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Modified Predictive Torque Control Based Ripple Reduction in Permanent Magnet Synchronous Motor

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Abstract— **A Model Predictive Control (MPC) is an advanced method of process control that has been in use in the process industries. The proposed approach takes into account constraints on voltages and currents, and allows the use of modulation techniques that eliminate the side effects caused by the direct transistor actuation performed by Direct Torque Control (DTC) approaches. The performance of the proposed Model Predictive Control (MPC) is a very attractive solution for controlling power electronic converters. It uses MPTC strategy which is based on the discrete-time state-space model of the PMSM. The torque ripple and cogging torque produced by the stator slot harmonics is reduced through feed-forward compensation signals. Results show that the proposed approach is able to improve the torque dynamics with respect to a conventional controller, and that an embedded implementation is feasible in terms of required computational power and memory.**

Index Terms— **Model predictive control, direct torque control, PMSM, feed forward compensation, discrete-time state-space model.**

I. INTRODUCTION

MPC for power converters and drives can be considered as a well-established technology in the research and development stages. MPC is a family of controllers that explicitly uses the model of the system to be controlled. In general, MPC defines the control action by minimizing a cost function that describes the desired system behavior. This cost function compares the predicted system output with a reference. The predicted outputs are computed from the system model.

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The main idea of MPC is to obtain the control actions by solving at each sampling time a finite horizon optimal control problem based on a given prediction model of the controlled process and an estimation of its current state. At the cost of a relatively high on-line computational burden, it provides a coordinated operation of the available actuators to track multiple references and satisfy bounds on inputs, outputs, and states of the process. The classification of MPC strategies applied is shown in Figure 1.

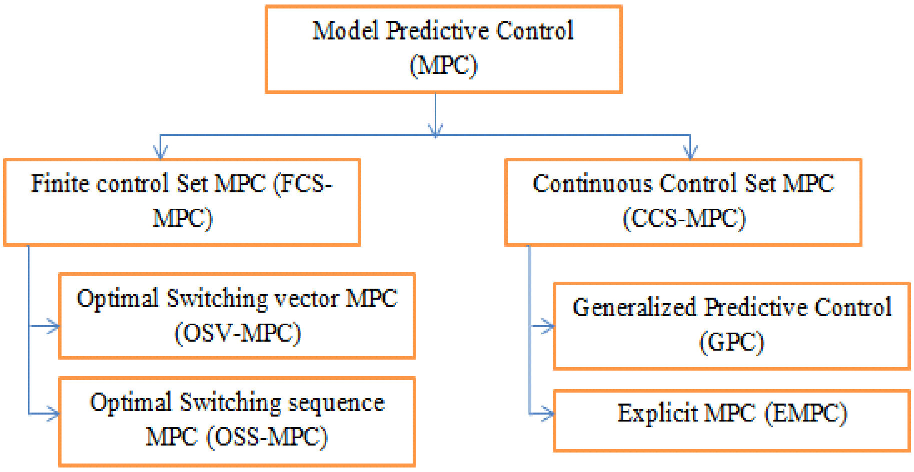

Fig. 1 Classification of MPC strategies applied to power converters and drives

The proposed method utilizes torque ripple reduction using MPTC for PMSM. High performance is achieved by speed of the motor. In recent years, the performance of MPC has been greatly improved by the use of this technique. With the combination of MPTC the torque ripple can be reduced to an acceptable extent, especially in the low speed range. It consists of torque and stator flux estimators, torque and flux hysteresis comparators, a switching table and a Voltage Source Inverter (VSI).

