A High Performance DTC Strategy for Torque Ripple Minimization Using duty ratio control for SRM Drive

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Abstract **- Direct torque control (DTC) of Switched reluctance motor is known to have simple control structure with comparable performance to that of field oriented control techniques Direct Torque Control has get more and more attentions, but there still are many problems need to be solved in this field. One of these is to minimize the torque ripple and current harmonics. As we all know the output voltage in DTC contains much harmonics for applying hysteresis band in this kind of system. In this paper the torque ripple in DTC is analyzed in detail with little signal model. It is found that the torque ripple can be divided into two parts, one is only related to the motor parameter and the other is related to not only the applied voltage but also the rotor angular velocity. Based on the analysis, a duty ratio modulation method is proposed that only sends the voltage vector in part of the sampling period, while in the rest time of the sampling period zero voltage vector is sent. The duty ratio modulation algorithm, which is induced from the torque ripple analysis, allocates the sampling period. Simulation results indicate the effectiveness of the proposed torque ripple minimizing method.**

Keywords **– Direct Torque Control, Fuzzy Logic Control, Duty Ratio Control, Switched Reluctance Motor Drive.**

I. INTRODUCTION

Switched reluctance motor, the doubly salient, singly excited motor has simple and robust construction. Although, the induction motor is still the workhorse of the industries, the promising feature of the high torque to mass ratio, high torque to inertia ratio, low maintenance, high specific output and excellent overall performance of SRM make it an efficient competitor for ac drives. The simplified converter topology and switching algorithm due to the unipolar operation avoiding shoot through faults makes SRM advantageous in applications of aerospace, which require high reliability. Also it finds wide application in automotive industries, direct drive machine tools etc [1]. However, significant torque ripple, vibration and acoustic noise are the main drawbacks of SRM to achieve high performance. As the control of SR motor is being the recent trend of research, schemes were developed involving linear and non-linear models to control torque ripple [2]. But due to inaccuracy in linear models and complexity involved in non-linear control, the Direct Torque Control (DTC) was proposed which provided simple solution to control the motor torque, speed and minimized torque ripple.

Proposed by Depenbrock and lsao Takahashi in the middle of 1980"**s,** Direct Torque Control has attracted more and more attention in the following decades. Besides its advantages in application, the conventional DTC system has its drawbacks. First, its switching frequency varies according to the motor speed and the hysteresis bands of torque and flux. Second, large torque ripple is generated especially in a low speed region. Thud, in DTC the stator current contains much more harmonics than that fed with sinusoidal voltage. In order to reduce the torque ripple and the current harmonics, high switching frequency is needed but this will bring high sampling frequency and increase the system cost. Takahashi proposed a double three phase inverter [3] and C.G. Mei used variable switching sectors to minimize the torque and flux ripple [4]. Multilevel inverter is another choice **[**5**],** which reduces the torque ripple and current harmonics by providing more selective voltage vectors. But this kind of topology needs more power devices and the control scheme becomes more complex, that make it only suitable for high power applications. Lixin Tang and Rahman, M.F have suggested solving this problem with Space Vector Modulation technique **[**6**],** but that will remove the basic advantage of DTC-simplicity. In this paper analysis work is done on the relationship between applied voltage and corresponding torque and stator flux variations. Based on the analysis, a new DTC strategy is introduced with torque ripple reduction by modulating the duty ratio of the applied voltage. Simulation results are presented to verify the effectiveness of the control algorithm.

II. THE CLASSICAL DTC SCHEME FOR SRM

DTC is based on theories of field oriented (FOC) control and torque vector control. Field Oriented Control uses space vector theory to optimally control magnetic field orientation. The DTC principle is to select stator voltage vectors according to the differences between the reference torque and stator flux linkage with exact value. Voltage vector are so chosen to limit the torque and flux errors within hysteresis bands. The required optimal voltage vectors are obtained from the position of the stator flux linkage space vector, the available switching vectors and the required torque and flux linkage [7],[8].

