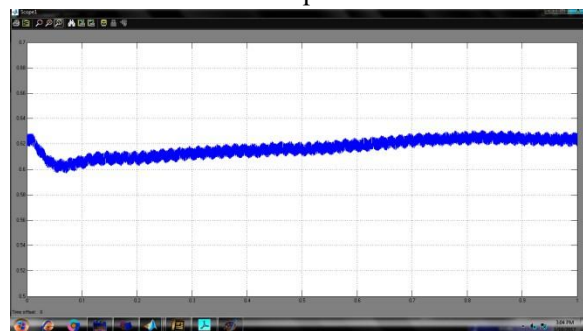


Flux

(b) Proposed PTC.



torque

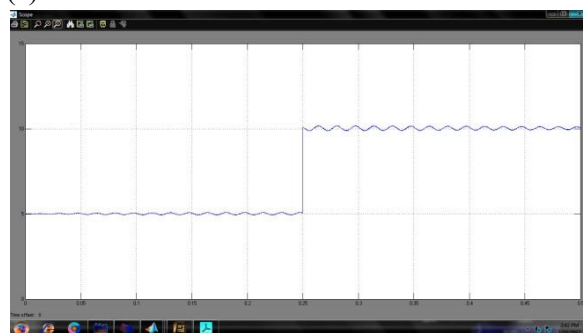


Flux

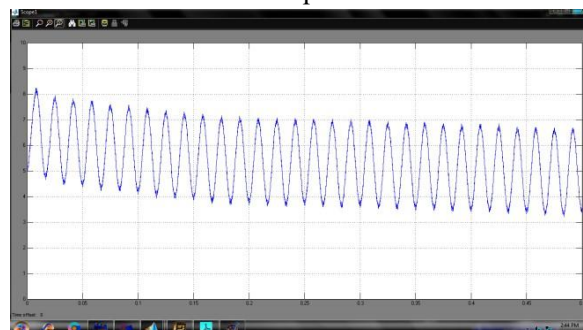
Transient state:

Simulation result of the torque step response from 5 to 10 Nm.

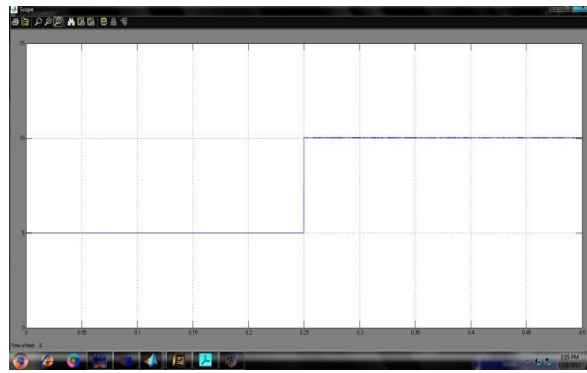
(a) Conventional PTC.



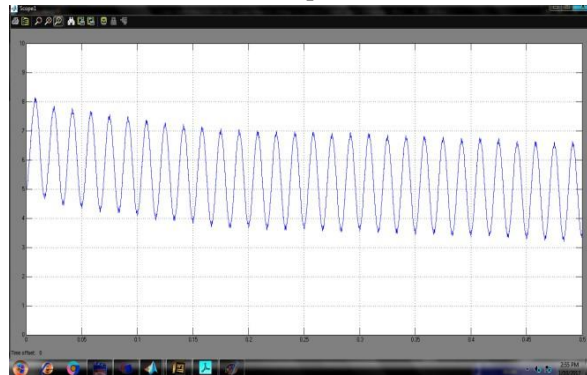
torque

Stator current I_{sa}

(b) Proposed PTC.



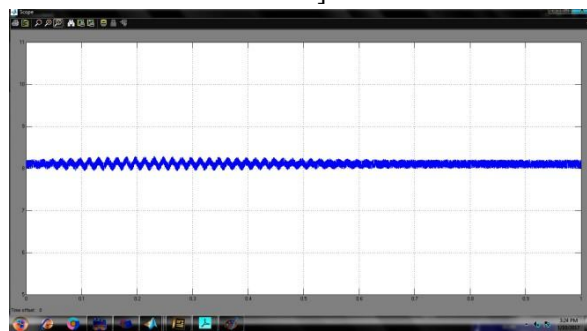
Torque



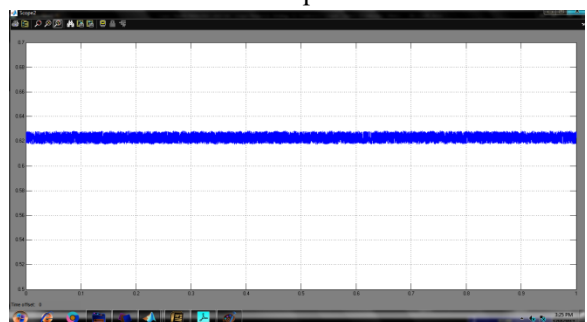
Stator current I_{sa}

Simulation results of the motor torque and stator flux with load at 500 r/min depending on inaccuracies of L_s and L_r .