II. METHODS OF MPC

Several MPC methods have been successfully implemented for a variety of power electronic applications. MPC strategies solve an optimization problem in order to define the control signal to be applied to the system. The cost function represents the desired behavior for the system. The MPC methods are classified based on the type of the optimization problem. The modulation strategy can be any one that is valid for the converter topology under consideration.

a) Continuous Control Set MPC (CCS-MPC)

CCS-MPC computes a continuous control signal and then uses a modulator to generate the desired output voltage in the power converter.. The main advantage of CCS-MPC is that it produces a fixed switching frequency. The most-used CCS-MPC strategies for power electronic applications are Generalized Predictive Control (GPC) and Explicit MPC (EMPC). GPC is useful for linear and unconstrained problems. EMPC allows the user to work with non-linear and constrained systems. The main problem of GPC and EMPC when applied to power converters is that both present a complex formulation of the MPC problem.

b) Finite Control Set MPC (FCS-MPC)

FCS-MPC takes into account the discrete nature of the power converter to formulate the MPC algorithm and does not require an external modulator. FCS-MPC can be divided into two types:

1. Optimal Switching Vector MPC (OSV-MPC)
2. Optimal Switching Sequence MPC (OSS-MPC)

OSV-MPC is currently the most popular MPC strategy for power electronic applications. OSV-MPC was the first FCS-MPC technique used for power electronics. For this reason, it can be found in the literature referred to as FCS-MPC. The MPC strategy formulation very intuitive. The main disadvantage of OSV-MPC is that only one output voltage vector is applied during the complete switching period.

OSS-MPC solves this problem by considering a control set composed of a limited number of possible switching sequences per switching period. In this way, OSS-MPC takes the time into account as an additional decision variable, i.e., the instant the switches change state, which in a way resembles a modulator in the optimization problem.

III. MPTC FOR PMSM

The proposed torque ripple reduction using MPTC method for PMSM will achieve high performance based on speed of the motor. The proposed MPTC model for PMSM is shown in figure as follows.

