Predictive Torque Control Of Induction Machine

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **Predictive Torque Control Of Induction Machine**, submitted by **K Saiveer Patnaik**, to the Indian Institute of Technology, Madras, for the award of the degree of **MASTER OF TECHNOLOGY**, is a bona fide record of the research work done by him under our supervision and Technical University Munich. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

This thesis presents a comprehensive study of Predictive Torque Control(PTC). The study shows a comparative analysis with DTC. PTC has proven as a effective strategy for industrial applications. The comparative study highlights the effectiveness and simplicity of this methodology using simulation studies in Simulink. Further to overcome the disadvantages of this strategy some improvements have been suggested. The improved version of the algorithm reduces the average switching frequency of the switches and also reduces calculation time. Both the strategies were simulated in Simulink.Implementations of both the strategies have been carried out and their results have been listed and analyzed. The conclusion also gives a brief overview of the possible research studies that can be carried after this study.

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ABBREVIATIONS

TUM	Technical University of Munich
DTC	Direct Torque Control
FOC	Field Oriented Control
PTC	Predictive Torque Control
NPTC	Normal Predictive Torque Control
RSPTC	Reduced Switching Predictive Torque Control

NOTATION

ψ_s	Stator flux
ψ_r	Rotor flux
ω	Rotor Speed
L_m	Mutual Inductance
L_s	Stator Inductance
L_r	Rotor Inductance
R_s	Stator Resistance
R_r	Rotor Resistance
λ	Weighting Factor
T_s	Sampling Time
p	Number of Poles

CHAPTER 1

Introduction

Control of electrical drives has a very important position in high performance industrial applications. Thus there has been an extensive study on different strategies of control of electrical drives. A wide range of research has been carried out in both linear and non-linear methods. The most studied linear method includes the use of proportional integral (PI) controllers employing Pulse Width Modulation (PWM) methodology. Non-linear methodology includes methods like hysteresis control.

The most widely used linear methodology for industrial applications is Field Oriented Control (FOC). This technique decouples the torque and flux such that the behavior of the AC machine is similar to that of a separately excited DC machine and hence linear controllers can be used. This decoupling is done by considering an appropriate coordinate reference frame.

A well-known non-linear hysteresis control strategy is Direct Torque Control (DTC). This strategy uses independent hysteresis controllers for torque and flux and it is one of the methodologies whose system implementation is considered easy. The behavior of FOC and DTC is well known in transient conditions. But recently due to advancements in the field of processors and development of high speed processors a methodology called Model Predictive Control (MPC) is becoming dominant in the high performance industrial applications in machine control. The term MPC does not imply a specific control strategy; rather it covers a wide variety of control techniques that make explicit use of a mathematical model of the process and a minimization of an objective function to obtain the optimal control signals The main concept of Predictive Control is based on the calculation of the future system behavior in order to use this information to compute optimal values for the actuating variables. The execution of the predictive algorithm can be divided in three main steps: **Estimation** of the variables that cannot be measured, **prediction** of the future plant behavior and **optimization** of outputs according to a reference condition.

MPC has the following advantages: The basic concept is easy to understand, the algorithm is simple to implement, it can handle multi-variable systems and constraints can be included. But this control scheme involves lot of calculations when compared to DTC and FOC. This is where the improved and faster processor research has proven advantageous. Before the fast processor technology existed MPC was used in slow dynamic applications such as in petrochemical industry where the sampling frequencies are very low. The slow dynamics of chemical processes allow long sample periods, providing enough time to solve the online optimization problem.

With the advent of Digital Signal Processors (DSP) and development of Field Programmable Gate Arrays (FPGA) it has become possible to use MPC in fast dynamic process industries such as power electronics and control of electrical drives. Due to the broad range of MPC methods, the MPC techniques applied to power electronics have been classified into 2 categories: Classical MPC and Finite State MPC (FS-MPC). In the first type, the control variable is usually the converter output voltage, in the form of a duty cycle that varies continuously between its minimum and maximum magnitude, while optimization problem is solved at every sampling step to calculate this voltage. FS-MPC uses the inherent discrete nature of the power converter to solve the optimization problem. The inverter is taken into consideration in the controller design. A cost function which generally consists of the difference between reference and measured control variables is optimized according to the all possible inverter switching states. The switching state which minimizes the cost function will be the next output signal.

In this study FS-MPC is used which is conceptually easier compared to the other category. This strategy is used for torque control of induction machine and hence is called Predictive Torque Control (PTC). When a new strategy is employed it is always better to compare it with already existing strategies to understand the advantages and disadvantages of the new strategy. A through comparative study of DTC, FOC and PTC through simulations is already done in [4]. In [3] an experimental comparison between PTC and FOC is made. In that study it is verified that PTC has a faster dynamic response. This study however attempts to give only a comparative study between DTC and PTC. Both strategies do not require modulator in their implementation unlike FOC and hence their implementation becomes easy.

This thesis paper is structured as follows: Chapter 2 the model of the induction machine. Chapter 3 deals with DTC and 4 with PTC. Chapter 5 gives the comparative study simulation analysis. Chapter 6 suggests improvements in PTC. Chapter 7 gives Simulation analysis of the improved strategy. Chapter 8 deals with hardware implementations and chapter 9 gives conclusions.

CHAPTER 2

Induction Machine Model

For the purpose of simulation to verify the working of PTC and DTC strategies a mathematical model of induction machine has to be done. The purpose of modeling is to mimic the behavior of an induction machine mathematically. This study considers modeling of the induction machine relative to the arbitrary reference frame.

The set of complex equations describing the induction machine is given in the following equations:

$$\vec{v_s} = \vec{i_s}.R_s + \frac{d}{dt}\vec{\psi_s} + j.\omega_k.\psi_s \tag{2.1}$$

$$0 = \vec{i_r}.R_r + \frac{d}{dt}\vec{\psi_r} + j.(\omega_k - \omega).\vec{\psi_r} \tag{2.2}$$

$$\vec{\psi_s} = L_s.\vec{i_s} + L_m.\vec{i_r} \tag{2.3}$$

$$\vec{\psi_r} = L_r.\vec{i_r} + L_m.\vec{i_s} \tag{2.4}$$

$$T_e = \frac{3}{2}.p.Im(\vec{\psi_s^*}.\vec{i_s}) \tag{2.5}$$

where $\vec{v_s}$ is the voltage vector of the stator, $\vec{\psi_r}$ and $\vec{\psi_s}$ are the rotor flux and stator flux respectively. $\vec{i_s}$ and $\vec{i_r}$ represent stator and rotor currents. R_s and R_r are stator and rotor resistances. L_r , L_s and L_m are rotor,stator and mutual inductances ω is the angular velocity p the number of poles and T_e is the electromagnetic torque.

Derivations of these equations can be seen in **[1]** and it is not explained in detail here.

CHAPTER 3

Direct Torque Control

This section deals with the basic algorithmic details of the implementation of DTC. This does not cover the strategy in detail. DTC being a well-known strategy will not be covered in depth.

The basic idea of DTC is as a consequence of two assumptions. We assume that the rotor speed is high enough to ignore the voltage drop across the stator equation. This assumption when applied to equation 2.2, brings about the stator flux approximation during a sampling step as seen in equation 3.1.

$$\Delta.\vec{\psi_s} \approx \vec{v_s}.T_s \tag{3.1}$$

The above approximation implies that stator flux control can be achieved by applying an appropriate voltage vector. The second assumption is a consequence of the rotor flux equation 3.2:

$$\vec{\psi_r} = \frac{K_s}{\sigma.\tau_r.s + 1}.\vec{\psi_s} \tag{3.2}$$

where $\tau_r = \frac{L_r}{R_r}$,$\sigma = 1 - (\frac{L_m^2}{L_s.L_r})$ and $K_s = \frac{L_m}{L_s}$

It can be concluded from the above equation that the rotor flux is slower than the stator flux and hence rotor flux can be assumed as constant during one sample step. The electromagnetic torque can be calculated as equation 3.3.

$$T = \frac{3}{2}.\frac{L_m}{\sigma.L_s.L_r}.p.|\vec{\psi_r}|.|\vec{\psi_s}|.\sin(\delta) \tag{3.3}$$

Applying the second assumption to the above equation we can observe that torque can be controlled by changing the angle of the stator flux which in turn can be controlled by applying an appropriate voltage vector.

Applying these two assumptions we reach to a conclusion that the stator flux and electromagnetic torque can be independently controlled. And to achieve this independent control hysteresis controllers for both stator flux and electromagnetic torque are used.

The basic ideology of DTC can be seen in Figure 3.1.

An external PI-controller is used to achieve zero steady state error on speed. This control loop also generates the torque reference which is an input to the torque hysteresis controller. A step input of 0.71 Wb is the flux reference which is an input to the flux hysteresis controller. The other inputs to the controllers are the estimated torque and estimated flux respectively. This estimation is done by considering the discrete machine model equations stated earlier.

Specifically the voltage equation is used to estimate the stator flux vector from which stator flux magnitude and angle can be calculated. Then in turn the estimated flux along with the measured current is used for torque estimation.

