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Torque Ripple Minimization of Switched Reluctance Motor by Implementing Model Predictive Control Strategy with IGBT Switching Converter Technique

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Abstract: This paper presents effective control characteristics to improve the performance of a tremendous effectual machine entitled Switched reluctance motor. Some of the controllers give better performance to get premeditated value; out of these controllers Model Predictive controller exhibit a good control strategy on power electronics devices. In this model predictive controller technique is employed in switched reluctance motor with a perfect switching converter. The main drawback of Switched reluctance motor is torque ripple and acoustic noise which are caused due to non linearity in winding current and electromagnetic property. The advantage of MPC is that it allows the easy inclusion of system constraints, thus different control objectives can be flexibly taken in account in different applications. Another remarkable merit of MPC is the inclusion of nonlinearities, such as harmonic spectrum control and switching frequency reduction. An effective IGBT controller is used as a switching circuit. By combing the characteristics of both the Model predictive controller algorithm and switching strategy of IGBT create a new effective control strategy technique for mitigating torque ripple and acoustic noise in switched reluctance motor.

Keywords: Switched Reluctance Motor, Model Predictive Controller, IGBT, Torque ripple

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I. INTRODUCTION

Switched Reluctance motor has remarkable properties like simple structure, high reliability, fault tolerance capability and variable speed which make the machine a highly preferable in commercial application [1, 7]. Switched reluctance motor has a simple structure with a singly excited steel stator wounded with coils and a winding less rotor made of soft iron with salient poles. The diametrical opposite poles are connected in series to make it as a single phase [3, 9]. As soon as the stator pair is energized the nearby rotor pole is attracted linear the position when the magnetic path has low reluctance. Hence the motion is created and torque has been developed in either direction of rotation. SRM has serious disadvantage of significant torque ripple and acoustic noise which reduces the performance of the machine. Torque ripple is of two parts; high frequency torque ripple and low frequency torque ripple. The low frequency torque ripple is produced because of the difference between the peak torque and angle where the overlapping phases produce equal torque at equal level of current [4,8]. This high frequency torque is reduced using switching strategy and converted circuit. Generally torque ripple minimization is done by nonlinearity functions of phase current and rotor position which is done by fixing a suitable control strategy for phase switching. High frequency torque ripple is a exigent problem which is reduced by providing consistent phase current [2, 10]. There are two approaches for minimizing the torque ripple: 1) by improving magnetic design of motor. 2) By using convenient electronic control/converter technique [5]. In this the electronic approach is based on optimizing the control parameters, which includes the supply voltage, turn on and turn off angles and current level [6].

II. OBJECTIVE

To design a control approach using Model Predictive control algorithm to a specially designed IGBT converter switching circuit of switched reluctance motor drive. The proposed control strategy will helps in uniformity of phase current which in turns reduces the ripple. The fast switching characteristic, low saturation voltage and hybrid combination capacity of IGBT and Model Predictive controller characteristics like inclusion of system constraints, harmonic spectrum control and switching frequency reduction jointly create a better performed high quality controller for torque ripple and acoustic noise reduction in switched reluctance motor.

III. ROTOR POSITION NONLINEAR ANALYSIS

Torque characteristics are dependent on the relationship between flux linkage and rotor position as a function of current, it is worthwhile to conceptualize the control possibilities and limitation of the motor drive. A typical inductance VS rotor position is shown in fig.1. The inductance corresponds to that of a stator phase coil of switched reluctance motor by neglecting the fringe effect and saturation.

