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Model Predictive Torque Control of Switched Reluctance Motor Drive

Gantasala Bhavana
Department of Electrical Engineering
NIT Warangal
Warangal, India, Pin 506004
gantas_ee19430@student.nitw.ac.in

B L Narasimharaju, Sr. Member IEEE
Department of Electrical Engineering
NIT Warangal
Warangal, India, Pin 506004
blnraju@nitw.ac.in

Vijaya Vardhan Reddy P
Department of Electrical Engineering
NIT Warangal
Warangal, India, Pin 506004
vardhan258@gmail.com

Vijay Babu K
Department of Mechatronics Engineering
Manipal Institute of Technology, Manipal
Karnataka, India, Pin: 576104
vijaybabukoreboina@gmail.com

***Abstract*—A comparative study between conventional torque control methods and model predictive torque control (MPTC) of an 8/6 configuration switched reluctance motor (SRM) drive is presented in this paper. For extending the SRM application to higher speeds, the algorithm is designed by maintaining low torque ripple and considering the dynamic response of controller. The cost-function based online optimization of drives, replace non-linear controllers and heuristic switching table. The cost function is built with torque and stator current constraints. The principle of the predictive control method is explained, and the system mathematical description is derived. The results are verified for conventional control techniques and model predictive torque control applied to a 4kW switched reluctance motor under different operating conditions using MATLAB/Simulink. The obtained simulation results exhibit that the proposed model predictive torque control of an 8/6 SRM performance is satisfactory and can be used for electric vehicular applications.**

***Index Terms*—Model Predictive Torque Control (MPTC), Switched Reluctance Motor (SRM), Hysteresis Current Control (HCC), Electromagnetic Torque (Te), Phase Torque (Tph).**

I. Introduction

The switched reluctance motors, owing to their simple cum robust construction, lower manufacturing cost, high reliability and better performance are increasingly becoming interest for researchers as well as for industry applications [1]. The stator and rotor iron cores are laminated by magnetic sheet steels, which have salient pole structure. This firm structure of the motor without brushes on the rotor makes it highly reliable compared to other machine systems. Thus, the SRM has gained much absorption for electric vehicles (EV) and hybrid electric vehicles (HEV), for its rugged and simple construction, extremely high speed and hazard-free operation [2]. The non-linear relationship i.e. double salient structure will result torque ripple [1-3]. Plethora of solutions are reported in the literature, aiming to develop the closed loop control methods that ensure minimization of the torque ripple.

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Many control methods, motor designs and power electronics converters are proposed which make SRM advantageous candidate for drive applications such as Hybrid electric vehicles (HEVs) [3]. In order to achieve low torque ripple, the research for SRM stator phase current shaping includes the hysteresis control (HCC) [4-5], PI based PWM regulation, model predictive control and other non-conventional methods.

However, in order to overcome the non-linear magnetic characterization of SRM, the direct torque control (DTC) of conventional ac machines is proposed [7]. The SRM stator phase needs independent excitation but the sequential excitation of phase winding is not balanced in DTC methodology. Hence, DTC is not considered as effective torque control method. Among all these control techniques, the model predictive control is promising method to handle the non-linearity of flux linkage characteristic. This research work is focused on reduction torque ripples and improvement of phase currents. In this work, a model predictive torque control with one predictive horizon is developed for the torque ripple minimization of a four phase SRM. The non-linear inductance profile of SRMand effect of back electromotive force (EMF) make its control essential for yielding satisfactory driving performance. The hysteresis current control and PWM control are commonly used approaches for motor phase current shaping or control. The MPC has many advantages, for instance relatively simple to include non-linearity, and constraints using the cost function [8]. The applications of MPC to control an 8/6 SRM are discussed in the literature [9]. The model predictive torque control (MPTC) is developed for four phase SRM, by predicting motor's behavior with horizon as one, considering all active possible converter-switching states. The model predictive type of control obtains good results for a wide range of speeds, also it is necessary to increase the sampling frequency of the MPC or improve the usage of control region.

