COPPER LOSS MINIMIZATION WITH USING MODIFIED DIRECT TORQUE CONTROL METHOD IN SWITCHED RELUCTANCE MOTOR DRIVES

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Abstract: *Switched reluctance motors are associated with such advantages as simple and robust structure, high reliability, and low cost. However, the high torque ripple is one of the major problems. Direct torque control (DTC) Method is widely used on ac machines, such as induction motors and permanent magnet motors. Pulsating torque in switched reluctance motors is high because of commutation. Implementation of DTC technique is simple with good accuracy. In this DTC method, switching strategy is modified and the torque ripple is significantly reduced by choosing the proper bandwidth of the output torque. Recently, a number of studies have been conducted on direct torque control for torque ripple reduction in SRM drives. This paper investigates the conventional DTC method from the standpoint of copper losses. In a second stage, an improved DTC method is proposed for reducing copper losses and increasing the SRM drive efficiency. The conventional DTC and the modified methods are finally compared and the simulation results are presented in MATLAB Simulink.*

Key words: *SRM, direct torque control, Copper loss, modified DTC.*

1. Introduction

Switched reluctance motors have inherent advantages such as simple structure and low cost, which make them suitable for a wide variety of applications. Moreover, they are highly reliable under long, continued working conditions, even when one or more phases are lost as is often encountered in difficult industrial environments [1]. In practice, however, switched reluctance motors have their own limitations such as high torque ripple and acoustic noise. In addition, the nonlinear characteristics of their torque make motor control difficult [2]. Research shows that the direct torque control method does not require complex mathematical models for the effective reduction of torque ripple in SRMs. While Direct Torque Control (DTC) had been reportedly successful in three-phase ac synchronous motors, it has only recently been used for switched reluctance motors with superb advantages over other torque control methods [3]. For instance, unlike the indirect torque control methods, DTC does not require torque-current transformations [4].

In [5], the DTC method is used for a three-phase SRM. A four-level converter is used in Ref [6] and the dynamics of the system is improved by increasing the DC link voltage. The disadvantage, however, is the increased hardware equipment required and the increased nominal voltage of the device.

In [7], a sensor less DTC method based on SVM is proposed. This method uses a Kalman filter that has its own design complexities.

Neural network is used to select the voltage vector output for improving the torque ripple [8]. The main disadvantage is that neural network implementation requires experience and prior knowledge of the system. In [9], a Lyapunov function based on DTC method is presented to reduce the torque ripple a nonlinear control is used in this method which not only adds to its complexity but has the additional problem of requiring a powerful processor for implementation.

Although works in this area are varied, none has investigated the DTC method in terms of its efficiency and copper losses. One of the problems associated with direct torque control is the negative phase torque produced. For example, given the switching mode in a four-phase motor, there are moments when current flows in more than two phases simultaneously. Due to the structure of the motor, this simultaneous current causes a negative phase torque at moments that increases the flow phase and, consequently, leads to greater copper losses.

This paper initially investigates the conventional

DTC method with respect to copper losses. In a second stage, an improved method is developed by making changes in the switching mode in order to reduce copper losses and increase the efficiency of the four-phase SRM drive. The proposed method is simulated for an industrial motor 8/6 in Simulink and the simulation results are compared with the results obtained for the conventional DTC method.

2. Voltage modes in the SRM drive

There are three modes of voltage for phase windings of the switched reluctance motor as shown in Figure 1.

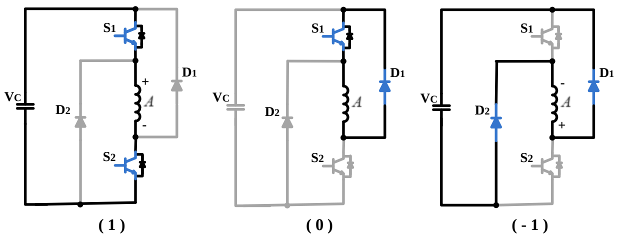

Figure. 1. Voltage modes in a SRM

As shown in Figure 3.1, when both T1 and T2 are on, the positive voltage is applied to the phase winding (mode 1).When T1 is off but T2 is on, the current is reduced smoothly and zero voltage is applied to the phase winding (mode 0). Finally, when both T1 and T2 are off, the voltage across the winding becomes negative and the current through the phase winding rapidly declines to zero (mode -1).

Based on the voltage modes in a four-phase 8/6 SRM motor, 8 voltage vectors may be defined as shown in the following Figure.