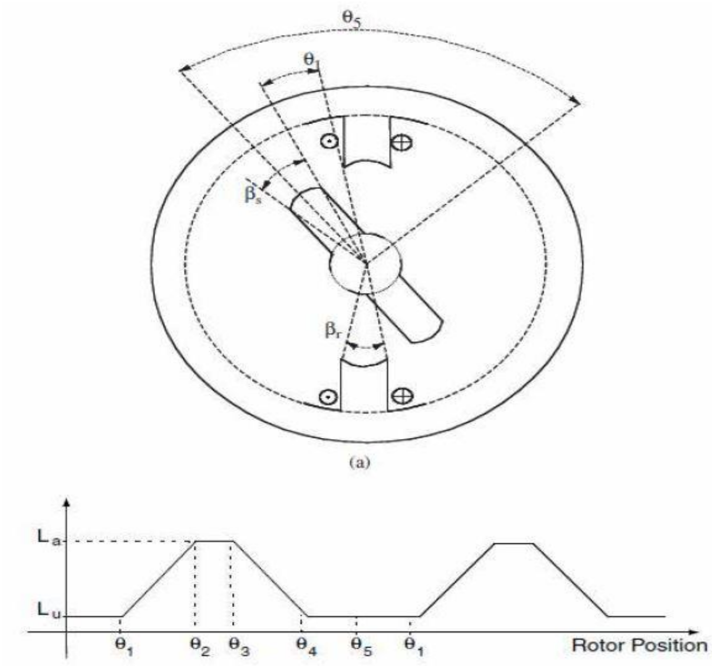


Fig.1 Relationship between flux linkage and rotor position

The various angles are derived as

$\theta_1 = \frac{1}{2}\left[\frac{2\pi}{P_r} - (\beta_s + \beta_r)\right]$ (1)

$\theta_2 = \theta_1 + \beta_s$ (2)

$\theta_3 = \theta_2 + (\beta_r - \beta_s)$ (3)

$\theta_4 = \theta_3 + \beta_s$ (4)

$\theta_5 = \theta_4 + \theta_1 = \frac{2\pi}{P_r}$ (5)

Four distinct induction regions emerge:

ANGLES	REGION
$\theta - \theta_1$ and $\theta_4 - \theta_5$	No overlapping
$\theta_1 - \theta_2$	Poles overlapping
$\theta_2 - \theta_3$	Complete overlapping
$\theta_3 - \theta_4$	Partial overlapping

IV. TORQUE EQUATION OF SRM

Basic voltage equation of SRM is given by

V=Ri+$\frac{d\lambda}{dt}$ [λ =Li] (6)

Where

V – input voltage
I – current through the phase winding
R – resistance of the phase winding
λ– flux linkages=Li

$\frac{d\lambda}{dt} = \frac{d(Li)}{dt}$

$\frac{\partial\lambda}{\partial t}$ = L$\frac{\partial i}{\partial t}$ + i$\frac{\partial L}{\partial t}$

$$= L\frac{\partial i}{\partial t} + i\frac{\partial L}{\partial \theta}.\frac{\partial \theta}{\partial t}$$
$$= L\frac{\partial i}{\partial t} + i\omega\frac{\partial L}{\partial \theta}$$

Where $\omega = \frac{\partial \theta}{\partial t}$

$$V = iR + L\frac{\partial i}{\partial t} + i\omega\frac{\partial L}{\partial \theta} \quad (7)$$
$$V = Ri + L\frac{\partial i}{\partial \theta} + e$$

It is the voltage equation of SRM.

Where ∂L -incrementalinductance *Type equation here.*

Ri- resistive drop

$L\frac{\partial i}{\partial t}$ → emf due to incremental inductance

$i\omega\frac{\partial L}{\partial \theta}$ → e = self emf depends on current , speed and rate of change of inductance with rotor angle.

From the voltage equation, easily we can draw the equivalent circuit for one phase of SRM. Thus the equivalent circuit of SRM consists of each phase, a resistance, an incremental inductance and self emf.

$L\frac{\partial i}{\partial t}$ emf due to incremental inductance is zero.

During the flat top period, emf 'e' is constant.

At some instant the inductance is constant, 'e' will be zero and $L\frac{\partial i}{\partial t}$ will be constant.

Thus the equivalent circuit of SRM changes from being mainly on inductance and emf.

Multiply Equation (7) by current 'I' on both sides, we get

$$Vi = \left(Ri + L\frac{\partial i}{\partial t} + i\omega\frac{\partial L}{\partial \theta}\right) i$$
$$Vi = i^2R + Li\frac{\partial i}{\partial t} + i^2\ \omega\frac{\partial L}{\partial t} \quad (8)$$

This equation is power equation of the SRM.