In this control algorithm proposed, it evaluates the cost function and tries to minimize it by limiting it to a specified hysteresis band. The switching states are generated accordingly to

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maintain the cost function i.e., error in the limits specified. The switching pulses are applied to stator that minimizes the cost function and for the next sampling instant, the cost function is evaluated, minimized with the new measurements. The closed loop controller is analyzed using of MALAB/Simulink simulations at lower and higher values of speed. The results present a good potential of MPTC for torque ripple minimization. The paper is arranged as follows. The modeling of SRM and its converter is discussed in sections II and I. The control algorithm proposed is discussed in section III. Relative formulations for the model predictive torque control in given in section IV, V and VI. Section V focuses on the simulation performance of SRM at low and high speeds. The concluding remarks are given in section VII.

II. Modeling of SRM Drive

A. Modeling of SRM Electrical Circuit

The important requirement in modelling is to determine the non-linear flux-linkage characteristic and static torque characteristics as SRM consists of salient poleconcentrated winding stator and a ferromagnetic salient pole rotor [6]. From the equivalent circuit diagram of SRM, the motor describing equations are

$$v = i \times R_s + \frac{d\psi}{dt} \tag{1}$$

where, v is the stator phase voltage, R_s is phase winding resistance and i is the phase current. The incremental flux linkage equation for each phase is obtained by integrating the difference between input DC-link voltage and the drop across the stator winding resistance. By neglecting the mutual inductance, the total flux-linkage equationfor the energized phase winding is given by

$$\psi = \int (v - i \times Rs)dt \tag{2}$$

The magnetization curves characteristics, corresponding to the aligned and unaligned rotor positions of SRM, are mathematically written as [3] The static flux-linkage characteristics can be approximated by the following mathematical expression

$$i = a_1(\theta).\psi + m.a_2.(\psi - \psi_1(\theta))^2 + n.a_3.(\psi - \psi_2(\theta))^3 \tag{3}$$

$$m = 1\, if\, \psi > \psi_1,\; else\, m = 0 \tag{4}$$

$$n = 1\, if\, \psi > \psi_2,\; else\, n = 0 \tag{5}$$

where i and ψ is phase current and flux-linkage; a_2 and a_3 are chosen as 11 and 185 respectively [7]. $\psi_1(\theta)$ and $\psi_2(\theta)$ are functions of position θ corresponding to aligned and unaligned positions of motor from $0\,\text{deg}$ to 30 deg. The above parameters $a_1(\theta)$, $\psi_1(\theta)$ and $\psi_2(\theta)$ are stored in look-up table for every $3\,\text{deg}$. The magnetization curves are plotted using the above curve equation in Fig. 1. At a given rotor position and stator phase current, the co-energy is the summation of area under

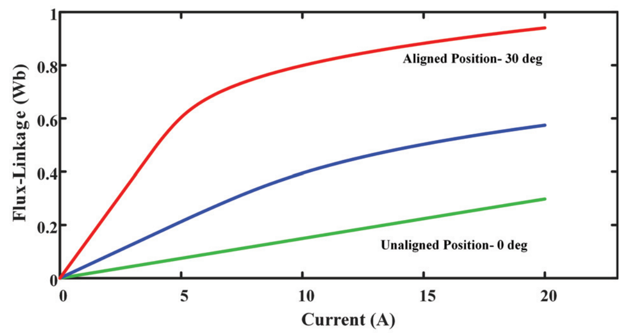

Fig. 1. Flux-Linkage characteristics at different rotor positions with the stator

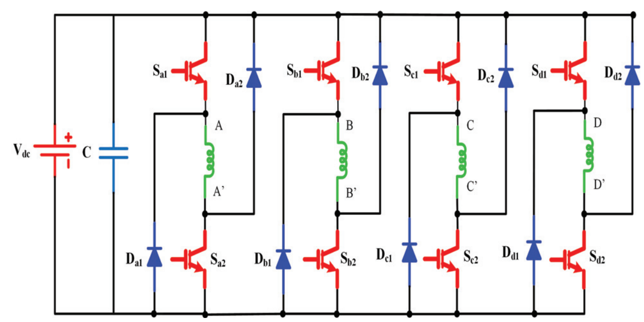

Fig. 2. Asymmetric Bridge Converter

the magnetization curve. The instantaneous electromagnetic torque generated by each phase of SRM can be evaluated by