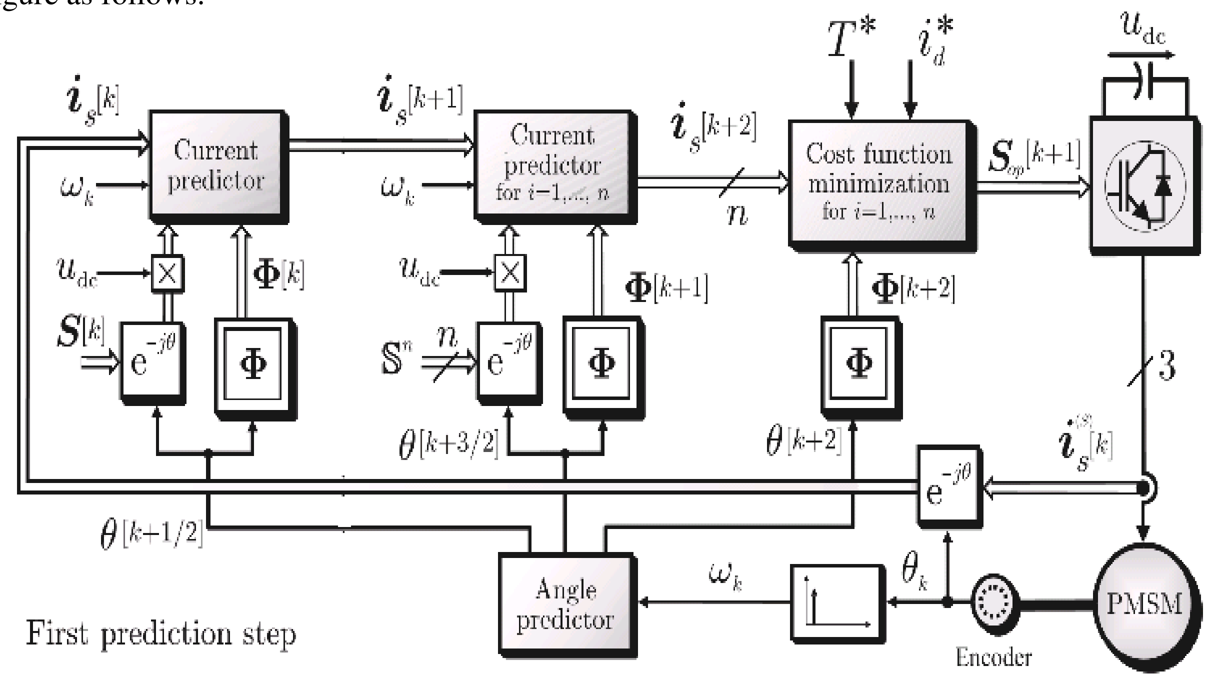

Fig. 2 MPTC scheme for PMSM

The proposed method, introduces a new control method based on an FCS-MPC controller. FCS means Finite Control Set, which is composed of nested loops. The external control loop is used to regulate the PMSM rotational speed using a conventional controller. An internal control loop, based on an FCS-MPC algorithm, directly regulates the torque and minimizes the torque ripple using a cost function based on the full model of the electromagnetic torque.

IV. MODEL OF CONVERTER

The representation of a 2L-VSI is shown in Fig. This converter is composed by a dc-voltage source and three half bridge units in the inverter stage. Each phase can be connected

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to the positive or negative terminal using the power switches of the corresponding half-bridge. The inverter switching states are determined by the gating signals S_x. For the 2L-VSI shown in Fig. , there are $2^3 = 8$ different switching states.

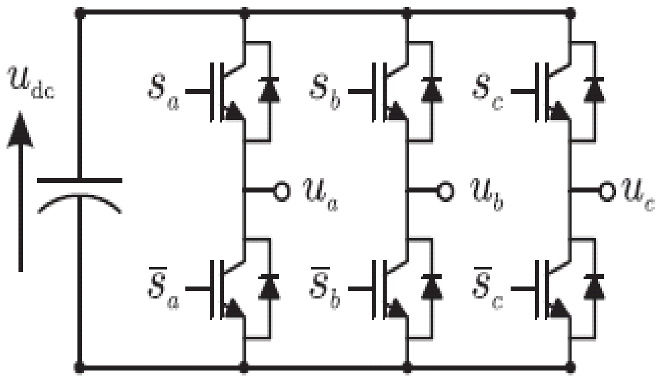

Fig. 3 2L-VSI: Topology

Using a vector notation, a given switching state can be written as equation given below which are represented in Fig.

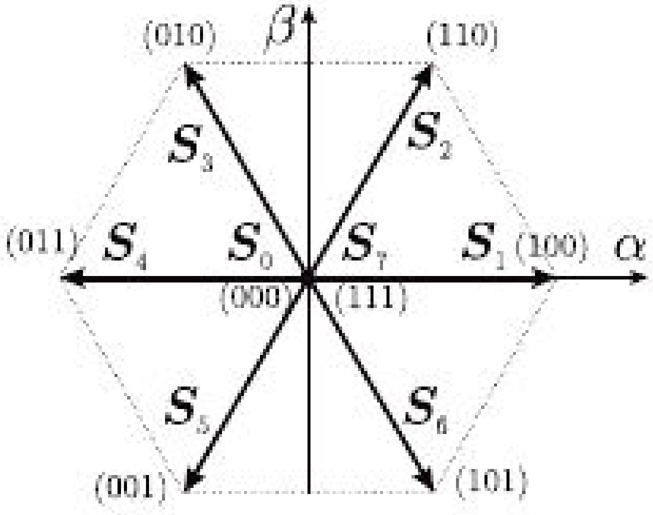

Fig. 4 Voltage vectors in α–β plane

Finally, the output voltage vector can be calculated as $u_s^{(S)} = u_{dc}$ S, where u_{dc} is the dclink voltage, and the superscript $^{(S)}$ denotes α–β coordinates referred to the stationary frame.