Where

Vi = electrical power supplied in watts

i^2 R = resistive loss

$Li\frac{\partial i}{\partial t}$ = power associated with incremental inductance

$i^2\ \omega\ \frac{\partial L}{\partial \theta}$ = ei = power due to self emf.

1. Power associated with change in stored energy
2. Power converted into mechanical stored energy in the magnetic field

$$W_{st} = ½ Li^2$$

Power associated with change in stored energy is $\frac{dWst}{dt}$

$$\frac{dWst}{dt} = \frac{1}{2}L(2i)\frac{\partial i}{\partial t} + \frac{1}{2}i^2\frac{\partial L}{\partial t}$$
$$= Li\frac{\partial i}{\partial t} + \frac{1}{2}i^2\ \omega\frac{\partial L}{\partial \theta}\left[\omega = \frac{\partial \theta}{\partial t}\right] \quad (9).$$

Power converted into mechanical P_m = Vi-i2R-Power associated with change in stored energy

$$P_m = Vi - i^2R - -\frac{dWst}{dt} \quad (10)$$

Substitute equations (7) and (8) in equation (9), we get

$$P_m = i^2R + Li\frac{\partial i}{\partial t} + i^2\ \omega\frac{\partial L}{\partial \theta} - i^2R - Li\frac{\partial i}{\partial t} - -\frac{1}{2}i^2\ \omega\frac{\partial L}{\partial \theta}$$
$$P_m = \frac{1}{2}i^2\ \omega\frac{\partial L}{\partial \theta}$$
$$P_m = \omega\ T$$

Torque developed by an SRM

$$T = \frac{P_m}{\omega}$$
$$= \frac{\frac{1}{2}i^2\ \omega\frac{\partial L}{\partial \theta}}{\omega}$$
$$T = \frac{1}{2}i^2\frac{\partial L}{\partial \theta}\ \text{N-m} \quad (11)$$

From the equation 11 current and flux linkage plays a prominent role in the torque generation, so phase current and flux in each phase must be maintained constant to attain fine torque generation without ripple and noise. This nonlinearity characteristic was attained by using a suitable converter for switching with control strategy.

V. MODEL PREDICTIVE CONTROL

Predictive controller has very special features when compared with the other controllers. Some of the features are: (i) concepts are perceptive and easy to understand, (ii) it can be applied to a variety of systems, (iii) constraints and nonlinearities can be easily included, (iv) multivariable case can be considered. Predictive controller has a high volume of calculations then a classic controller but implementation became possible by fast running microprocessors available nowadays. The main characteristic of predictive control is the use of the model of the system for the prediction of the future behavior of the controlled variables. Different classification of predictive controllers are shown in fig.2 In deadbeat control, the optimal actuation is the one that makes the error equal to zero in the next sampling instant. A more flexible criterion is used in MPC, expressed as a cost function to be minimized. The optimization criterion in the hysteresis-based predictive control is to keep the controlled variable within the boundaries of a hysteresis area, while in the trajectory based, the variables are forced to follow a predefined trajectory. The principle of trajectory-based predictive control strategies is to force the system's variables onto precalculated trajectories. Control algorithms according to this strategy are direct self control or direct mean torque control.