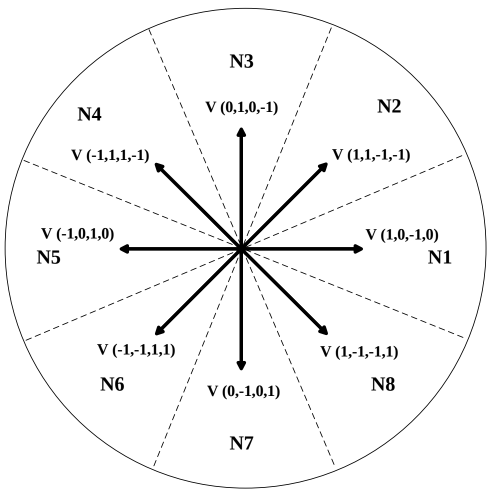

Figure. 2. Voltage vector in conventional DTC method

3. flux linkage vector in switched reluctance motor

4.

The relation (1) holds between stator voltage and flux linkage in SRM drives:

$$U_s = R_s i_s + \frac{d\psi_s}{dt} \qquad (1)$$

Neglecting the effect of the stator resistance, we will have:

$$\psi_s = \int u_s dt, \Delta\psi_s = u_s \Delta t \qquad (2)$$

Clearly, the stator flux linkage vector changes with the timing and magnitude of the stator winding phase voltage vector applied. The tip of the stator flux linkage vector is in the same direction as the voltage vector applied. Amplitude and direction of flux linkage of the stator voltage vector can be manipulated by selecting the right stator voltage so that the stator flux linkage amplitude remains constant and the direction of the stator flux linkage becomes polygonal or circular in shape. If the stator flux linkage vector is in the Kth region, its amplitude can be increased by the voltage vectors Vk-1 and VK+1 or decreased by Vk+3 and Vk-3. When the stator flux linkage rises to its upper limit, it will be reduced by Vk+3 and Vk-3. In contrast, when the stator flux linkage falls to the lower limit, it will be increased by the voltage vectors Vk-1 and Vk+1.

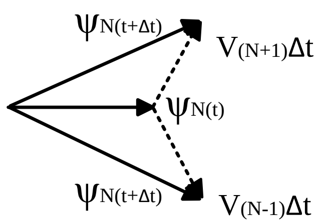

Figure. 3. Increase of flux linkage vector

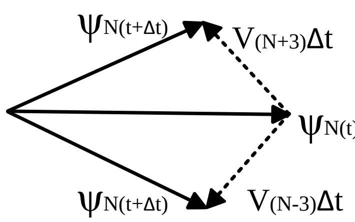

Figure. 4. Decrease of flux linkage vector

5. Principles of torque production based on flux linkage vector in SRM

Under ideal conditions, the current winding remains constant in a control cycle of the controller. The SRM torque equation is of the following form:

$$T = \frac{dW_m}{d\theta}\Big|_{i=const} = \frac{d\left(W_e - W_f\right)}{d\theta}\Big|_{i=const}$$
$$= \frac{dW_e}{d\theta}\Big|_{i=const} - \frac{dW_f}{d\theta}\Big|_{i=const} \qquad (3)$$
$$= i\frac{\partial\psi\left(\theta,i\right)}{\partial\theta} - \frac{dW_f}{d\theta}$$

Because the switched reluctance machine works usually under magnetically saturated conditions, the value for the term $\frac{dW_f}{d\theta}$ is very small. Essentially, the magnetic field energy of switch reluctance motor does not change by changing the rotor angle. In this case, the above equation can be simplified to the following form:

$$T \approx i\frac{\partial\psi\left(\theta,i\right)}{\partial\theta} \qquad (4)$$

In addition, the torque direction is just determined by the term $\frac{\partial\psi\left(\theta,i\right)}{\partial\theta}$ because the current through the phase windings is unipolar. Hence, the phase current is always positive. If the flux amplitude is increased relative to the rotor position (i.e., $\frac{\partial\psi\left(\theta,i\right)}{\partial\theta} \geq 0$), the stator flux vector (defined as the peak position of the stator flux) must be ahead with respect to the direction of the rotor movement [11]. However, if the flux amplitude is decreased relative to the rotor position (i.e., $\frac{\partial\psi\left(\theta,i\right)}{\partial\theta} \leq 0$), the stator flux vector must be behind with respect to the direction of rotor movement. Thus, the torque may be changed with either positive or negative momentum of the stator flux linkage vector rotor relative to the position of rotor.

Changes in the amplitude of the stator flux linkage vector are controlled by the stator voltage vector. Thus, motor torque can be controlled by applying the required voltage vector. If the torque needs to be increased, the voltage vectors are selected that change the flux linkage vector in the direction of rotor movement; that is, Vk+1&Vk+3. Alternatively, if the torque needs to be decreased, the voltage vectors are selected that change the flux linkage vector in the opposite direction of rotor movement; that is, Vk-1&Vk-3.

Flux linkage vectors of phase for a four-phase switched reluctance motor is defined as fig.3.