V. Compensation Techniques

a) Cogging Torque Compensation

Compensation of the cogging torque is proposed using a methodology based on a state observer and a feed-forward compensating signal. The proposed cogging torque compensation scheme is shown in figure, where MPTC is modeled as a 2*Ts* delay, whereas the cogging torque compensation is achieved using a feed-forward signal *T*FF. This signal is obtained using an

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observer and a look-up table, where information about the cogging torque, as a function of the rotor position angle is stored.

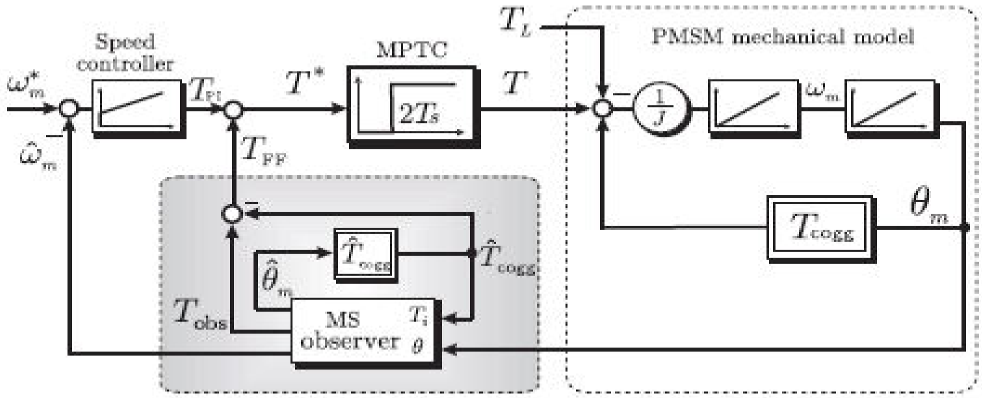

Fig. 5 Speed control scheme with hybrid cogging torque compensation

b) Closed Loop Observer

This closed-loop observer requires the quantized rotor position θ_m and the estimation of disturbances as inputs as shown in the Fig.

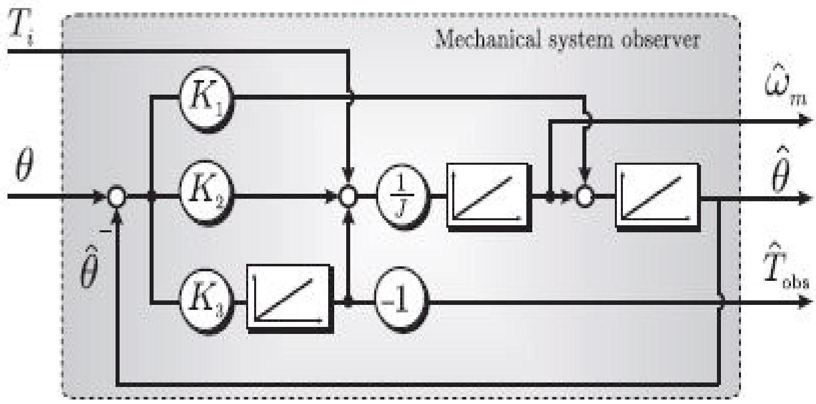

Fig. 6 Closed-loop MS observer

In the observer compensation method, $T_i = 0$ (see Fig.5.5) and, within the observer bandwidth, the observed torque is $\hat{T}_{obs} = -T_{cogg} + T_L - T$ whose value is used as the feedforward signal T_{FF}.

Finally, the cogging torque as a function of the rotor position is experimentally estimated by operating the machine in speed control mode and no-load condition. Thus the effect of $\mathbf{\Phi}(\theta)$ in the electromagnetic torque is neglected and oscillations in the torque are produced by the cogging torque. Thus, the oscillating torque, which is assumed equal to the slot torque $\hat{T}_{cogg}$ (θ), can be compensated by the speed controller output signal T_{PI} as shown. This tests the signal T_{FF} is disabled and the value of $\hat{T}_{cogg}$ is estimated from the output of the speed controller

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VI. EXPERIMENTAL RESULT

The MATLAB / Stimulant tool is used to simulate the results of MPC with designed building blocks as shown in figure.