To drive the control scheme for the SR motor, the non-uniform torque characteristics will firstly be examined. The motor torque output can be found using the motors electromagnetic equation. (1)

$$v = Ri + \frac{d\psi(\theta,i)}{dt} \tag{1}$$

The energy equation is

$$dW_e = dW_m + dW_f \tag{2}$$

Where dW_m = differential mechanical energy, dW_f =differential field energy. But

$$dW_e = eidt \tag{3}$$

$$dW_f = \frac{\partial W_f}{\partial i} di\,|_{\theta=const} + \frac{\partial W_f}{\partial \theta} d\theta\,|_{i=const} \tag{4}$$

The instantaneous torque expression is

$$T = \frac{dW_m}{d\theta} \tag{5}$$

Hence by substitutions torque expression is derived considering the variation of magnetic co-energy and is given by

$$T \approx i\frac{d\psi(\theta,i)}{d\theta} \tag{6}$$

This approximate equation is sufficient for control purpose as it controls the general characteristics of torque production and not the magnitude of torque. The current is always positive as SRM is a unipolar drive. Hence, the sign of torque is directly related to the sign of $\partial\psi/\partial\theta$. The increase of stator flux amplitude with respect to rotor position (positive value of $\partial\psi/\partial\theta$) produce a positive torque and is called "flux acceleration". Whereas a negative value of $\partial\psi/\partial\theta$ called "flux deceleration" produce a negative torque. As this is held for both directions of rotation a four quadrant operation is achieved using unipolar currents.

The DTC technique can be defined as follows.

a)The stator flux linkage vector of the motor is kept at constant amplitude.

b) Torque is controlled by accelerating or decelerating the stator flux vector.

III. VOLTAGE VECTORS FOR SRM

Similar to the AC drives, equivalent space vectors can be defined for SRM. The voltage space vector (Fig. 1) for each phase is defined as lying on the center axis of the stator pole because the flux linkage for a current and voltage applied to the motor phase will have phasor direction in line with the centre of the pole axis. This does not need any change in physical winding topology.

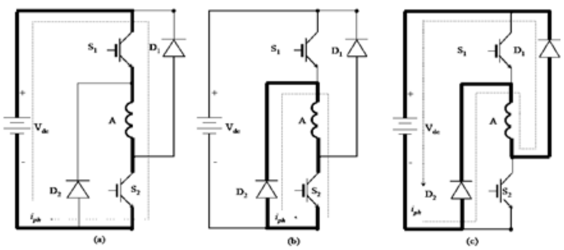

Fig. 1. SR motor phase voltage states.

In SRM, each motor phase can have three possible voltage states (S_q) for a unidirectional current.

i. When both devices are ON and positive voltage is applied S_q=1.

ii. For S_q=0, one device is turned OFF and a zero voltage loop occurs.

iii. For negative state S_q=-1, both devices are OFF. The freewheeling current flows through the diodes.

So with each phase having three possible states (0, 1,-1) unlike conventional DTC for ac drives with two states, a total of 27 possible configuration is possible.

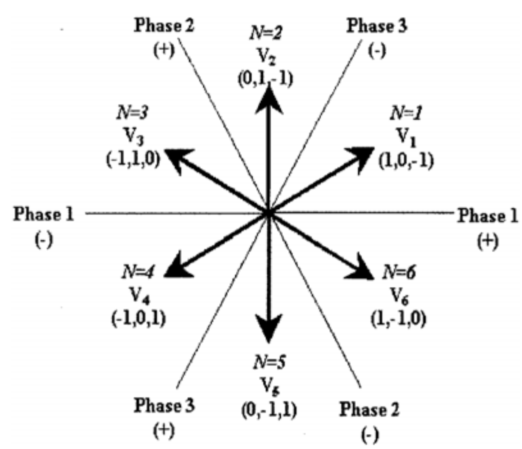

Fig. 2. Definition of SR motor voltage vectors for DTC drive

Fig.2. shows only six equal magnitude voltage vectors separated by π/6 radians is considered as DTC allows no other states to be chosen by the controller. One out of the six states is chosen to keep torque and flux within the hysteresis bands. Let the stator flux vector be located in the K^{th} sector (K=1,2,3,4,5,6). In order to increase the amplitude of the stator flux, the voltage vector V_K,V_{K+1},V_{K-1} can be applied and V_{K+2},V_{K+3}, V_{K-2}, can be applied to decrease the flux. V_K and V_{K+3} are zero space vectors.

The control scheme of SRM is based on the results as follows.

a) The motor is solicited only through the converter component of voltage space vectors along the same flux.

b) The motor torque is affected by the component of the voltage space vector orthogonal to the stator flux.

c) The zero space vectors do not affect the space vector of the stator flux.