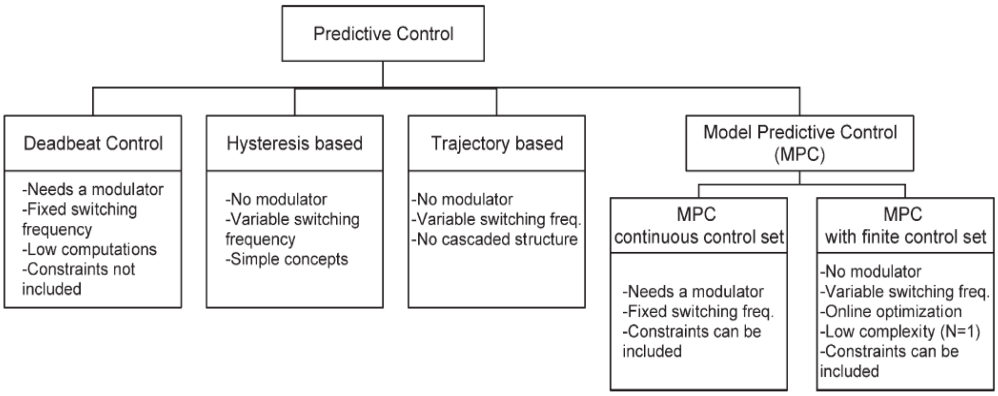


Fig.2 Classification of predictive controllers

Deadbeat control and model predictive control always need a modulator for generating reference voltage, but the advantage of predictive control is that concepts are very simple and. Depending on the type of predictive control, implementation can also be simple.

The saliency of the stator and rotor, the torque ripple is produced when the former phase is being excited opposite voltage and the latter phase has been excited. The point of intersection between the two excited phases must be advanced to a higher value to minimize the torque ripple. To attenuate the torque ripple, the addition of a compensating current signal is proposed. This signal is dependent of the rotor position and the reference current which in turn depends on the motor speed and the torque load value. The output compensating current signal produced by the controllers, Ic is added to the reference current signal, which ideally, should be constant in steady state, but producing significant ripple. The compensating signal should then be adjusted in order to produce a ripple free output torque. In fact, it is a function that possesses high mathematical complexity and therefore the production of this signal is quite complicated so there is a need of easy compensation for the above problems. The model predictive control is applied to reimburse the process. The advantage of MPC is that it allows the easy inclusion of system constraints, thus different control objectives can be flexibly taken in account in different applications. Another remarkable merit of MPC is the inclusion of nonlinearities, such as harmonic spectrum control and switching frequency reduction. The key is to choose the appropriate weighting factors to get a satisfactory tradeoff between the control objectives.

- To regulate and keep its torque close to a reference value
- Further, minimization of the winding currents and the operation within the rated values
- Finite switching frequency make it impossible to regulate the torque
- Every switch transition causes a heat loss in the converter, hence switching frequency should minimize.
- Finally, to achieve low torque ripple and operating at a low switching frequency.
- Minimizing an objective function at each time step
- The major advantage of MPC is its straightforward design procedure.
- Given a model of the system, including constraints, one only needs to set up an objective function that incorporates the control objectives.
- By putting different weights on the control objectives, to balance torque ripple, winding currents, and switching frequency.

In Model Predictive Controller, the behavior of the variable is predicted by a system model over a certain time horizon, and a cost function as the criterion is used to select the optimal switching states. The principle of this control scheme is illustrated in fig.6. All the possible system transitions *yp*(*tk*+1) can be predicted using the measured value *y*(*tk*) at the control actions according to a prediction model {*y*(*tk*), *N*}. This prediction model is directly derived from the discrete-time model of the system which depending on the control objectives. By considering a short time horizon (usually equal to 1)called finite state predictive control take *N* = 1, the system behavior at *k* + 1 instant can be predicted with the measured value *y*(*tk*) and *n* possible voltage vectors, resulting in *n* possible values *yp*1, *yp*2, …, *ypn*, as depicted in fig.3. Finite state predictive control method is the simplest method for model prediction control.