$$T_e(i_{ph}, \theta) = \frac{\partial W_c}{\partial \theta} \tag{6}$$

where W_c is the co-energy. The summation of individual phase torques give the total instantaneous torque as

$$T_{ins}(i_{ph}, \theta) = \sum T_{e,j}(i_{ph}, \theta) \tag{7}$$

where T_{ins} is the instantaneous phase torque i.e. $j = 1 - 4$ which depends on phase current and rotor position . The load dynamics of the SRM machine is expressed as

$$T_e = J \times \frac{dw}{dt} + B \times w + T_l \tag{8}$$

where, T_e total electromagnetic torque generated by SRM, J is inertia of the load, B is the frictional co-efficient and w is the rotor speed in radians/second.

B. Modeling of Converter

SRM needs a power electronic for sequential excitation of stator phase winding for motoring or generating mode of operation [10]. The choice of converter topology of SRM is highly dependent on application areas characterized by driving performance and driving cost. The asymmetric half-bridge for four-phase SRM as shown in Fig. 2. This topology has three distinguished different states [10]. The control signal of each phase is denoted as g_1, g_2 and g_3 and have the values as shown in Table I. The gate signals denoted as S_a,

TABLE I
SWITCHING STATES

State	Value	State
g_1	1	Magnetizing
g_2	0	Free-wheeling
g_3	-1	De-Magnetizing

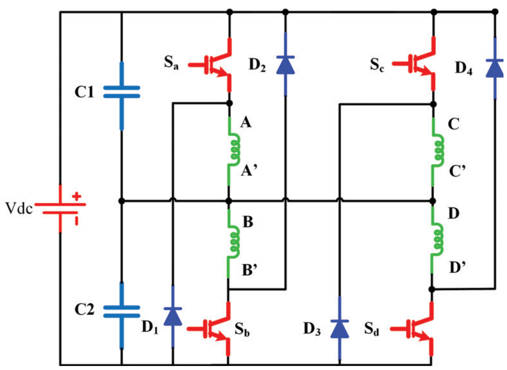

Fig. 3. OULTON Converter

S_b, S_c and S_d are obtained from the control signals g_1, g_2 and g_3. In this topology, motor phase currents and voltages is controlled independently, which gives good driving performance.However, this configuration require more components which results in increased switching losses and overall system cost. The commercially used OULTON converter is considered for the MPC controller for an 8/6 SRM as shown in Fig. 3. This configuration has one switch per phase, thus produces higher efficiency with reduced switching losses. The DC link voltage is split by the two capacitors. However, it requires charge balance for DC-split capacitors and don't permit soft chopping under low-speed operations leading to noise.

III. MODEL PREDICTIVE TORQUE CONTROL

A. Proposed Algorithm

The main aim of the proposed control strategy is maintaining a low torque ripple align while maintaining the required load torque. For each phase, the torque is calculated considering rotor speed and position theta. And the reference torque is generated using the speed loop. The technique used here is hysteresis based MPTC, in which the error i.e., cost function is maintained in the limits specified by hysteresis band. The error signal to PI controller is the difference between the motor actual speed and the reference speed and using this PI controller, the reference phase torque is generated. The main objective of this speed controller is to keep the motor speed tracking the reference speed by generating the required reference phase torque for MPC controller. The MPC evaluates the cost function i.e., deviation of phase currents and torques from the reference signals. It thus determines the ON and OFF periods for each switch of the asymmetrical bridge converter according to the theta i.e., rotor position data. The stator current waveform shaping of SRM is implemented using

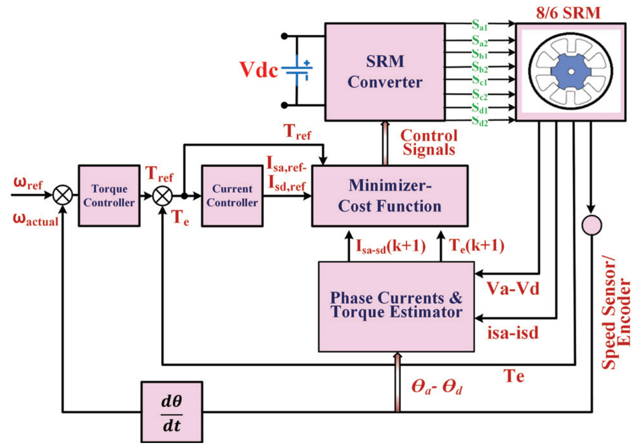

Fig. 4. Block diagram of proposed control method for torque ripple minimization

hysteresis current control (HCC) has easy implementation along with robustness, but this technique generates a current ripple. The proportional controller (PI) based pulse width modulation control needs a modulator to calculate the turn ON and turn OFF and can be implemented easily. The tuning of PI controller in PI-PWM makes it dis-advantageous.