So the stator flux when increased by V_{K+1} and V_{K-1} vectors and decreased by V_{K+2} and V_{K-2} affect the torque. As V_{K+1} and V_{K+2} vector advance the stator flux linkage in the direction of rotation they tend to increase the torque. But V_{K-1} and V_{K-2} decelerate the flux in opposite direction and decrease the torque. So the switching table becomes as TABLE. I

TABLE I
STATOR FLUX AND TORQUE VARIATIONS DUE TO APPLIED INVERTER VOLTAGE SPACE VECTOR.

T↑ ψ↑	**T↑** ψ↓	**T↓** ψ↑	**T↓** ψ↓
V_{K+1}	V_{K+2}	V_{K-1}	V_{K-2}

IV. CONCEPT OF DUTY RATIO CONTROL

In conventional DTC, in steady state with constant load, an active switching state causes the torque to continue to increase past its reference value until the end of the switching period. Then a zero voltage vector is applied for the next switching period causing the torque to continue to decrease below its reference value until the end of the switching period. This results in high torque ripple as shown in Fig. 3. A possible solution to reduce the torque ripple is to use a high switching frequency; however, that requires expensive processors and switching devices. A less expensive solution is to use duty ratio control. In DTC with duty ratio control, the selected voltage vector is applied for a part of the switching period rather than the complete switching period as in conventional DTC.

By applying a nonzero voltage vector for only a portion of the switching period, and the zero voltage vectors for the remainder of the period, the effective switching frequency is doubled. Therefore, over any single switching period, the torque variations above and below the average value are smaller. Further, as the duty ratio is controlled, the average stator voltage is adjusted directly.

Also there is no need to make fine corrections by the use of multiple switching periods with a nonzero voltage vector or a whole switching period with a zero voltage vector. The average phase voltage is adjusted more smoothly, and the overall torque ripple is reduced.

(a) DTC with Duty Ratio Fuzzy Control

In the conventional DTC a voltage vector is applied for the entire switching period, and this causes the stator current and electromagnetic torque to increase over the whole switching period. Thus for small errors, the electromagnetic torque exceeds its reference value early during the switching period, and continues to increase, causing a high torque ripple. This is then followed by switching cycles in which the zero switching vectors are applied in order to reduce the electromagnetic torque to its reference value. The ripple in the torque and flux can be reduced by applying the selected inverter vector not for the entire switching period, as in the conventional DTC drive, but only for part of the switching period.

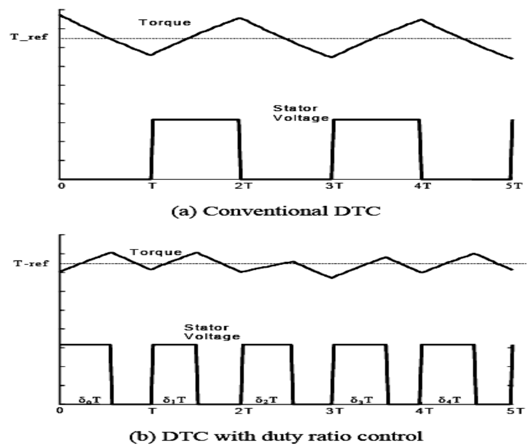

Fig. 3. Effect of Duty Ratio Control on the Torque Ripple.

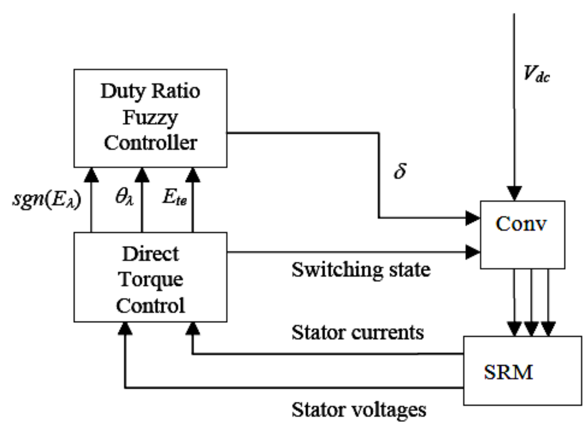

Fig. 4. DTC with Duty Ratio Fuzzy Control

The time for which a non-zero voltage vector has to be applied is chosen just to increase the electromagnetic torque to its reference value and the zero voltage vectors are applied for the rest of the time in the inverter. During the application of the zero voltage vectors, no power is absorbed by the machine, and thus the electromagnetic flux is almost constant; it only decreases slightly. Fig. 4 shows a DTC drive with a duty ratio fuzzy logic controller for SRM. The average input DC voltage to the motor during the application of each switching vector is δV_{dc}. By varying the duty ratio between zero and one, it is possible to apply voltage to the motor with an average value between 0 and V_{dc} during each switching period. Thus, the torque ripple will be less when compared to applying the full DC link voltage for the complete switching period. This increases the choice of the voltage vector, without an increase in the number of semiconductor switches in the inverter.