Table 1. Selection of voltage vector

	V_{k-3}	V_{k-1}	V_{k+1}	V_{k+3}
Torque	↓	↓	↑	↑
Flux	↓	↑	↑	↓

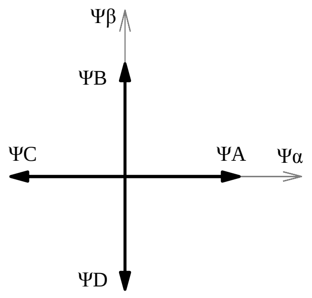

Figure. 5. Flux linkage vectors of phase for a four-phase switched reluctance motor

Based on the above Figure, the stator flux vector components are determined as follows:

$$\begin{cases}\psi_\alpha = \psi_A - \psi_C \\ \psi_\beta = \psi_B - \psi_D\end{cases} \qquad (5)$$

And stator flux linkage vector magnitude and angle are determined as follows:

$$\begin{cases}\psi_s = \sqrt{\psi_\alpha^2 + \psi_\beta^2} \\ \theta = \arctan\left(\frac{\psi_\beta}{\psi_\alpha}\right)\end{cases} \qquad (6)$$

6. The modified Direct Torque Control Method

In the conventional DTC method, the four voltage vectors of v1, v3, v5, v7 are defined such that they apply the zero voltage state to the two phases perpendicular to them. For example, the voltage vector V1 that is coaxial with phase A applies the zero voltage to phases B and C since these latter two are perpendicular to the axis of phase A.

As the simulation results show for a 8/6 SRM, the current in the conventional DTC control method is constantly non-zero in at least three phases. According to the above assumption, the current present in phases B and C remains almost constant with little reduction, if any, when a voltage vector V1 is applied.

It may be noted that the fluxes of phases B and C cancel each other out due to the angular difference of 180° between these phases. On the other hand, at any given point in time up to two adjacent phases can produce positive torques in an SRM 6/8. One of the B or C phases may, therefore, generate a negative torque. It may be concluded then that it will be of no positive effect to have both B and D phases on simultaneously. The same holds true for all the four phases.

In the proposed method, the negative voltage state, rather than the zero-voltage one, is applied to the phases in order to reduce copper losses and, thus, improve the efficiency of the system. The objective is to rapidly reduce to zero the current of the phase generating the negative torque. This provision not only reduces the effective phase currents by preventing the generation of negative torques but for the same reason also leads to a lower torque to be generated and, thereby, a lower current required.

Based on the above observations, the new voltage vectors may be defined as follows:

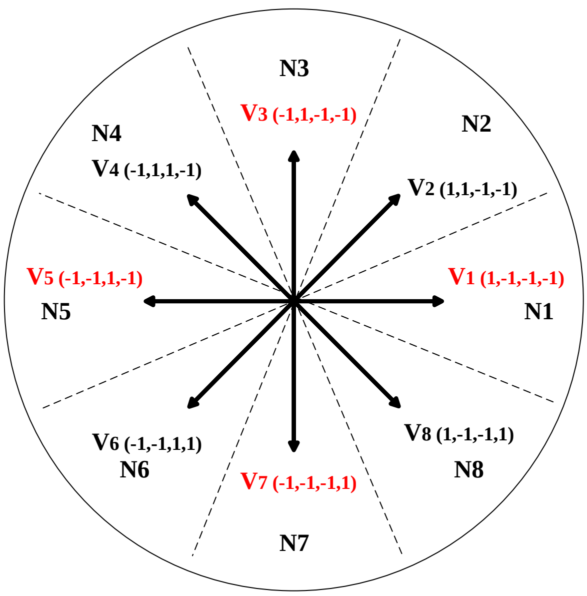

Figure. 6. Voltage vector in proposed DTC method

7. Simulation results

In this paper, data from a four-phase 6/8 Industrial motor is used for simulation in the MATLAB software. Motor Specifications are given in Table 2. In order to model, the three-dimensional flux and torque characteristics of the motor based on the current and position are shown in the figure (7) and (8) respectively. Copper losses to demonstrate ability of proposed method must be obtained. Figures (9),(10) illustrate copper losses for various rotor speeds and output torques with conventional and proposed method, respectively. It is obvious that copper losses in proposed method reduced about 46 percent.

Table 2.