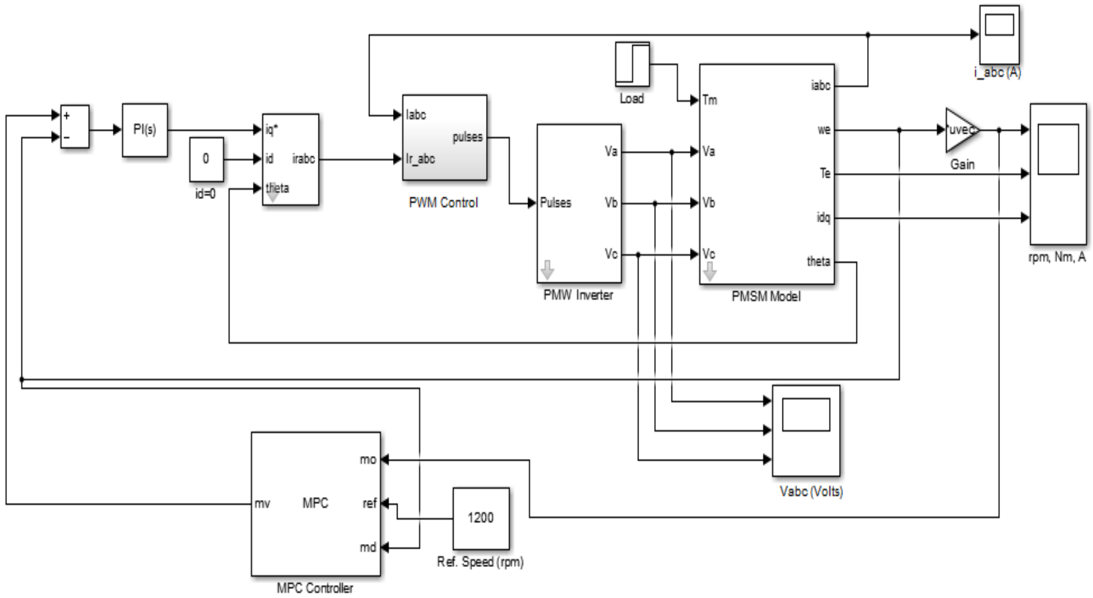

Fig. 7 Simulation Module for MPC

The simulation results displays three characteristics results namely,

a) Current Characteristics

The three phase sinusoidal current wave forms are obtained during MPC based PMSM as shown in Figure.