The duty ratio of each switching period is a non-linear function of the electromagnetic torque error, stator flux-linkage error, and the position of the stator flux-linkage space vector. Thus, it is difficult to model this non-linear function. However, by using a fuzzy-logic-based DTC system, it is possible to perform fuzzy-logic-based duty-ratio control, where the duty ratio is determined during every switching cycle. In such a fuzzy-logic system, there are three inputs, the electromagnetic torque error ($E_{te}=T_{ref}$ - T), the stator flux-linkage space vector position (θ_{λ}) within each sector associated with the voltage vectors and the sign of the flux error (sgn(E_{λ})) where ($E_{\lambda}=\lambda_{ref}$ -λ). The output of the fuzzy-logic controller is the duty ratio (δ).

(b) Design of Duty Ratio Fuzzy Controller

There are many types of fuzzy logic controllers for this particular application. A Mamdani-type fuzzy logic controller, which contains a rule base, a fuzzifier, and a defuzzifier, is chosen. In this fuzzy controller, two sets of rule base are used. The first set is used when the stator flux is smaller than the reference value (positive flux error) and the second set is used when the stator flux is greater than the reference value (negative flux error). The inputs and the output of the fuzzy controller are assigned Gaussian membership functions as shown in Figs. 5-7. The universe of discourse for the torque error and the duty ratio is adjusted using simulations to get optimal torque ripple reduction. Since there are three membership functions for each input, it follows that there are nine rules in each set of fuzzy rules. The presented fuzzy controller is for both forward and backward rotation whereas for backward rotation the absolute value of the torque error is used, and the flux position calculation is adjusted according to the rotation direction.

The emphasis in the fuzzy rule is to reduce the torque ripple. Generally the duty ratio is proportional to the torque error, since the torque rate of change is proportional to the angle between the stator flux and the applied voltage vector, the duty ratio depends also on the flux position within each sector. The use of two fuzzy sets is due to the fact that when the stator flux is greater than its reference value a voltage vector that advances the stator flux vector by two sectors is applied which results in a higher rate of change for the torque when compared to the application of a voltage vector that advances the stator flux vector by one sector when the stator flux linkage is less than its reference value.

The duty ratio is selected proportional to the magnitude of the torque error so if the torque error is small, medium or large then the duty ratio is small, medium or large respectively. The fuzzy rules are then adjusted and tuned to reflect the effects of the flux error and position.

If the torque error is medium and the stator flux lies in sector k with a magnitude greater than its reference value (negative flux error) then the voltage vector V_{k+2} is selected. If the flux position is small then there is a large angle between the flux and the selected voltage vector. Thus makes the selected vector more effective in increasing the toque so the duty ratio is set as small rather than medium. The fuzzy rules are stated as

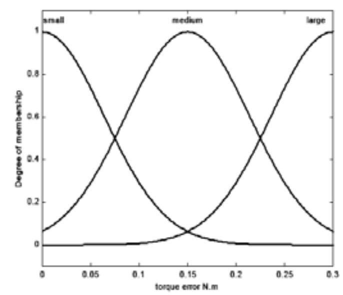

Fig. 5. Membership Functions Distribution for the Torque Error Input)

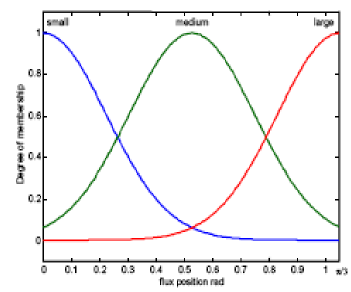

Fig. 6. Membership Functions Distribution for the Flux Position (Input)

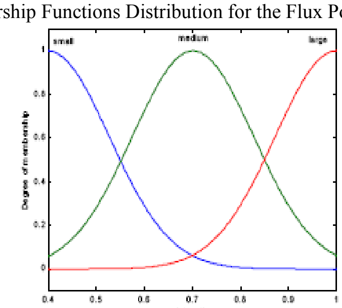

Fig. 7. Membership Functions Distribution for the Duty Ratio (output)

- If (torque error is medium) and (flux position is small) then (duty ratio is small)
- If (torque error is large) and (flux position is small) then (duty ratio is medium)

Using the above reasoning to find the fuzzy rules, the two sets of fuzzy rules are summarized in Table II.