The errors of the estimated torque and estimated flux with respect to their reference values are inputted to the respective hysteresis controllers. The output of these controllers decides whether flux has to increase or decrease and torque has to increase or decrease or remain same. These outputs along with the stator angle calculated earlier forms the basis to select the switching vector. This is done by using a look up table which has been filled up earlier according to the strategy discussed in **[2]**. The look up table used is shown in figure 3.2

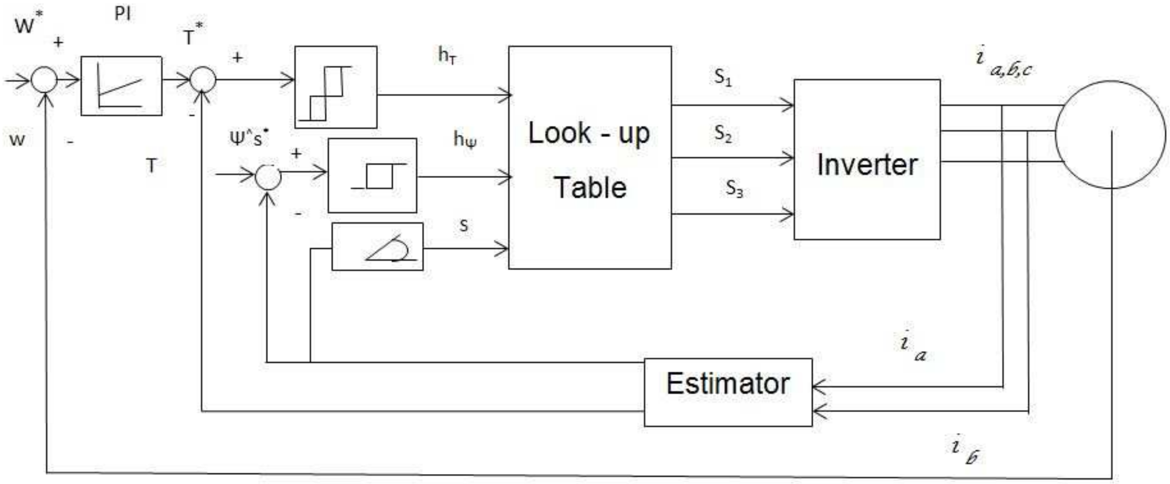

Figure 3.1: Block Diagram of DTC

Φ, τ, θ		Θ(1)	Θ(2)	Θ(3)	Θ(4)	Θ(5)	Θ(6)
Φ=1	τ=1	S(1,1,0)	S(0,1,0)	S(0,1,1)	S(0,0,1)	S(1,0,1)	S(1,0,0)
	τ=0	S(1,1,1)	S(0,0,0)	S(1,1,1)	S(0,0,0)	S(1,1,1)	S(0,0,0)
	τ=-1	S(1,0,1)	S(1,0,0)	S(1,1,0)	S(0,1,0)	S(0,1,1)	S(0,0,1)
Φ=0	τ=1	S(0,1,0)	S(0,1,1)	S(0,0,1)	S(1,0,1)	S(1,0,0)	S(1,1,0)
	τ=0	S(0,0,0)	S(1,1,1)	S(0,0,0)	S(1,1,1)	S(0,0,0)	S(1,1,1)
	τ=-1	S(0,0,1)	S(1,0,1)	S(1,0,0)	S(1,1,0)	S(0,1,0)	S(0,1,1)

Figure 3.2: LookUp Table for DTC

CHAPTER 4

Predictive Torque Control

Predictive control in general can be divided in 2 steps as an algorithm:

1. Prediction of control variables
2. Optimization of the cost function

But while applying to torque control as a PTC algorithm it can be divided into 3 steps:

1. Estimation of the unmeasured variables for the present step i.e. estimation of stator and rotor flux
2. Prediction of control variables for the next step. The variables include stator flux and electromagnetic torque. And additionally stator current in order to predict electromagnetic torque
3. Cost function optimization.

The reason for addition of one step in PTC is the inability to measure stator and rotor flux. Hence estimation of these variables is required and this is done by the same methodology used in DTC.

The PTC algorithm can in general be described as seen in the flowchart in fig 4.1 And its architecture is described as in fig 4.2 . For speed control the usual method of PI-controller is used same as the one used in DTC.

The 3 steps of the algorithm are described in the subsequent sections.

4.1 Flux Estimation

As explained earlier an estimation of stator flux and rotor flux at the present sampling step k is required. This is done by again considering the induction machine mathematical model equations which was discussed in the earlier section.

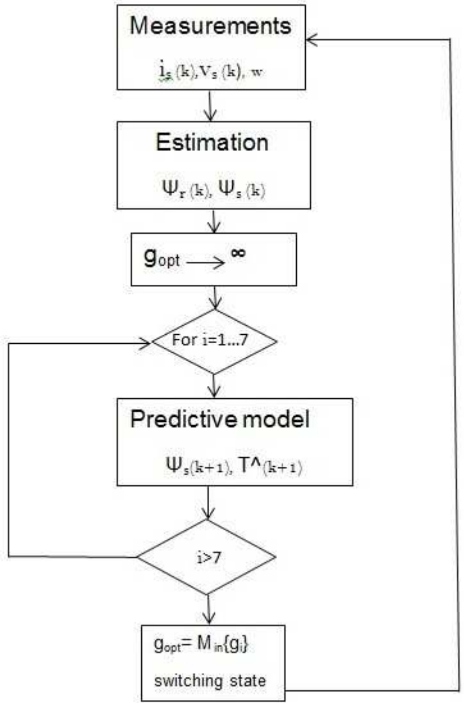

Figure 4.1: Flow Chart for the PTC algorithm

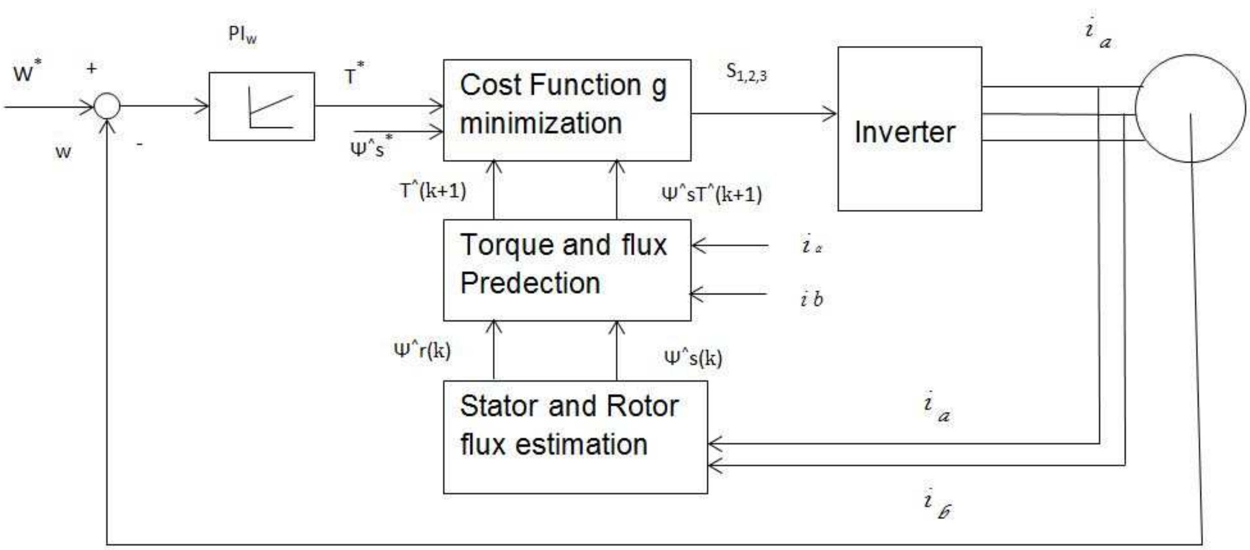

Figure 4.2: Block Diagram of PTC

Consider the rotor and stator flux equations:

$$\vec{\psi_r} + \tau_r.\frac{d\vec{\psi_r}}{dt} = L_m.\vec{i_s} \tag{4.1}$$

$$\vec{\psi_s} = L_m.(\frac{\vec{\psi_r} - L_m.\vec{i_s}}{L_r}) + L_s.\vec{i_s} \tag{4.2}$$

The above equations are discretized using Euler backward approximation:

$$\frac{dx}{dt} \approx \frac{x(k) - x(k-1)}{T_s} \tag{4.3}$$

Thus the discrete equation for rotor flux is:

$$\vec{\hat{\psi}}_r(k) = \frac{L_r}{L_r + T_s.R_r}.\vec{\hat{\psi}}_r(k-1) + \frac{L_m}{\tau_r/T_s + 1}.\vec{i_s}(k) \tag{4.4}$$

Upon substitution of eqn 4.4 into eqn 4.2 we get:

$$\vec{\hat{\psi}}_s(k) = k_r.\vec{\hat{\psi}}_r(k) + \sigma.L_s.\vec{i_s}(k) \tag{4.5}$$

4.2 Stator Flux and Electromagnetic Torque Prediction

Stator flux and electromagnetic torque being the control variables for the induction machine system are to be predicted at the next sampling step k+1. Again from the mathematical model equations of induction machine discussed earlier the relationship between the stator flux, rotor flux, current, speed can be described as:

$$\vec{i_s} = 1/R_\sigma(L_\sigma.\frac{d\vec{\psi_s}}{dt} - k_r.(1/\tau_r - j.\omega).\vec{\psi_r} - \vec{v_s}) \tag{4.6}$$

where $R_\sigma = R_s + k_r^2.R_r$ and $L_\sigma = \sigma.L_s$

To predict the electromagnetic torque and stator flux forward Euler discretization is followed:

$$\frac{dx}{dt} \approx \frac{x(k+1) - x(k)}{T_s} \tag{4.7}$$

The stator flux can now be predicted as:

$$\vec{\hat{\psi}}_s(k+1) = \vec{\hat{\psi}}_s(k) + T_s.\vec{v_s}(k) - R_s.T_s.\vec{i_s}(k). \tag{4.8}$$

And the prediction of stator current is:

$$\vec{\hat{i}}_s(k+1) = (1 + \frac{T_s}{\tau_\sigma}).\vec{i_s}(k) + \frac{T_s}{\tau_\sigma + T_s}.[\frac{1}{R_\sigma}.((\frac{k_r}{\tau_r} - j.k_r.\omega).\vec{\hat{\psi}}_r(k) + \vec{v_s}(k))] \tag{4.9}$$

where $\tau_\sigma = \sigma.\tau_s$

Now since we have predicted stator flux and current, torque is predicted as:

$$\hat{T}(k+1) = \frac{3}{2}.p.Im[\vec{\hat{\psi}}_s(k+1)^*.\vec{\hat{i}}_s(k+1)] \tag{4.10}$$

4.3 Cost Function Optimization

The final step of the algorithm is to develop an appropriate cost function to optimize. The cost function is very flexible and can handle multi-variable problem. It is designed with respect to the control objective that is to control electromagnetic torque and stator flux. Thus the cost function includes these two components:

$$g_i = |T^* - \hat{T}(k+1)_i| + \lambda.|\|\vec{\psi_s}^*\| - \|\vec{\psi_s}(k+1)_i\||| \tag{4.11}$$

where *i* denotes the index of the applied voltage vector for the prediction, i.e. *i*=1,2,.,8 for each of the 8 different switching states.