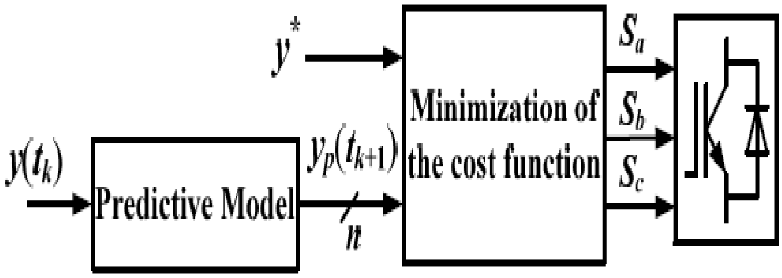


Fig.3 Control scheme of Model Predictive Control

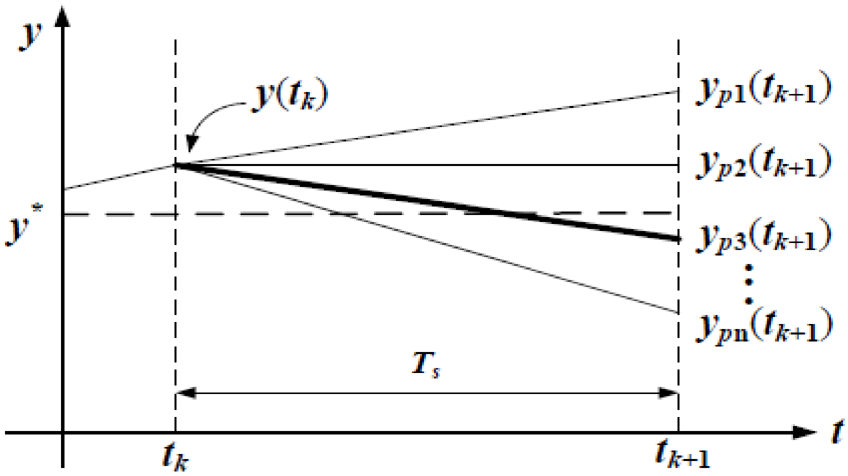


Fig.4 n- possible voltage vectors at (N=1)

Next, a cost function will be formulated to evaluate the effectiveness of all the possible voltage vectors on the system performance. The voltage vector that minimizes the cost function will be chosen for the next sampling period. For example, if *yp*3 is closest to *y**, the voltage vector producing *yp*3 will be selected to control the converter between *k* and *k* + 1 instants. In this way different values are interacted and the right value is predicted in model predictive control which is close to reference value. Fig.5 shows the magnetization curve of SRM.

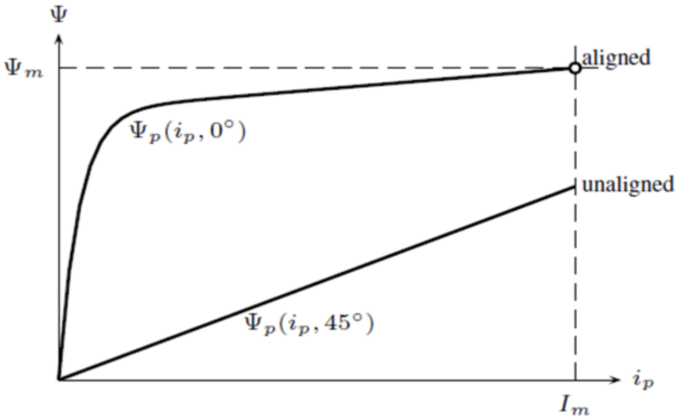


Fig.5 Magnetization curve of SRM

The Magnetization Characteristics of the 6/4 SRM are described by the equations 12, 13 and 14. In this Equation 12 gives the magnetization characteristic of motor at unaligned position and Equation.14 gives the magnetization characteristic of motor at aligned position.

$$\varphi_p\left(i_p, 45^o\right) = L_q i_p \quad (12)$$
$$\varphi_p\left(i_p, 0^o\right) = L_{dsat}\, i_p + A\left(1 - e^{-Bi_p}\right) \quad (13)$$
$$\varphi_p = L_q i_p + \left[L_{dsat}\, i_p + A\left(1 - e^{-Bi_p}\right) - L_q i_p\right] f(\theta_p) \quad (14)$$

5.1. Torque expression of SRM

The electromagnetic torque [Te] which is given by the Equation 17 generated by a phase p is given by the derivative of the machine co energy which is given by

$$W_p'\left(i_p, \theta_p\right) = \int_0^{i_p} \varphi_p\left(i_p, \theta_p\right) di_p \quad (15)$$
$$T_{e,p} = \left[\frac{L_{dsat} - L_q}{2} i_p^2 + Ai_p - \frac{A}{B}\left(1 - e^{-Bi_p}\right)\right] f'(\theta_p) \quad (16)$$
$$T_e = \sum_p T_{e,p} \quad (17)$$

5.2. Controller Objectives

Model predictive control problem is expressed by appropriate cost term for the cost function and it is given by Equation 18 and Equation 19. The main objective of MPC is to keep the torque close to the reference value which is achived by putting the quadatic penalty.