B. Cost Function Estimation

The cost function includes the stator current deviation with respect to reference currents to achieve the control objectives. The cost function is considered with single-step prediction. The cost function G, can be defined considering the performance requirements as

$$G_p(k) = \varepsilon_T(k) + \varepsilon_i(k) \quad (9)$$

$$\varepsilon_{Ts,p}(k) = T_{e,ref} - T_{e,p} \quad (10)$$

$$\varepsilon_{i,p}(k) = \sum (i_{p,ref} - i_{s,p})^2 \quad (11)$$

$$where\, p = a,\, b,\, c,\, d \quad (12)$$

where G is the cost function at k^{th} instant, and the switching states which obtains the minimum value of cost function, will be applied to the converter at $k+1^{th}$ instant. The gate signals S_a, S_b, S_c and S_d are selected according to optimization of the cost function of each phase i.e. G_a, G_b, G_c,and G_d respectively. Then the stator phase currents and torque is determined accordingly from voltage equations shown in equation (12).

$$V_{DC,p} = S_p \times V_{DC} \quad (13)$$

C. Torque Estimation

The MPTC for an 8/6 SRM uses the analytic model to determine the future values of phase currents and phase torques. This requires the measurement of rotor position, phase currents and the DC-link voltage. The stator phase currents are evaluated from the flux-linkage characteristic and rotor position. The switching states evaluated was chosen based upon the rotor position i.e., theta, alsoturn-on, and turn-off

TABLE II
MOTOR PARAMETERS

Parameter	Value	Units
Vdc, DC-Link Voltage	560	Volts
Rs, Stator Resistance	0.7	Ohms
B, Frictiona Coefficient	0.0065	Nms
J, Moment of Inertia	0.08	kgm2
Prediction Horizon	1	Unit
Ts, Sampling Time	1e-6	Sec

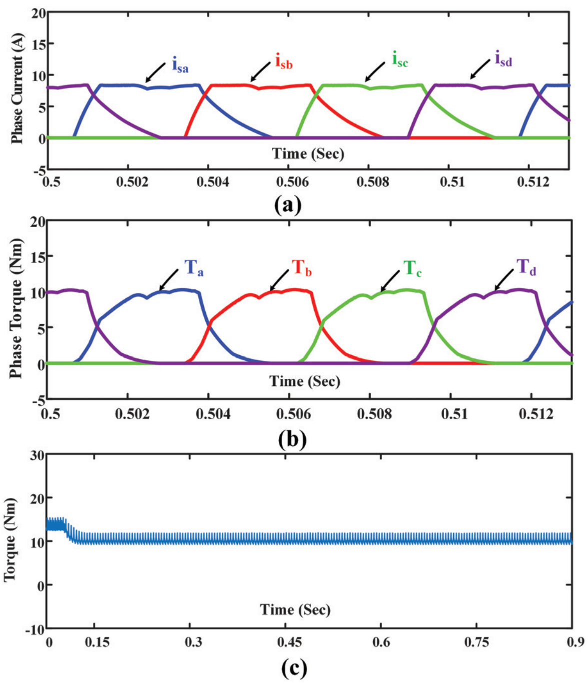

Fig. 5. Waveforms of MPC based 8/6 SRM drive (a) Phase currents, (b) Tph and (c) Te at 900 RPM

angles. The reference torque is estimated from outer speed control loop using a PI controller. The proposed controller's control block diagram is shown in Fig. 4 for the torque ripple minimization of SRM Drive.