(a) Conventional PTC [$L_s = L_r = 146.213$ mH].

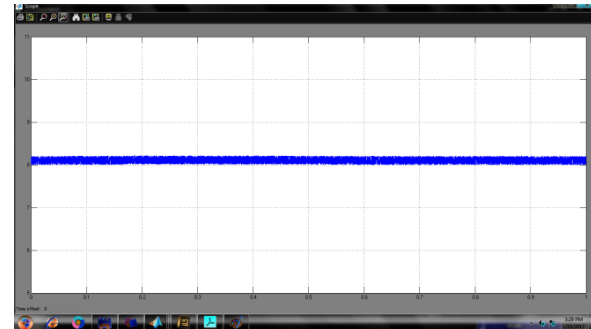


Torque

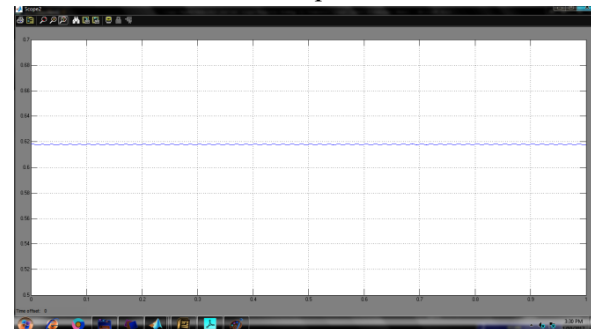


Flux

(b) Proposed PTC [$L_s = L_r = 146.213$ mH].

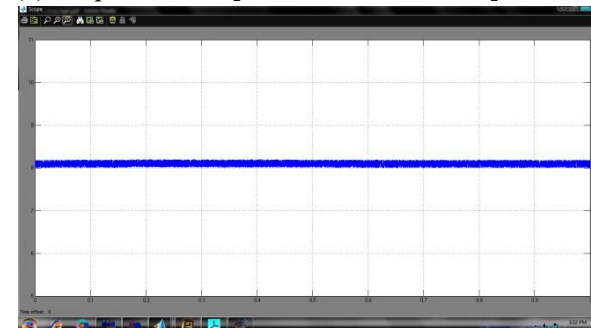


Torque

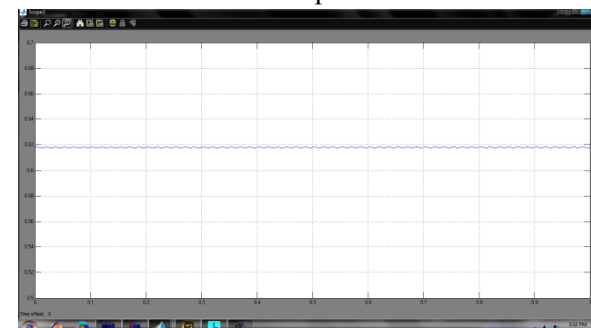


Flux

(c) Proposed PTC [$L_s = L_r = 141.213$ mH].

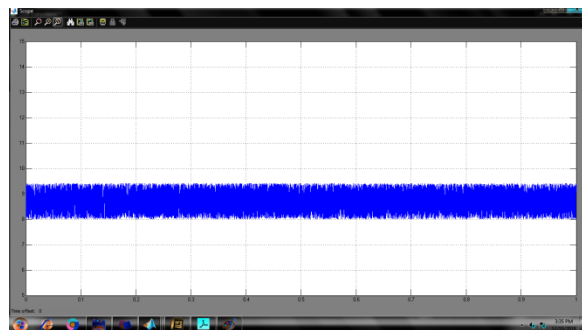


Torque

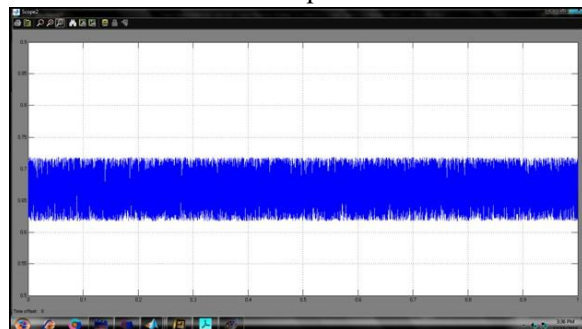


Flux

(d) Proposed PTC [$L_s = L_r = 156.213$ mH].