The torque reference T^* is the output of the speed PI-controller. Λ is the weighting factor which represents the relative importance of the electromagnetic torque control to the flux control. But typically equal importance is given and then the coefficient is chosen as $\Lambda = \frac{T_{nom}}{|\vec{\psi}_{nom}|}$

CHAPTER 5

Simulation results and analysis on Comparative Study

Both the strategies were simulated using MATLAB/SIMULINK to do a comparative study.

Table 5.1 gives the parameters used for simulation

Table 5.1: Parameters Used For Simulation for comparative study of DTC and PTC

Parameter	Value
p	1
J	0.062 Kg/m^2
Lm	291.1 mH
Ls	301 mH
Lr	301 mH
Rs	2.65 Ω
Rr	2.24 Ω
Ts	$100 * 10^{-6} s$
ψ_{nom}	0.71 Wb
T_{nom}	12 Nm

Figures 5.1 and 5.2 shows the voltage output of the inverter model of PTC and DTC respectively. A close up comparative figure of the voltage output is shown in FIGURE 5.3 at a particular transient state. As expected DTC has lesser number of switching than PTC.

FIGURE 5.4 shows stator currents, torque, speed and stator flux in sequence of PTC. Similarly Figure 5.5 shows that of DTC. A comparative plot is shown in figure 5.6.

There is a speed reversal happening at 1.2 sec. Since DTC has less number of commutations compared to PTC it has higher distortions in stator current and higher ripple in torque.

In DTC, torque and flux hysteresis controllers are essential and these controllers are to be tuned to obtain better results. It is essential to estimate the stator flux angle for the algorithm and the accuracy of the control implementation will be affected by incorrect