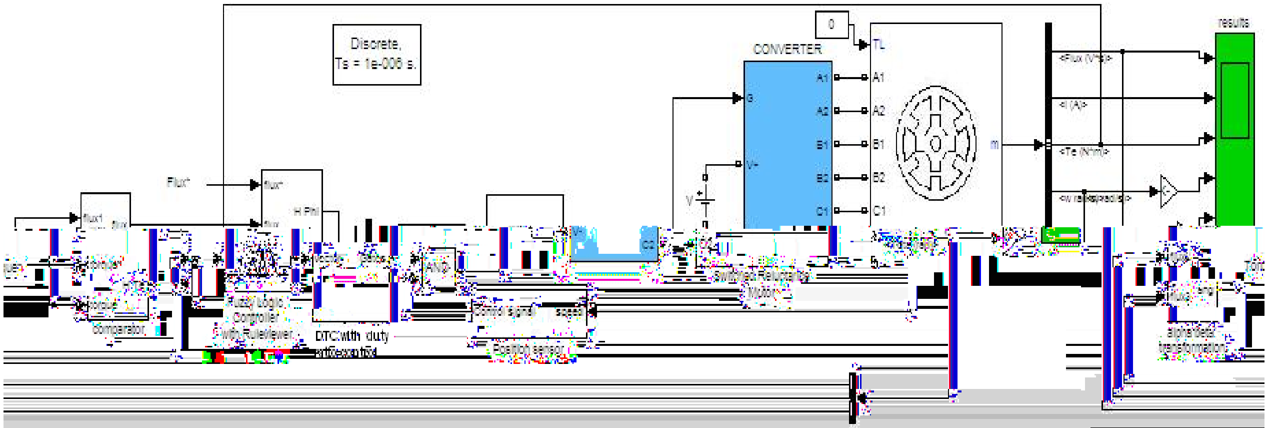

Fig. 8. Block diagram for proposed duty ratio control with fuzzy logic approach

TABLE II
RULES FOR DUTY RATIO FUZZY CONTROLLER

Flux error	Torque error	Small	Medium	Large
Negative $d\lambda = 0$	small	small	small	medium
	medium	small	medium	Large
	Large	small	medium	Large
positive $d\lambda = 1$	Small	small	medium	Large
	medium	small	medium	Large
	Large	medium	Large	Large

V. SIMULATION RESULTS

The Conventional DTC and DTC with the duty ratio fuzzy control were simulated and compared. Constant torque and flux commands of 1.5 Nm and 0.16 Wb were used. The simulation was run at switching frequencies of 20 kHz. Fig.9 and 10, shows the torque response of the motor using conventional DTC and DTC with duty ratio fuzzy control. It shows the torque ripple is reduced with the duty ratio fuzzy control.

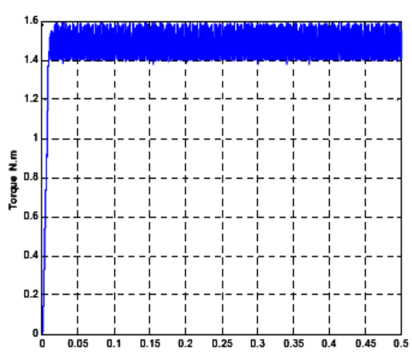

Fig. 9. Electric Torque Using Conventional DTC

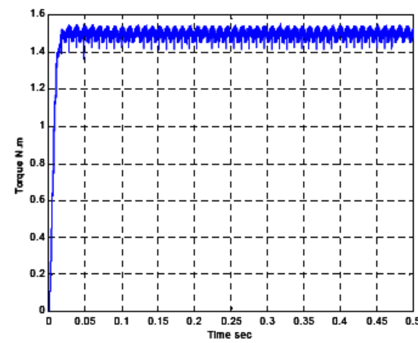

Fig. 10. Electric Torque Using DTC with Duty Ratio Fuzzy Control

VI. CONCLUSION

In this paper the torque ripple in DTC is analyzed in detail. And a novel torque ripple minimization method is proposed. In this method the output voltage duty ratio is calculated and applied during every sampling period. And this duty cycle modulation module is very easy to be embedded in conventional DTC scheme without increasing the system complexity greatly. Simulation results prove the advantages of this method.

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