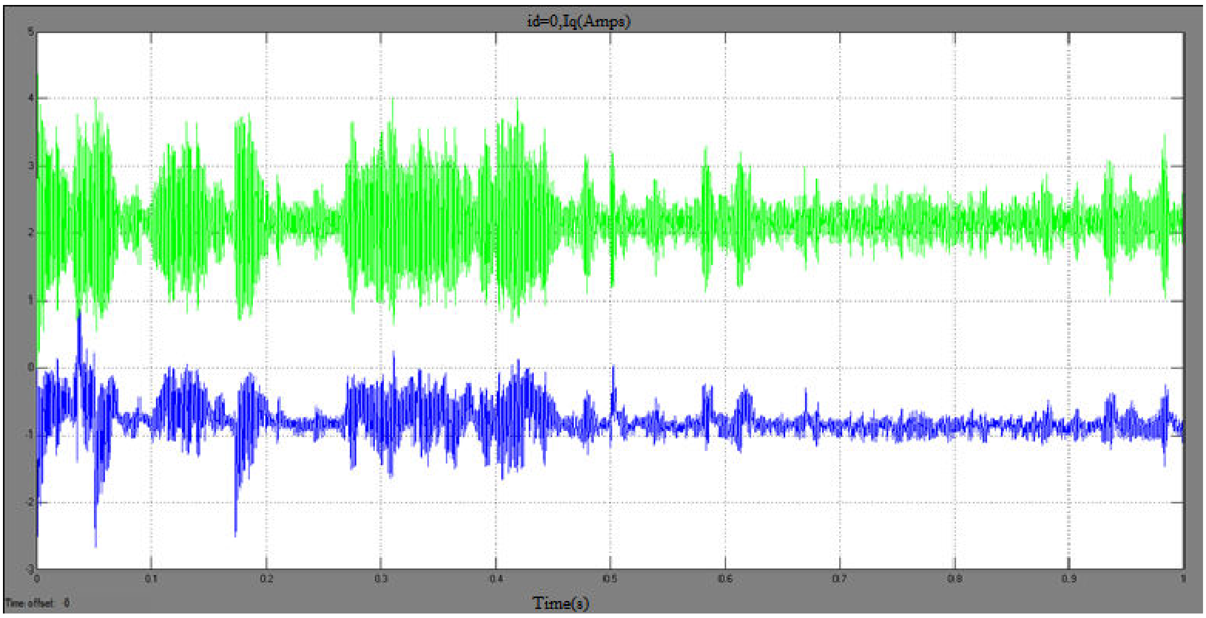

Fig. 8 Current Characteristic

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b) Torque Characteristics

The Torque is very high at starting. Beyond certain time limit, it is reduced and maintained within the rated torque. Torque characteristics is shown in figure as follows.

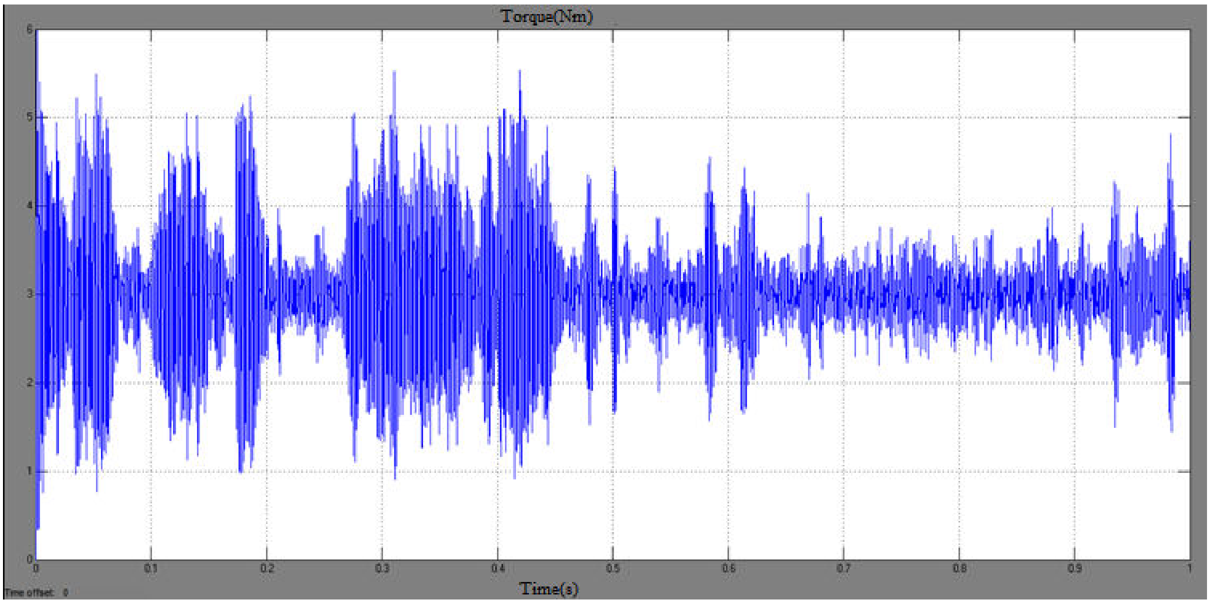

Fig. 9 Torque Characteristics

c) Speed Characteristics

PMSM with MPC is started from zero speed and reaches its speed of 150 rpm within very short duration. Speed Characteristics is shown in Figure.