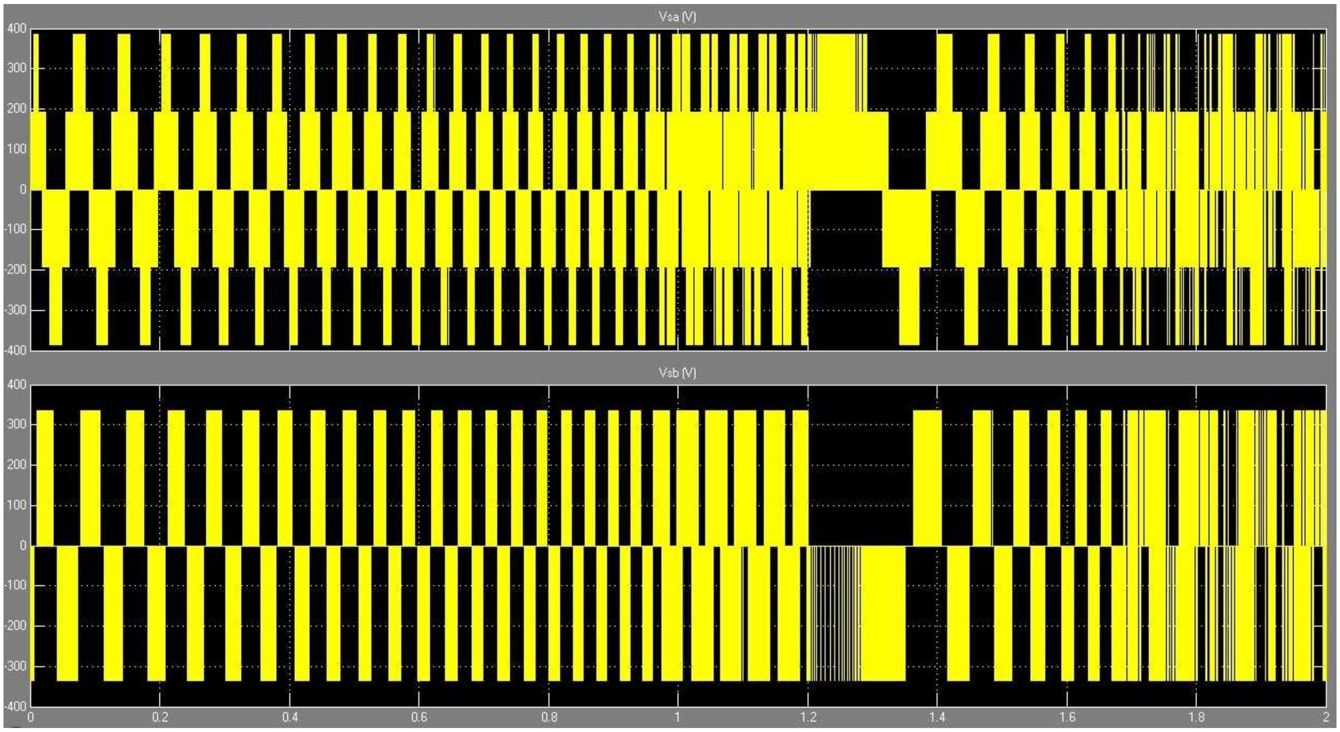

Figure 5.1: Voltage output of inverter for PTC

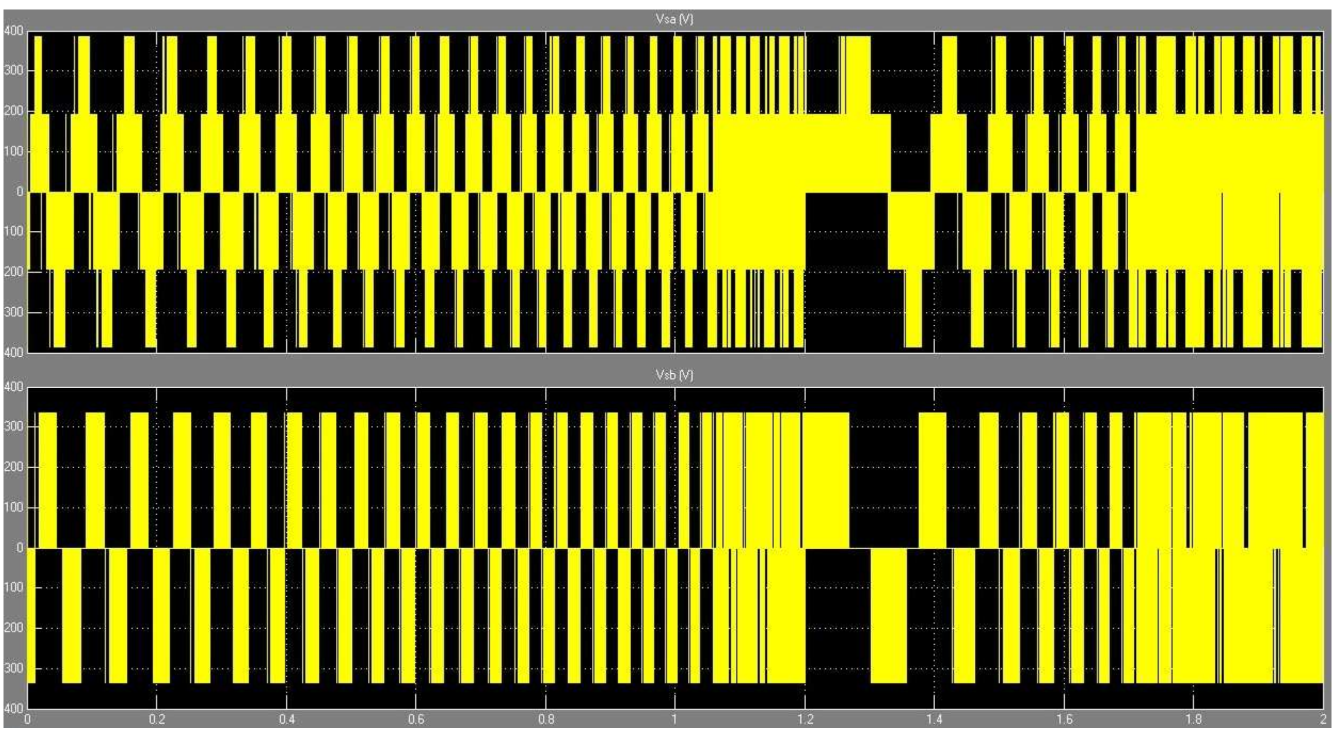

Figure 5.2: Voltage output of inverter for DTC

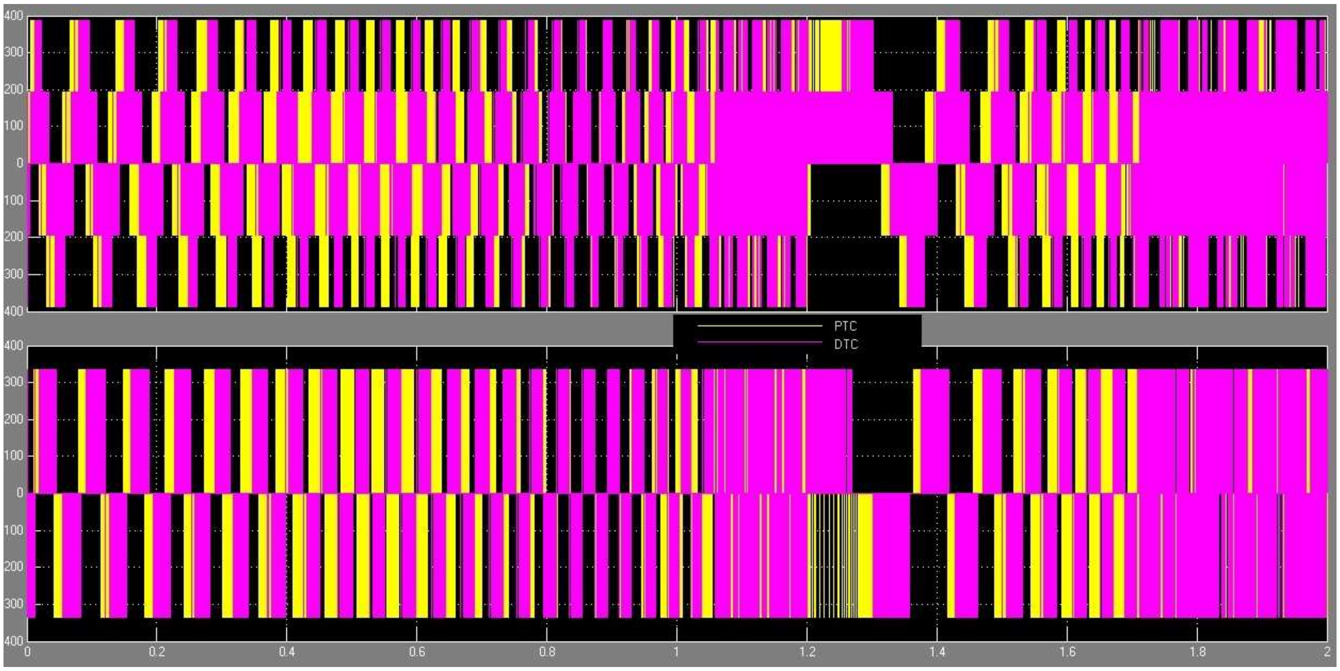

Figure 5.3: Voltage output of inverter for both PTC and DTC

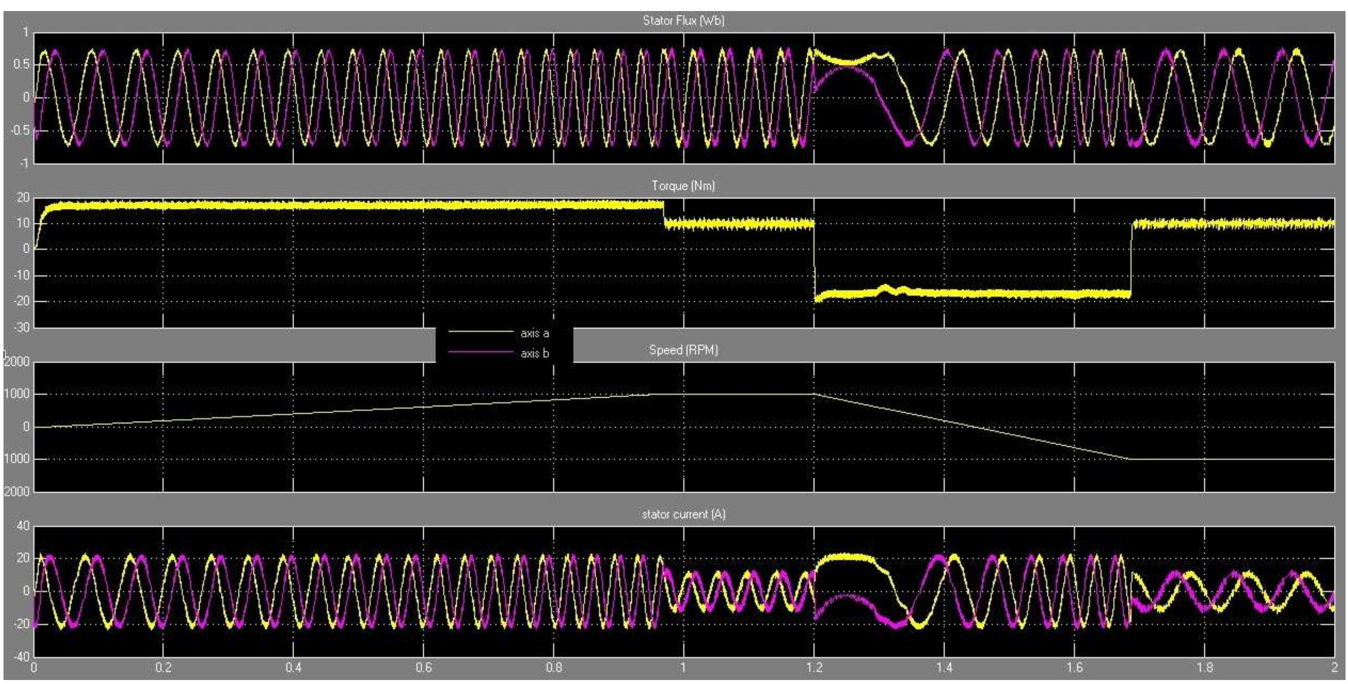

Figure 5.4: Simulink output for PTC

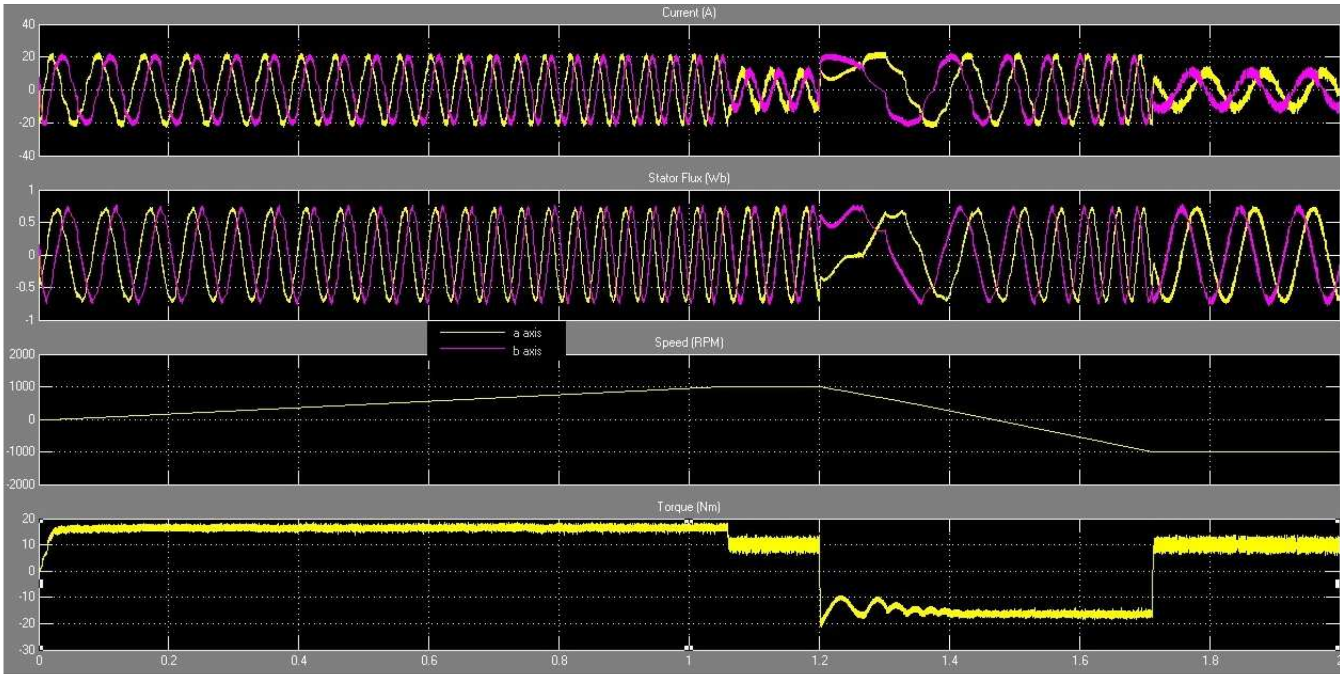

Figure 5.5: Simulink output for DTC

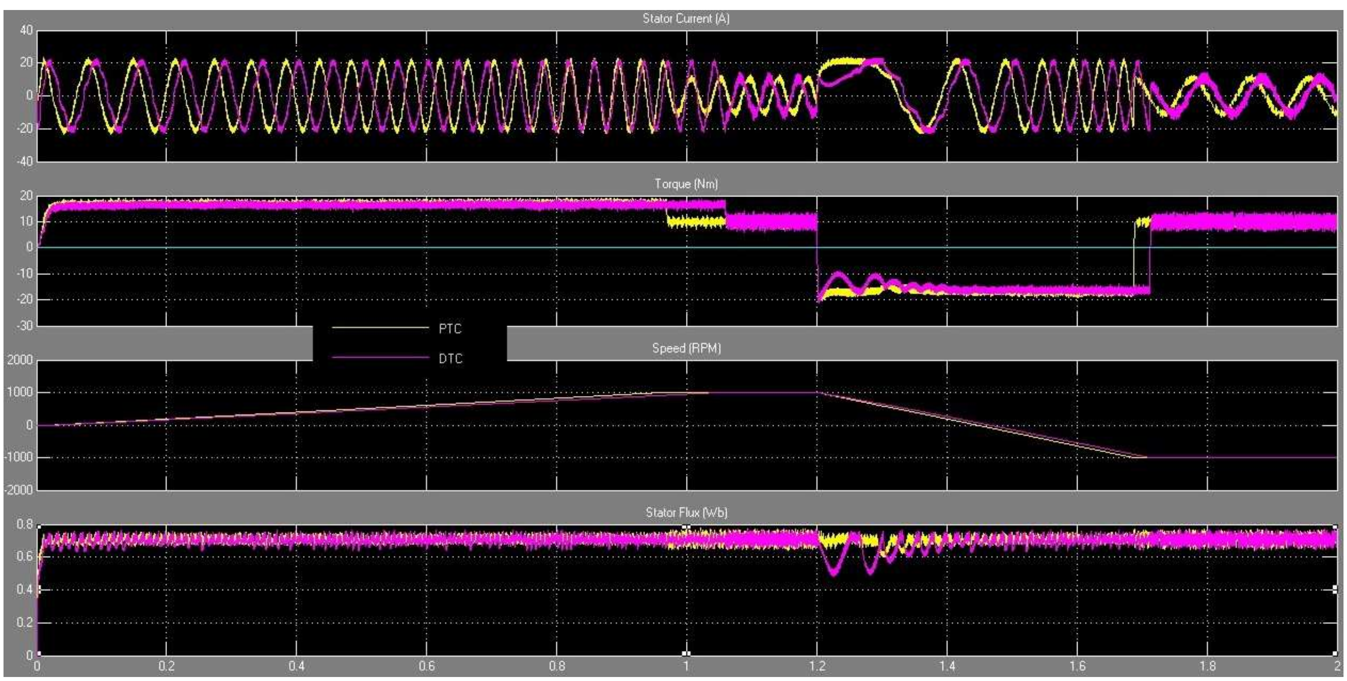

Figure 5.6: Simulink output for PTC and DTC for comparision

estimation of this variable. If this algorithm is implemented on hardware in order to avoid damage of the machine current limitation has to be implemented. One has only one option to choose a zero voltage vector when over-current is passing to the motor which does not allow for any optimization for over current protection.

In PTC there is only one parameter to deal with i.e. weighting factor of the cost function. Thus compared to DTC implementation PTC implementation is much easier. Another advantage is to avoid estimation of stator flux angle. Optimization for over current protection can be easily done by introducing this factor in the cost function. Then the vector which produces over-current can be avoided besides still optimizing the control variable errors.

CHAPTER 6

Improvements in PTC

Simulation of the PTC with the previous mentioned strategy was implemented using

Simulink by taking into consideration the original Induction machine parameters. This was implemented so as to get a close enough results for when implemented on hardware.

This simulation also takes into consideration the time delay compensation which is explained in the subsequent subsection.

6.1 Time Delay Compensation

Time delay compensation in reality is not necessary since the machine and inverter are mathematical modeled. The voltage vector chosen can be applied to the machine model at the same instant when the stator current and speed are measured. However this is not the case during the real implementation. This is as a consequence of the time taken by the microprocessor to execute the PTC algorithm. As it is the calculation time involved in PTC is the highest when compared to other methodologies. Thus during hardware implementation time delay compensation is required.

Nevertheless this compensation strategy is also applied during the simulation to study the results when this strategy is applied. The strategy explanation is as follows: It takes one sampling cycle to generate the optimum switching state if the variables are measured at time k. Thus, the optimum actuating variables are given to the inverter at the time step k+1 and not at step k. To compensate for this delay this compensation strategy is used which is shown in FIGURE 6.1. The previous voltage vector is used for the next prediction, i.e. the present voltage vector $V_s(k)$ is used to predict the stator flux and torque at time k+1. According to these values the controller selects the proper vector which will be applied at time k+1 in order to optimize the reference tracking criterion at time k+2. This ensures that the control strategy is time-consistent.

The equations used in Simulink for the time delay compensation is given below: $Kr = Lm/Lr;$

$Tr = Lr/Rr;$

$Rsigma = Rs + ((Lm/Lr)^2) * Rr;$

$sigma = 1 - (((Lm)^2)/(Lr * Ls));$

$Tsigma = (sigma * Ls)/(Rsigma);$

$x = Tsigma/(Tsigma + Tptc);$

$y = Tptc/(Rsigma * (Tsigma + Tptc));$

$z = Kr * Tptc/(Rsigma * (Tsigma + Tptc));$

$w - el = p * w;$

Time Delay Compensation

Stator Currrent Prediction

$Isk1a = x * Iska + y * v - old(1) + (z/Tr) * Psi - r(1) + z * w - el * Psi - r(2);$

$Isk1b = x * Iskb + y * v - old(2) + (z/Tr) * Psi - r(2) - z * w - el * Psi - r(1);$

Stator Flux Prediction

$Psi - s = Psi - s + Tptc * v - old - Rs * Tptc * [Isk1a; Isk1b];$

Rotor Flux Estimation

$Psi - r = (Lr/Lm) * Psi - s + (Lm - Lr * Ls/Lm) * [Isk1a; Isk1b];$

Where all the parameters used are described earlier and Isk1a, Isk1b is the stator current vector, v-old is the stator voltage vector for the previous step. Psi is flux vector with s for stator and r for rotor.

After this time delay compensation the rest of the strategy is same as before with stator current, torque, flux prediction and cost function optimization.