Where weight of the torque is greater than zero.

$q_T > 0$, q_T – weight on the torqe.

Next is to minimize the ohmic loses in the winding current where weight on the current is greater than zero.

$q_I > 0$, q_I – weight o the current

$$\epsilon\, T(l) = qT\,(T_e(l) - T_{e,ref})^2 \quad (18)$$
$$\epsilon\, I(l) = qI \sum_{p=1}^{3} i_p(l)^2 \quad (19)$$

VI. PROPOSED MODEL

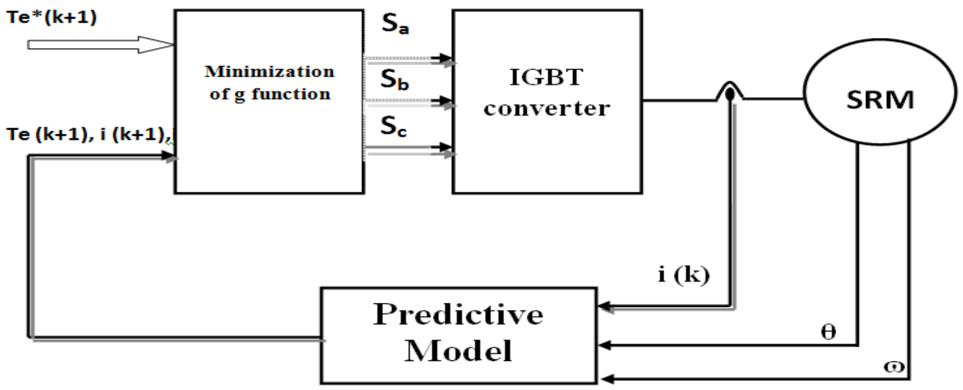
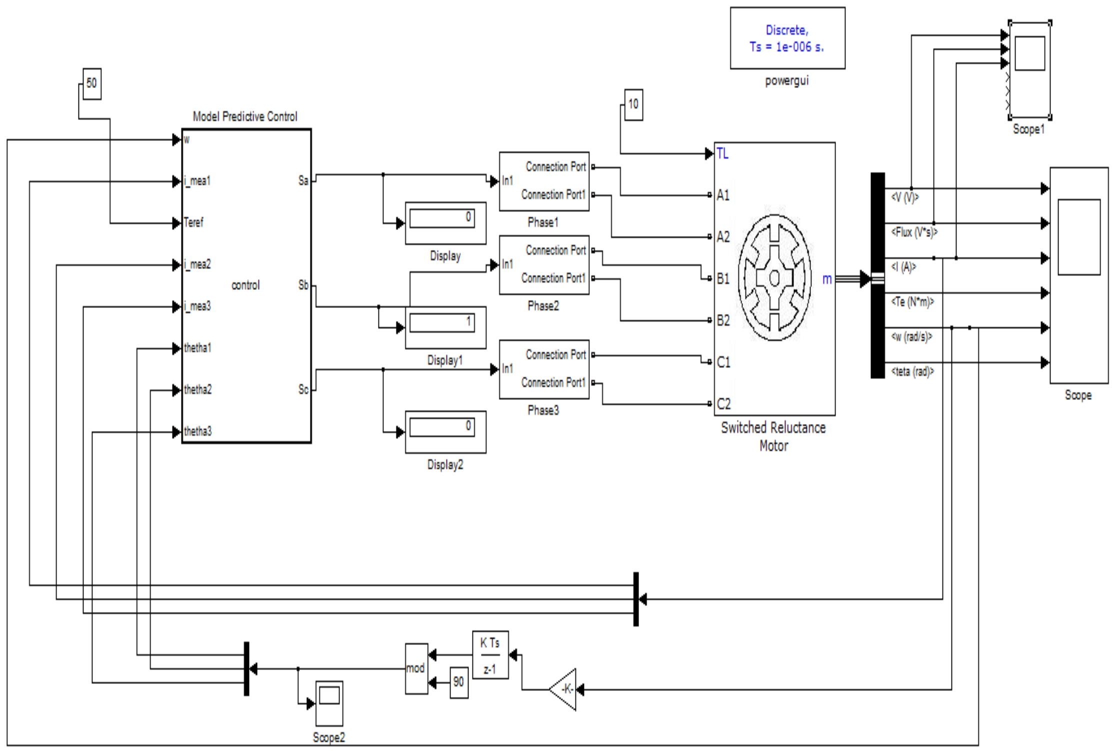