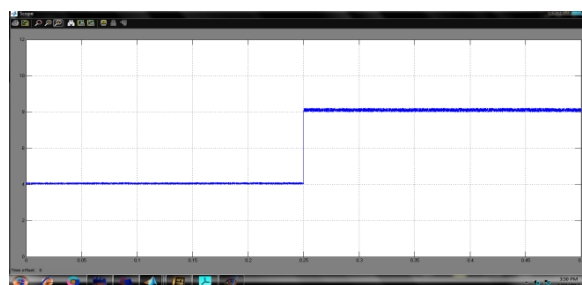


Torque

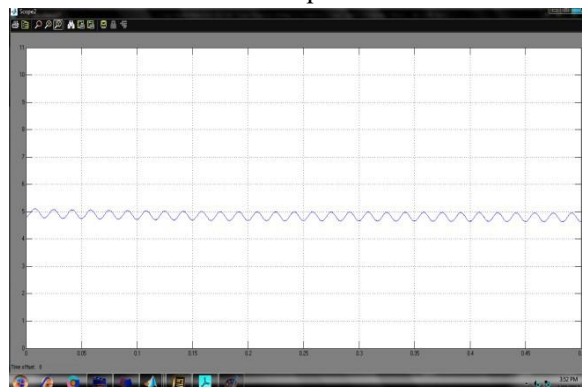


Flux

Fig. 10. Simulation result of the torque step response from 4 to 8 Nm. (a) $L_s = L_r = 146.213$ mH.

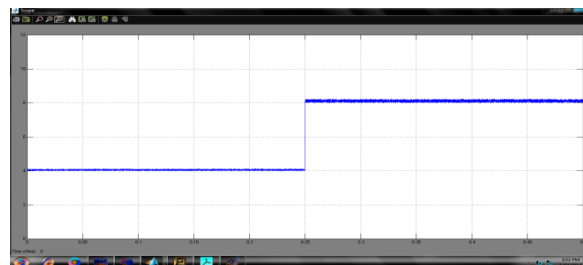


Torque

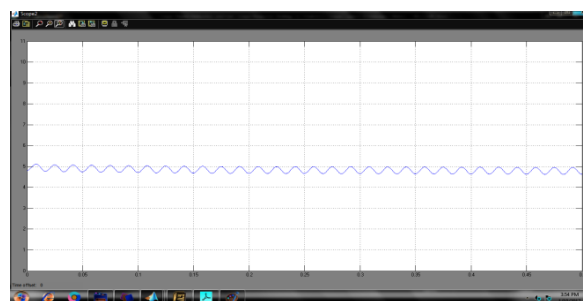


Stator current I_{sa}

(b) $L_s = L_r = 141.213$ mH.

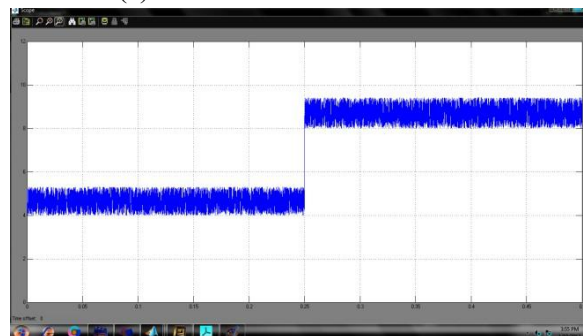


Torque

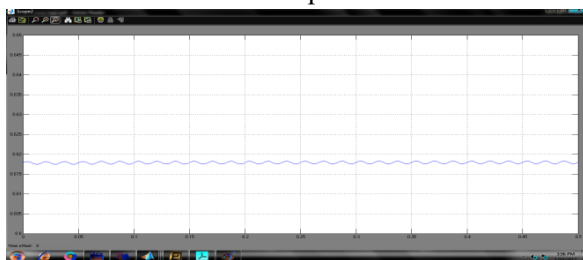


Stator current I_{sa}

(c) $L_s = L_r = 156.213$ mH.



Torque



Stator current I_{sa}

V.CONCLUSION: in this paper we propose a novel PTC controller to suppress torque ripple response and not only torque stator flux control ripple also in steady state and transient state. This voltage is obtained through a simple mathematical calculation. The proposed system is conducted in the inviernment of MATLAB/SIMLINK with different torque and different time intervals. The simulation results

are compared with traditional system with proposed system exposed better torque ripple reduction. The simulation results confirmed that the proposed PTC technique recommends the feasibility of efficiently improving the system dynamics and greatly reducing the torque ripple.

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