A particular mention on how the voltage vectors are chosen is necessary. There are 8 possible switching states for the inverter and each switching state is stored in a vector S. For example S(1) corresponds to [0 0 0] vector state and S(7)corresponds to [1 1 0] vector state. Note the indexing difference for Matlab. Corresponding to each

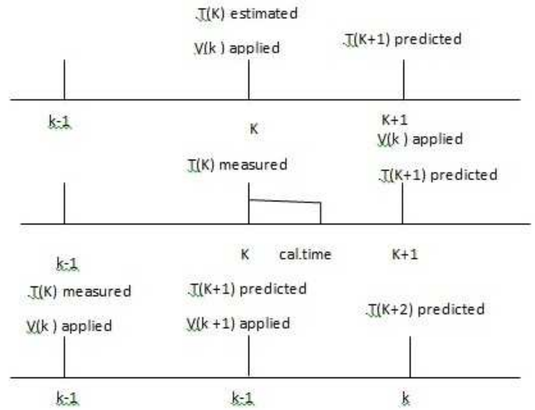

Figure 6.1: Time Delay Compensation

of this state 2 stator voltage vectors Vsa, Vsb for each axis are formed according to the relation:

$$Vsa = (2/3) * 520 * (s1 - 0.5 * s2 - 0.5 * s3);$$

$$Vsb = (2/3) * 520 * ((sqrt(3)/2) * s2 - (sqrt(3)/2) * s3);$$

Where s1, s2, s3 form a vector of S. After the Vsa and Vsb vectors are formed using the appropriate index one can access the stator voltage for prediction calculations.

As mentioned in chapter 4.3 cost optimization takes 8 different calculations for each switching state and chooses the best state for that sampling step. However on observation the switching states [0 0 0] and [1 1 1] produce the same voltage vector thus making this switching state redundant for calculation. Thus a slight modification is made by considering on 7 switching states. There is no huge reduction in the calculation time by adopting this but redundancy in calculation is avoided along with a slight reduction in calculation time.

Further calculation of total number of switching in all the three switches is added to calculate the average switching frequency. Average is considered since for PTC switching frequency is variable.

6.2 Reduced Switching Frequency

One of the drawbacks of PTC methodology is that it involves lot of switching actions. This creates a lot of power dissipation in the power electronic circuitry and effective heat sinks are to be used. This also reduces efficiency and power losses. Thus it is better to formulate strategies to reduce the total number of switching. Another drawback is the calculation time required to implement the algorithm. As it can be seen clearly within one step there are quite a few complicated calculations and 7 such calculations has to be done in a single iteration of the algorithm. Thus it would be an advantage to develop a method which attempts to reduce the calculation time by reducing the number of calculations

For this purpose a new methodology has been implemented which gives the advantage of reducing average switching frequency and reducing the calculation time simultaneously.

Table 6.1: Parameters Used For Simulation

Parameter	Value
p	1
J	0.062 Kg/m^2
Lm	275.1 mH
Ls	283.4 mH
Lr	283.4 mH
Rs	2.6827 Ω
Rr	2.1290 Ω
Ts	$60 * 10^{-6}s$
ψ_{nom}	0.71 Wb
T_{nom}	20 Nm

The idea behind this method is as follows: From a present switching state allow only one of the 4 more switching states for the next step instead of 8 possible ones. From the present state allow a state which can be reached with just 1 or 0 switching. For example if the present state is [1 1 0] allow the next change to be one of [1 1 1] or [1 0 0] or [0 1 0] or [1 1 0] itself. Thus out of the four possible states choose the one which optimizes the cost function.

Thus it is trivial that by allowing only 4 possible states we are nearly reducing the calculation effort to half and by allowing only one transistor to switch we are reducing the total number of switching and hence average switching frequency.

It has to be noted that however this methodology might introduce distortions in stator currents and ripple in torque. And the settling time might also increase. But the torque will surely converge to the reference value, since we can access every 8 states of the inverter even though allowing only 4 states.

This strategy bring about one change in the code that we have to consider all 8 switching states in vector S if not it will affect the overall convergence. The reason is straightforward that even though [0 0 0] and [1 1 1] produce same voltage vectors, the states are different and it affects the accessibility.

The parameters for the machine are given in table 6.1.

CHAPTER 7

Simulation Results and Analysis Of PTC

A load torque of 4 Nm is given as a step with 0.5 sec as the step time. An external PI controller for speed control and to generate torque reference is used. The speed reference to PI controller is 100 rad/s. Sampling time for the algorithm $Tsim = 60 * 10^-6$. Nominal Torque Tnom is 20 Nm and nominal flux is 0.71Wb. Thus λ is 28.17.

The results are discussed for both strategies i.e. Normal PTC (NPTC) and Reduced Switching PTC (RSPTC).