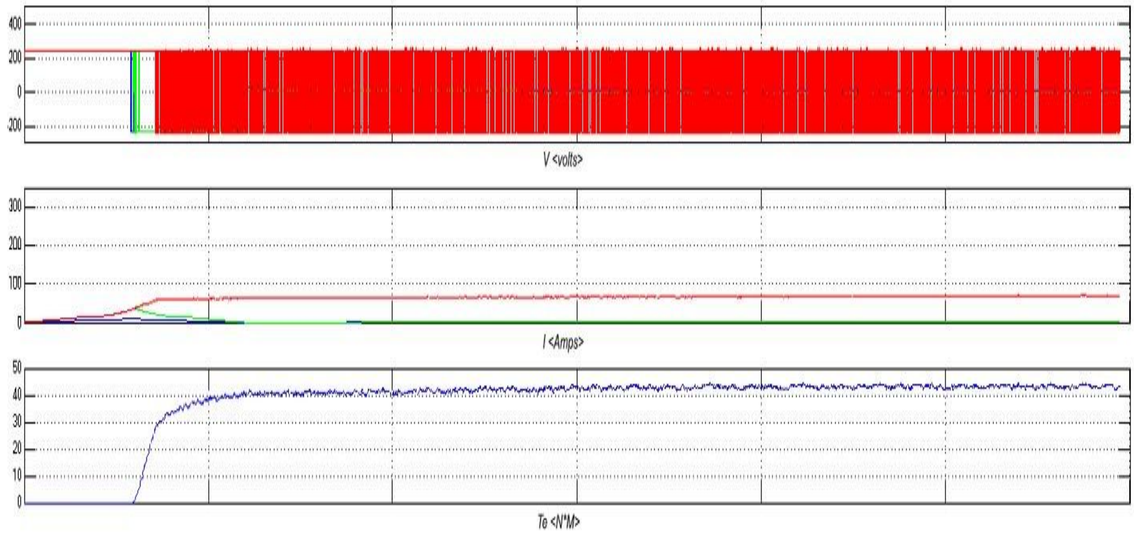
Fig.6 Proposed Model Predictive Controller with IGBT converter

In this proposed method Model Predictive controller give effective result on bringing the torque value close to the reference value and minimizes the ohmic loses in winding current. The above property reduces the torque ripple and acoustic noise to the great extent and the fast switching characteristics of IGBT helps to avoid overlapping of current. The winding current, angular velocity and displacement are feedback to the predictive model controller to predict the values which brings the torque close to the reference value and also brings the winding current to the correct level.

VII. SIMULATION DIAGRAM AND RESULTS



Simulation Results



VIII. CONCLUSION

In this paper, torque ripple and acoustic noise which is caused due to nonlinearity in electromagnetic property and winding current is reduced to the concern level by model predictive control with IGBT switching converter. MPC uses predicted value which produces response close to the reference value even in nonlinearities. IGBT switching converter offers fast switching to avoid overlapping of phase current which leads to produce a consistent phase current profile. From the simulation results Model predictive controller with IGBT switching converter is suitable for torque ripple reduction and acoustic noise control in Switched reluctance motor. Hence the proposed method can be well suited for practical applications of SRM drive which can pave a simple way for the industrial applications

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