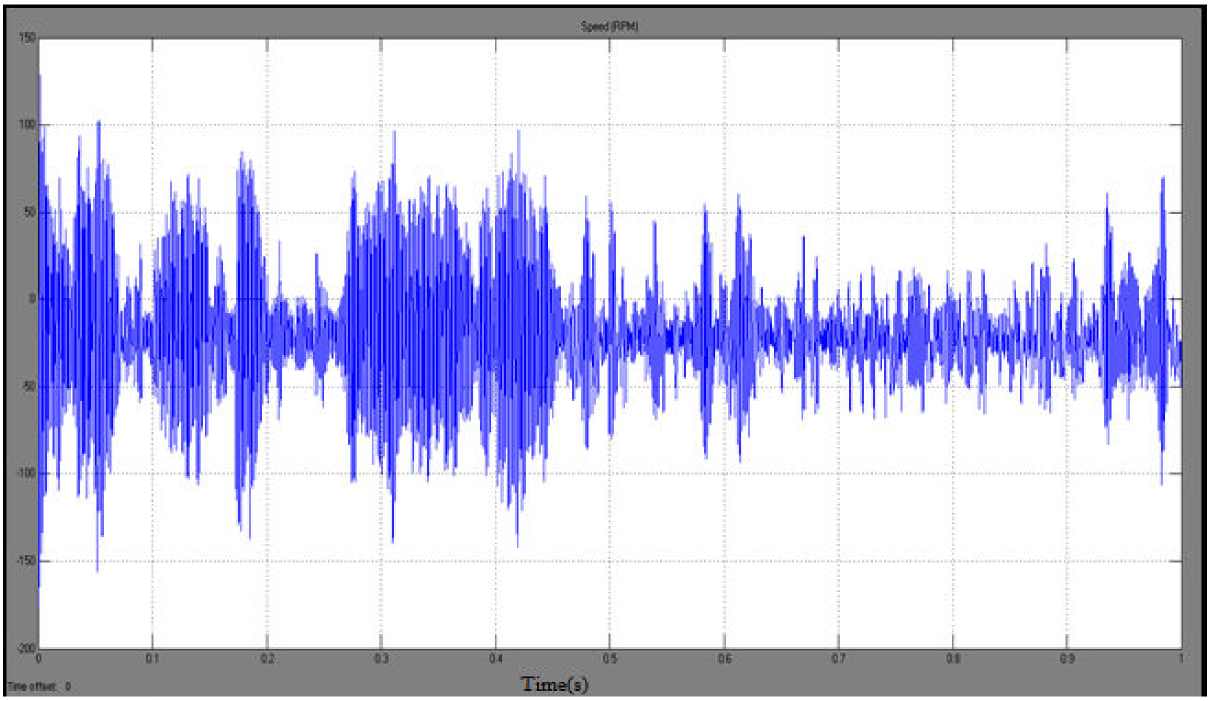

Fig. 10 Speed Characteristics

VII. Conclusion

Model Predictive Torque Control (MPTC) is a very attractive solution for controlling power electronic applications. This paper presents the current state of MPC for power converters and drives including the most recent advances and trends. It can be concluded that the implementation of MPC depends on three key elements, the prediction model, the cost function and the optimization algorithm. MPTC strategy which is based on the discrete-time state-space model of the PMSM is derived. A torque equation that includes the oscillatory torque produced by spatial harmonics in the permanent-magnet field has been developed. The torque oscillations produced by the non-sinusoidal flux linkage is minimized by using an additional term in the cost function of the FS-MPC scheme. The methodology proposed in this paper produces an automatic injection of harmonics in the q-axis current, which significantly reduces the ripple in the electromagnetic torque. The results show that the torque ripple produced by the stator slot harmonics is reduced through feed-forward compensation signals and best compensation of the cogging torque is ensured.

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