The stator currents for NPTC are shown in FIGURE 7.1 there are two current waveforms each for one axis. Similarly stator currents for RSPTC are shown in FIGURE 7.2. FIGURE 7.3 shows the torque, flux and speed characteristics of NPTC and FIGURE 7.4 shows that of RSPTC. Comparative study figure is shown in FIGURE 7.5, comparing torque, flux and stator current of one axis. One can observe a slight increase in the ripple of the torque of RSPTC but the transient response and steady state response is same. Thus the performance of RSPTC has not been compromised. Next parameter to be scrutinized is the total number of switching. NPTC has around 12000 switching states in 2 seconds of simulation. Thus the average switching frequency is around 6 KHz whereas for RSPTC the number is around 8200 which implies average switching frequency is around 4.1 KHz. Few switching states at a particular instant were observed during the transient times to verify the difference in switching in the matlab command window.

The difference in the switching states is evident from the below given data. The conclusion of reduced number of switchings can also be drawn from observing FIGURES 7.6 and 7.7 which show the switching states of NPTC and RSPTC respectively.

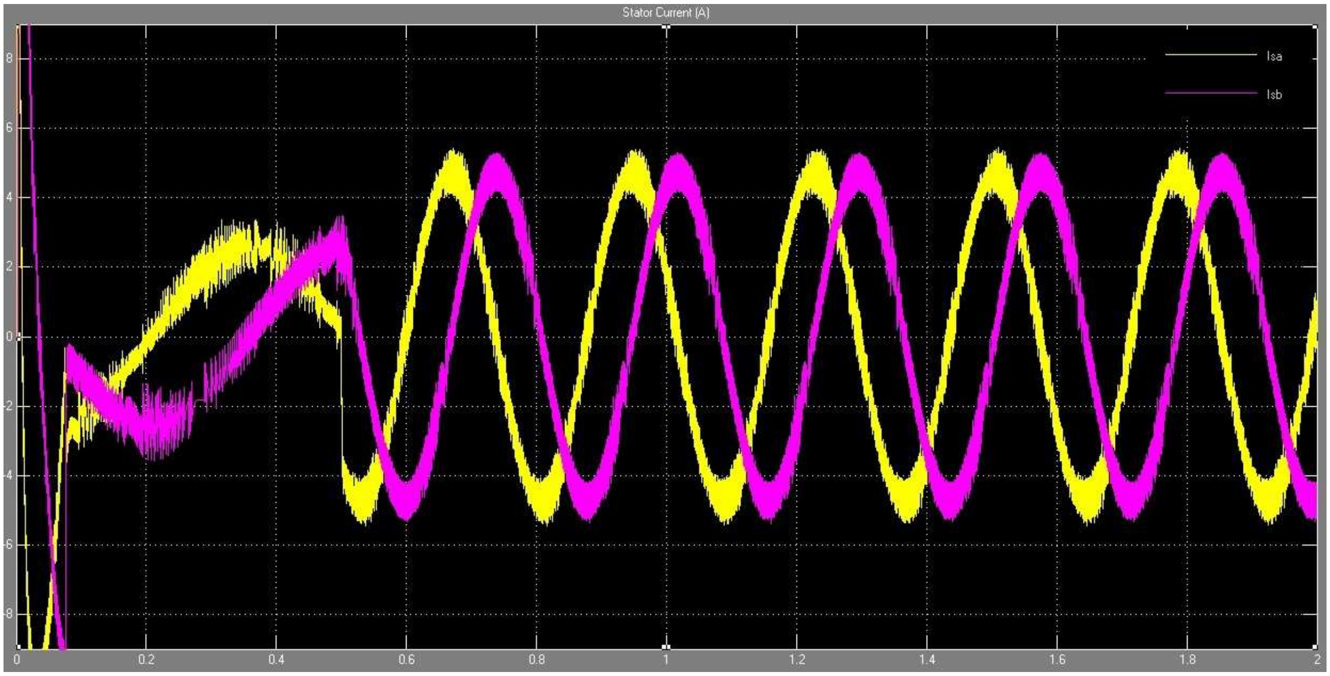

Figure 7.1: Stator Current for NPTC

Switching Sequence for RSPTC:

$$\begin{bmatrix} 0.0716 & 1.0000 & 0 & 0 \\ 0.0717 & 0 & 0 & 0 \\ 0.0718 & 0 & 0 & 0 \\ 0.0719 & 0 & 0 & 0 \\ 0.0720 & 0 & 0 & 0 \end{bmatrix},$$

Switching Sequence for NPTC:

$$\begin{bmatrix} 0.0716 & 0 & 0 & 1.0000 \\ 0.0717 & 0 & 0 & 0 \\ 0.0718 & 0 & 0 & 0 \\ 0.0719 & 1.0000 & 0 & 1.0000 \\ 0.0720 & 0 & 0 & 0 \end{bmatrix},$$