IV. Results and Discussion

A. Simulation Results

To verify the proposed control method, the machine used here is 4 phase, 2 HP, 8/6 SRM. Table II shows the motor specifications. The simulations are performed for two modes of operation i.e. low speed and high-speed operation. Fig. 5 shows the waveform of phase currents, phase torque and total electromagnetic generated at low speed i.e., 900 RPM. Fig. 6 illustrate the simulation results for high-speed operation i.e., 3000 RPM of SRM drive. The simulations are performed on 8/6 SRM. The results tabulated in Table III shows that the proposed model predictive torque control has reduced torque ripples on comparing with traditional techniques such as HCC and PI-PWM. Thus, MPTC is considered as one of the best

TABLE III
TORQUE RIPPLE

Speed	Control Methods	Torque Ripple Percentage
900 RPM	PI-PWM	46.31
	HCC	42.6
	MPC	24.22
3000 RPM	PI-PWM	72.26
	HCC	57.42
	MPC	12.07

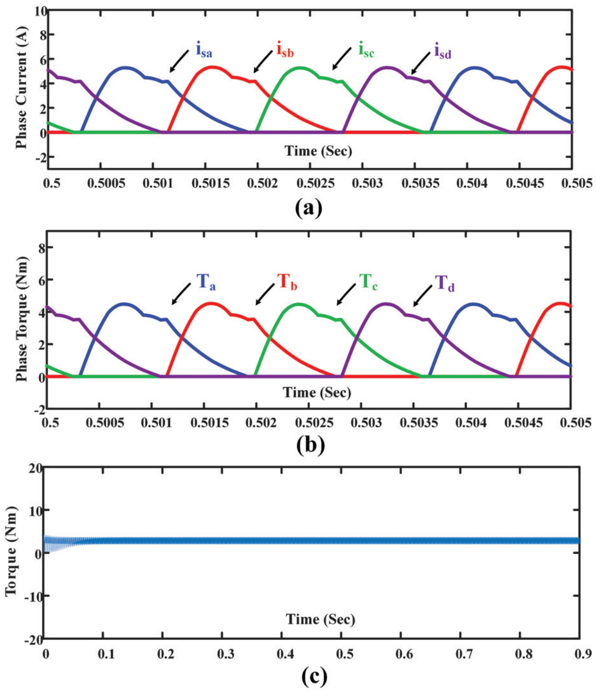

Fig. 6. Waveforms of MPC based 8/6 SRM drive (a) Phase currents, (b) Tph and (c) Te at 3000 RPM

control strategies showing its effectiveness to reduce the torque ripples of SRM. Finally, the dynamic behavior and quick response of MPTC controller is depicted in Fig. 6, wherein the reference step speed increases from 150 RPM to 900 RPM at 0.4^{th} second and step speed decreases from 900 RPM to 600 RPM at 0.6^{th} second is given to the controller. The SRM drive takes $t = 0.08$ seconds and $t = 0.02$ seconds to achieve the required load-torque which shows the fastness of the controller to dynamic changes.

B. Discussion and Conclusion

This paper put forward a model predictive control-based control of an 8/6 switched reluctance motor. The proposed control algorithm is simulated in MATLAB/Simulink environment. By utilizing the proposed controller and adjusting the turn-on and turn-off angles, the SRM can be used to obtain a wide adjustable speed range. The controller was tested under different modes of operation i.e., at low and high speed and the

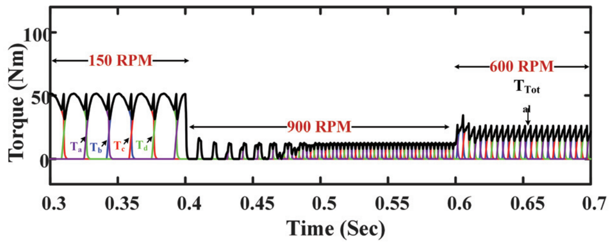

Fig. 7. Waveform of MPC based 8/6 SRM drive Tph and Te generated with transition in reference speed

simulation results obtained shows that output torque always has low ripple. According to the reference speed, required voltage vectors are applied and reference values of torque and currents are tracked precisely, which shows the fast dynamic response. The proposed algorithm can easily be applied to industrial applications due to its simplicity. Thus, this paper put forward a new orientation of the non-linear controller design for switched reluctance motor drive system.

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