4	Number of phase
8	Stator pole
6	Rotor pole
5.5 ph.	power
9 A	Current for choose the Connection cable
1500 R.P.M	speed
0.75 ohm	Phase resistance

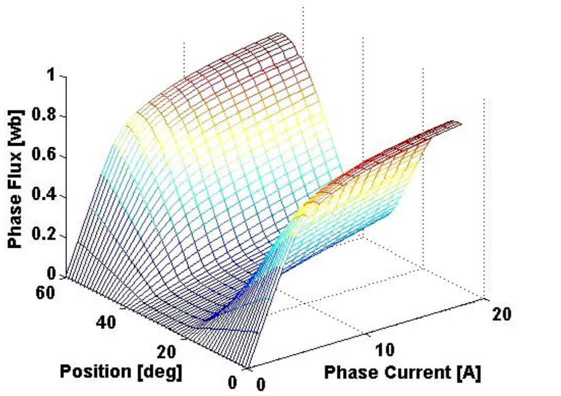

Figure. 7. Characteristic of flux linkage in terms of Position and phase current

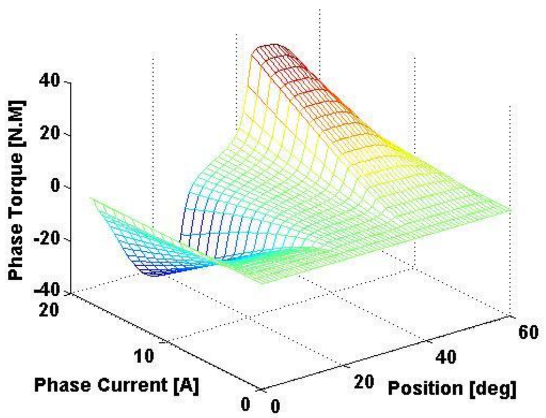

Figure. 8. Characteristic of torque in terms of Position and phase current

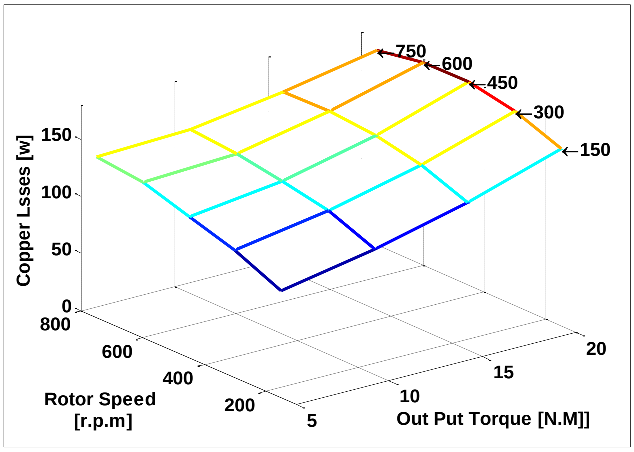

Figure. 9. Copper losses in terms of torque and rotor speed in conventional DTC

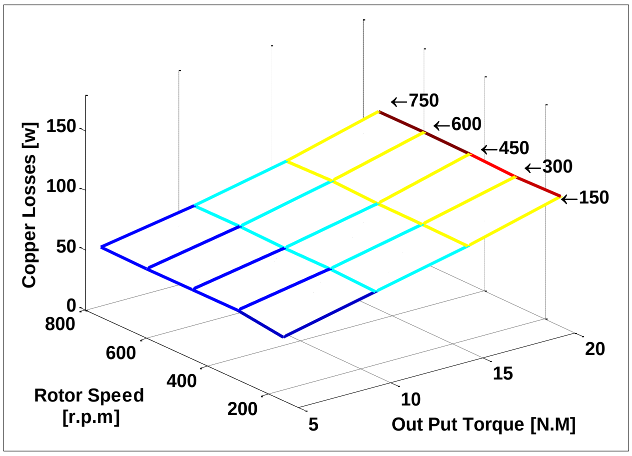

Figure. 10. Copper losses in terms of torque and rotor speed in proposed DTC

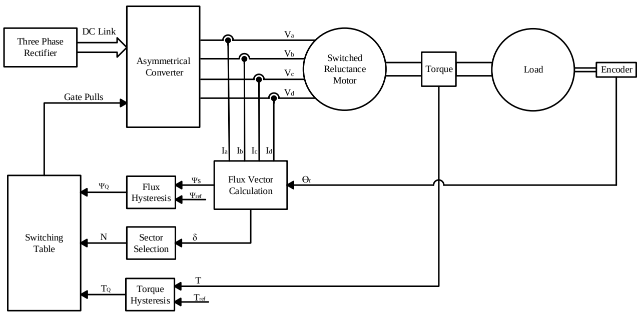

Figure. 11. The general diagram of the DTC control method

8. Experimental results

Conclusions

In this paper, the conventional direct torque control of switched reluctance motor was studied with respect to copper losses. An improved method was also proposed for enhancing the efficiency of the drive system. Both methods were simulated for an industrial switched reluctance motor 6/8. The simulation was accomplished in MATLAB environment and the results were compared. It may be concluded that as the proposed scheme does not require additional hardware and also because copper losses may be reduced only by reducing the negative torque phase and the phase current, the proposed method is acceptable for application to SRMs.

. It is clear that the flux has somewhat declined in the four areas between those that have the same directions as the phases. This is due to the decreasing current of the phases. As already mentioned, however, this reduced flux will have no negative impact on the torque generated.

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