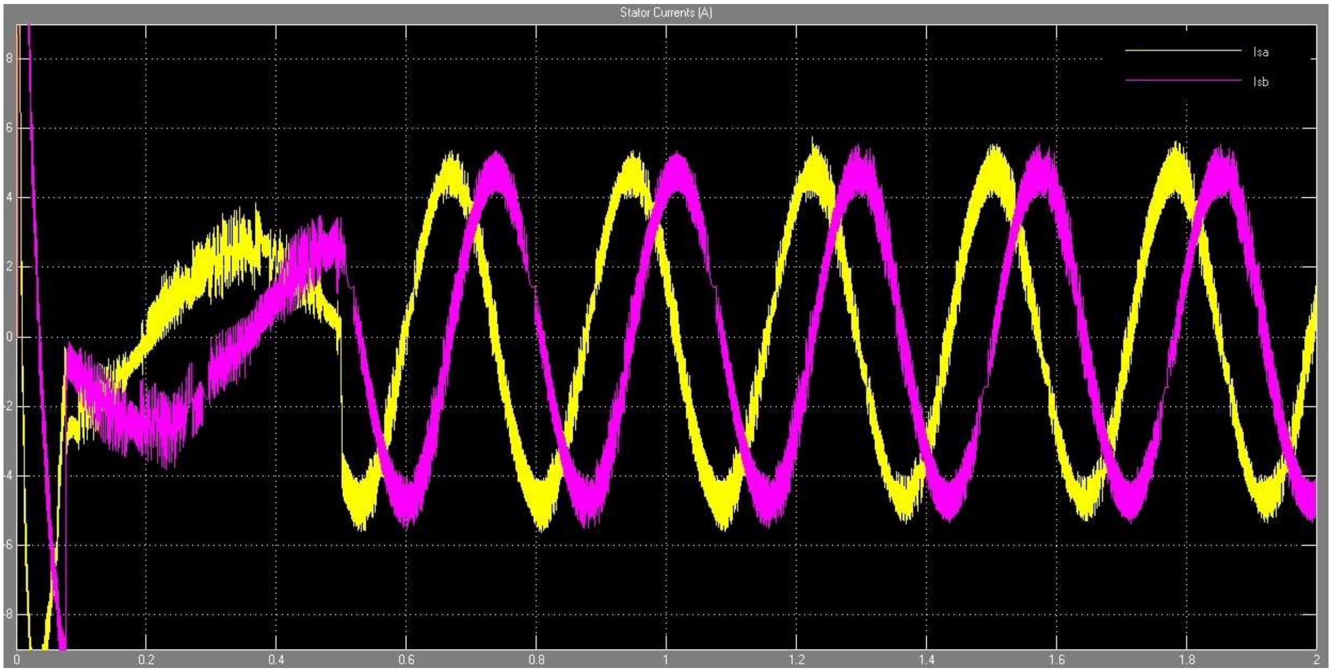

Figure 7.2: Stator Current for RSPTC

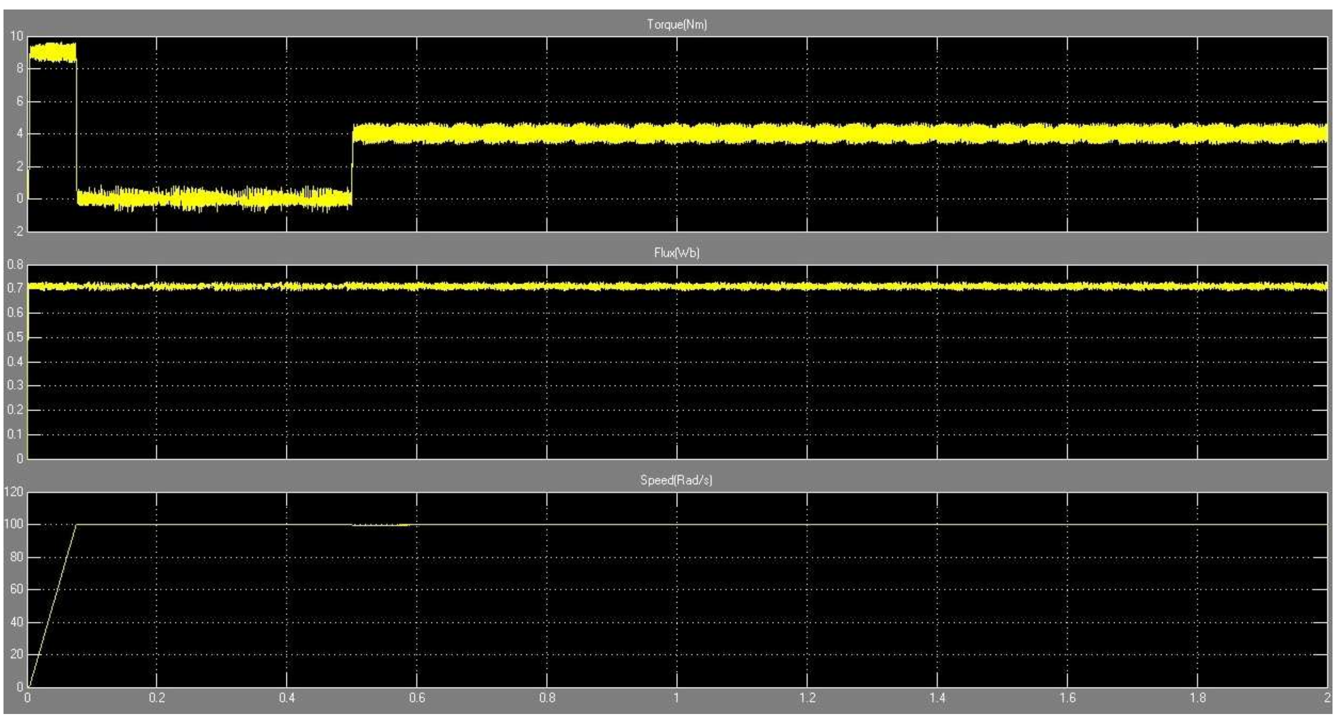

Figure 7.3: Torque,Flux and Speed Characteristics for NPTC

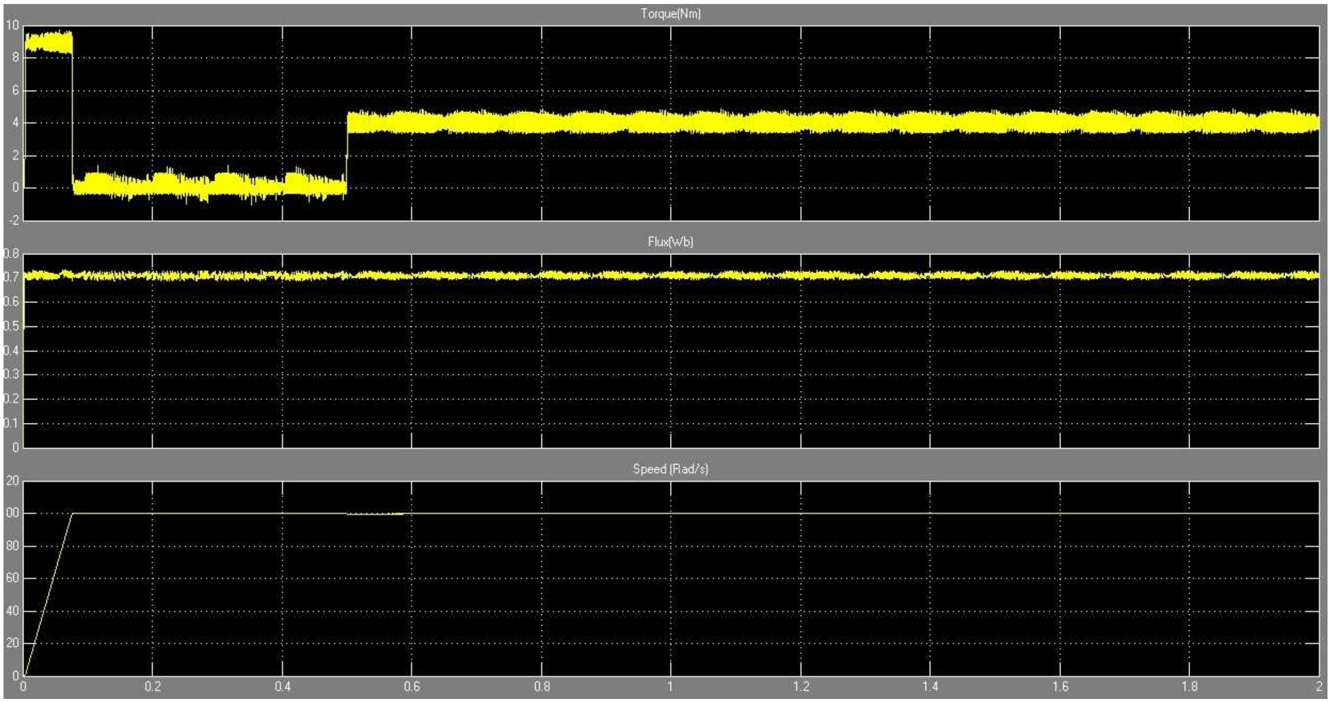

Figure 7.4: Torque,Flux and Speed Characteristics for RSPTC

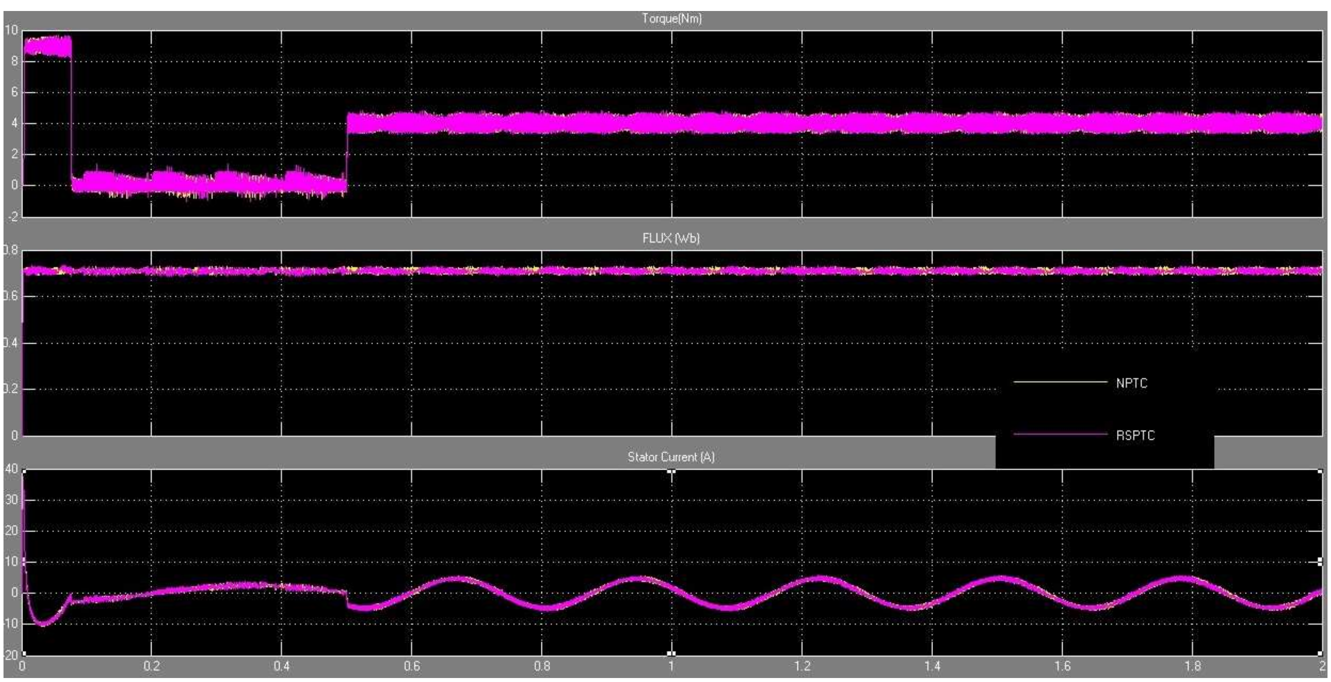

Figure 7.5: Torque,Flux and Speed Characteristics comparision

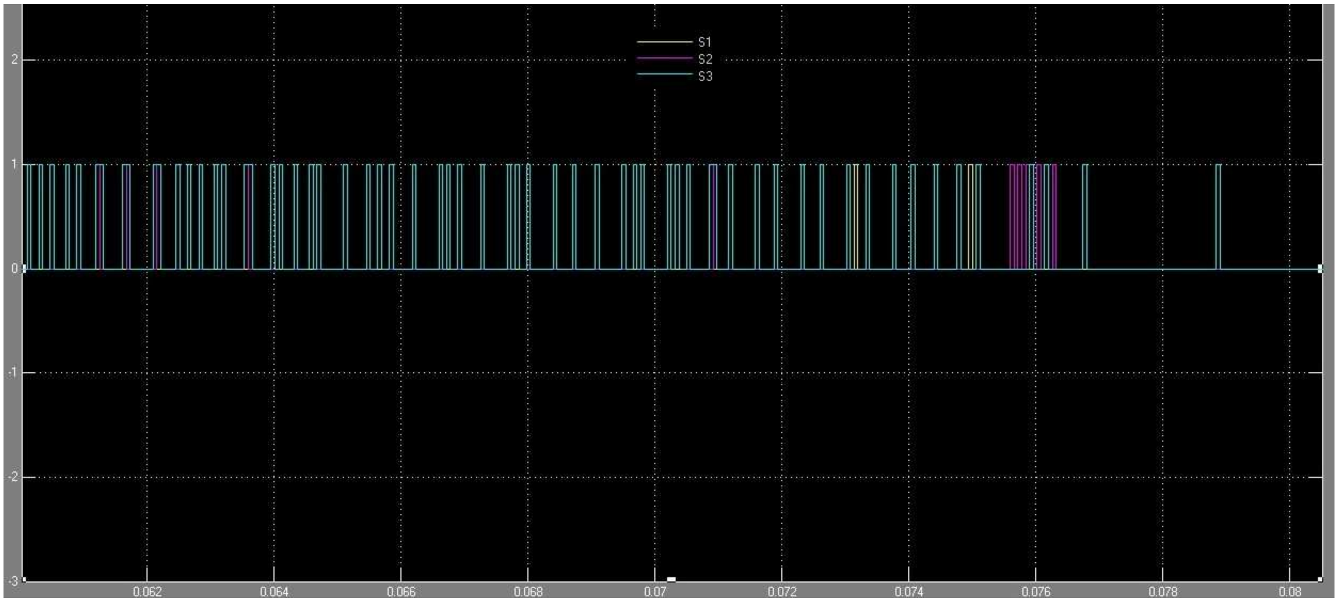

Figure 7.6: Switching Seqence of NPTC

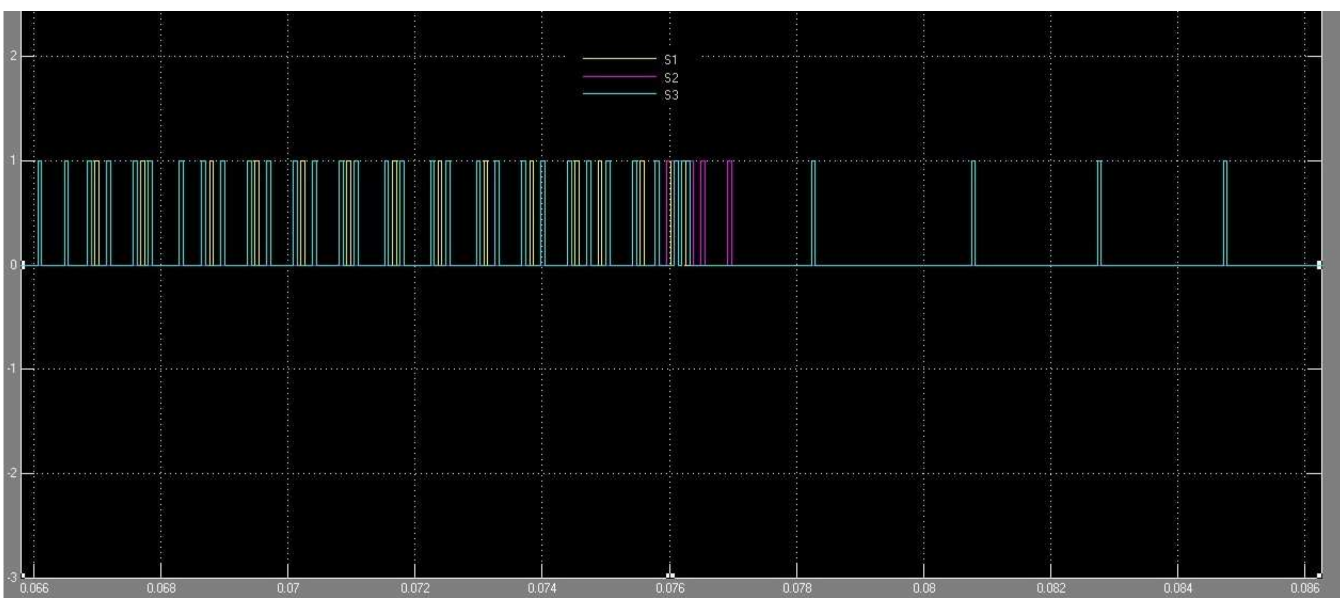

Figure 7.7: Switching Seqence of RSPTC

CHAPTER 8

Hardware Implementation

Both the algorithms of PTC have been tested on an experimental test bench. It is a real time system. This test bench has been setup in the Institute for Electrical Drive Systems and Power Electronics of the Technical University of Munich. It consists of a computer system connected to an industrial inverter through PWM cards and ADCâĂŹs.

This test bench consists of two 2.2kW squirrel-cage induction machines. One machine is connected through a Danfoss VLT FC-302 3kW inverter and is used as a load machine. The other one is the machine which the user controls by a modified SERVOSTAR 620 14kVA inverter. This inverter is modified so as to access the gate terminals of the IGBTâĂŹs. The terminals are connected through PWM card to the self - made 1.4GHz computer system [3]. A 1024 points incremental encoder is used for measuring the rotor speed. The parameters of the main motor are given in Table 8.1.

Table 8.1: Parameters of The Induction Machine

Parameter	Value
DC link voltage V_{dc}	582 V
p	1
J	0.005 Kg/m^2
Lm	275.1 mH
Ls	283.4 mH
Lr	283.4 mH
Rs	2.68 Ω
Rr	2.13 Ω
Ts	$60 * 10^{-6} s$
ω_{nom}	2772 RPM
T_{nom}	7.5 Nm

The PTC and Reduced Switching PTC algorithm was loaded on the RTS and implemented on the test bench. PI controller was mathematically modeled for speed control. Over current protection is given by the usual method with optimization. Through push button one can reverse the speed of the load machine instantly. The response of the

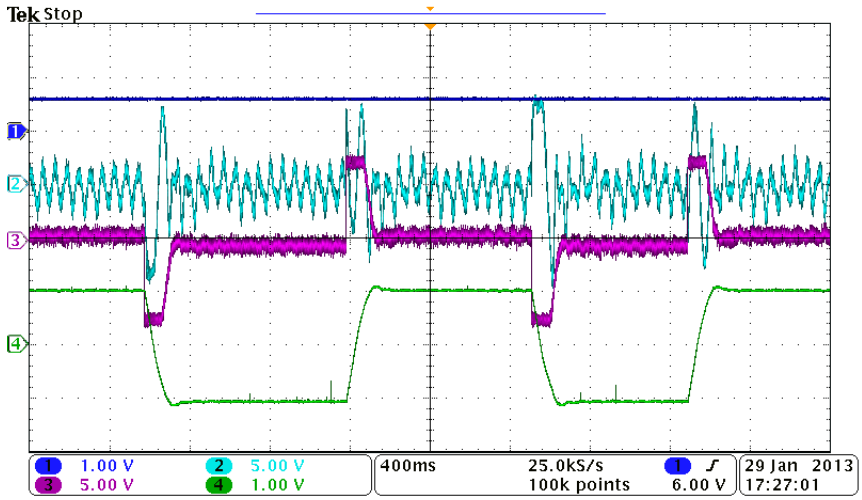

Figure 8.1: Oscilloscope output for NPTC

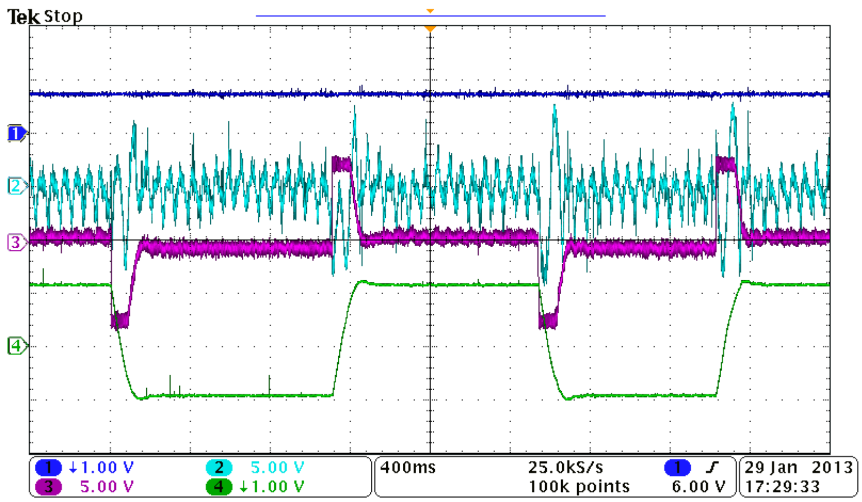

Figure 8.2: Oscilloscope output for RSPTC

machine by measuring the stator current, torque and speed is observed through and oscilloscope. The output of the oscilloscope is saved as an image file. Figure 8.1 and 8.2 shows the image of the output on the oscilloscope for NPTC and RSPTC respectively.

Channel 1 show that the controller is on. Channel 2 gives the stator current. Channel 3 depicts the torque characteristics and Channel 4 shows the rotor speed. The load torque is 7 Nm and rotor speed is switched from 2600 rpm to -2600 rpm.

It can be seen from the figures that the distortion in current waveform is more in RSPTC. The average switching frequency for NPTC is about 9 KHz and that of RSPTC is about 7.5 KHz. The response to speed reversal is similar in both cases. Thus proving that the Reduced Switching strategy is a better option to reduce switching losses and reduce calculation time.

CHAPTER 9

Conclusions

Predictive Control has proved as a very strong alternative in the field of Power Electronics and drives,especially Predictive Torque Control which is conceptually different strategy from traditional methods like FOC and DTC.

In this study, PTC strategy has been extensively studied. A comparative study with respect to DTC has been done. The performance of PTC was found better than DTC in certain aspects like simplicity of algorithm, lesser number of parameters to deal with and the ease of introducing current over protection.PTC has less implementation issues and the torque ripple produced using PTC is less compared to that of DTC.

The main disadvantage of PTC when compared to DTC is its computational effort. The calculation time necessary for implementing the algorithm is higher due to the presence of higher level of calculations and also higher number. But this has been proved less of a disadvantage due to the continuous development in the field of microprocessors. With the advent of high speed devices like FPGA's and DSP's higher sampling frequency operation of PTC is becoming possible.

An attempt was made to improve certain issues faced while hardware implementation of PTC. The issues being time delay and very high average switching frequency of IGBT's. To remedy these issues a compensation for the time delay and method for reduced number of switching was introduced in this study . Simulation study was first done to verify this improvement.

The improved strategy has then been verified on an experimental test bench. There was a considerable decrease in the average switching frequency of the switches and additionally this alternative method reduced the calculation time. The control performance was not affected as verified from the experimental results.

The results obtained in this study encourages to pursue research to develop more efficient PTC strategies especially on the cost function. It is interesting to modify the cost function to consider more than two control variables. This introduces the question of finding a formal method to find the weighting factor. The answer to this question finds an important application in sensor-less technologies i.e. avoiding the external speed PI-controller. It is to be pointed out that at present this work is being carried out in the lab, to develop PTC for sensor-less systems.

Simulations on the application of PTC to PMSM have also been carried out but are not presented in this study.

Implementation of this strategy on DSP is a very interesting challenge. It is always useful to have a stand alone system which finds many applications in various industries. DSP implementation of PTC is the next step of this study and has been started in Institute for Electrical Drive Systems and Power Electronics, TUM.

CHAPTER 10

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