A Comparative Study of Pre-computed Current Methods for Torque Ripple Minimisation in Switched Reluctance Motor

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Abstract- **One of the few drawbacks of Switched Reluctance Motor (SRM) is the high torque ripple when compared to the conventional AC and DC drives. In this paper, some of the pre-computed current methods for torque ripple minimisation in SRM are compared with the method proposed by the authors. The approach to the problem of finding the current trajectories to minimise the torque ripple in different proposed schemes are briefly explained. For all the schemes considered for comparison, the current trajectories are computed using the test data available for a 4 kW 8/6 pole SRM. A comparative study is made using simulation results.**

I INTRODUCTION

Simple construction and high torque to inertia ratio are striking advantages of SRM as compared to conventional AC and DC motors. The construction and the operating principles of SRM are well documented [1,2]. The primary disadvantage of SRM is the higher torque ripple compared to conventional machines. The torque ripple is objectionable in a high performance servo application especially at low speeds. It also adds to the vibration and acoustic noise. Higher torque pulsation in SRM is due to the non-linear and discrete torque production mechanism. The total torque in SRM is the sum of the torque produced by each phase of the stator phases. The torque pulsation are significant during the commutation when the torque production shifts from one active phase to the other.

For a given machine, the torque ripple can be sigificantly reduced by controlling the phase current as a function of rotor position. The desired phase currents can be obtained either in real time or by pre-computations. Several approaches are available to pre-compute the desired phase currents [3-8]. Some of the published work in the area of pre-computed currents for torque ripple minimisation in SRM are considered here for comparison. The results presented in each of these paper are obtained from SRMs with different converter configuration and rating. The objective of this paper is to apply the essence of these methods to a single machine and compare the schemes. This approach not only helps in understanding the schemes qualitatively but also quantifies the difference. In this paper, four approaches including the one suggested by the authors earlier are briefly described and the computed results are given. Simulation studies are made for comparisons. The experimental results of the schemes are reported in the corresponding reference papers.

All the computed results are obtained from the flux-linkage characteristics and the static torque characteristics of 4 kW 8/6 pole OULTON SRM which are shown in Fig 1 and Fig. 2 respectively. [9]

II. DESCRIPTION OF THE METHODS

Four methods are considered for comparison and they are as follows.

Method 1

In this method [5], the current gets decided uniquely by a phase when it is dominating thus giving maximum torque per ampere. In the commutation interval torque linearly falls to zero in one phase and rises in the other linearly. The commutation interval is chosen such that at the central point of commutation the currents are equal. The computed currents and the corresponding torque using the above criteria is as shown in Fig. 3, for a torque level of 20 Nm.

Method 2

In this method [6], the phase is identified as strong, rising or falling depending on the component of the torque it produces. The phase is strong when it can produce the desired torque with minimum current. Rising or falling phases appear during commutation when the dominance change from one phase to the other. The commutation is such that at the central point of commutation the torque per amperes of the two commutating phases are equal. The incoming phase current is allowed to rise linearly up to the central point of commutation and later the current in the out going phase is allowed fall linearly. During commutation interval, there will only two phase currents and the torque produced by them will be either strong and rising or strong and falling. The current in the strong phase is computed based on the difference between the desired torque and the torque developed by either rising or falling current phase. The commutation duration has been modified as the machine characteristics considered here for comparison do not permit to use the same commutation interval proposed in the paper. The computed currents and the corresponding torque using this strategy are as shown in Fig 4.

Method 3

In this method [7], a contour function is used for the torque produced by each phase to obtain a constant resultant torque $T_{ref.}$ The contour function is defined as follows,

$$T_{total} = T_{ref} * f_T(\theta) \quad (1)$$

Where,

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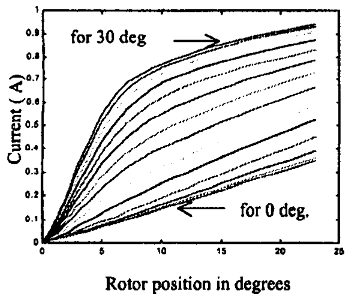


Fig 1.Flux-linkage characteristics of 4 kW SRM

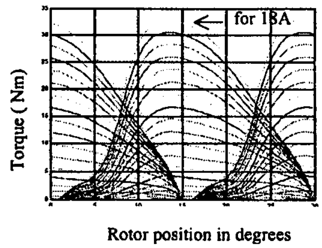


Fig. 2 Static torque characteristics of SRM

$$f_T = \sum_{k=1}^{n} f_k(\theta) = 1 \qquad (2)$$

Here f_k is the contour function of the k^{th} phase.

One of the possible choice for contour function f_k, chosen in the paper [7] for 8/6 pole SRM for the phase 1 is as follows,

$$f_1 = .5 - .5\cos 4(\theta - \theta_0) \qquad \theta_0 \le \theta < \theta_1$$

$$= 1 \qquad \theta_1 \le \theta < \theta_2$$

$$= .5 + .5\cos 4(\theta - \theta_2) \qquad \theta_2 \le \theta < \theta_3$$

$$= 0 \qquad \text{otherwise.} \qquad (3)$$

The choice of the reference angle depends on the inductance profile of the motor.

The computed currents and the corresponding torque with $\theta_0 = 5^0$, $\theta_1 = 12^0$, $\theta_2 = 20^0$, $\theta_3 = 27^0$ are shown in Fig. 5 for a resultant torque of 20 Nm.

Method 4

The next method is the numerical approach method and is proposed by the authors [8]. It is briefly described here.

A. Problem Formulation

The resultant torque of the motor must be constant for all rotor positions. This can be mathematically expressed as,

$$t = k1 \quad \text{for all } \theta \qquad (4)$$

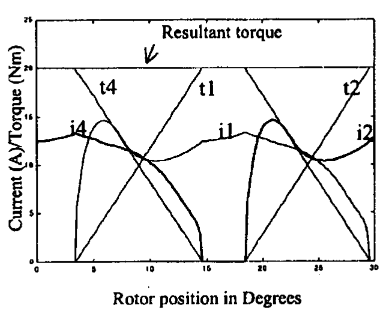
where the value of the constant k1 is equal to the desired torque (td), and t is given by

$$t = \sum_{k=0}^{k=4} t_k \qquad (5)$$

and

$$t_k = \frac{\partial w_k}{\partial \theta_k}\Big|_{i=\text{constant}} \qquad (6)$$

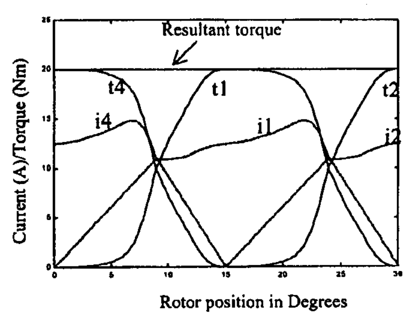
The solution is sought subjected to the following condition;



i4, i1, i2 phase currents

t4, t1, t2 Phase torques

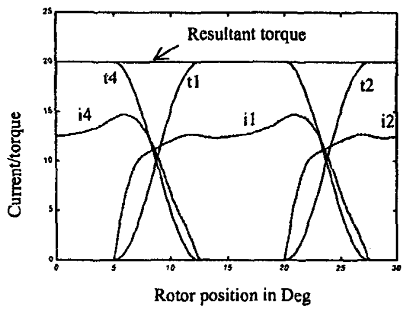
Fig.3 Computed current and the torque using Method 1



i4, i1, i2 phase currents

t4, t1, t2 Phase torques

Fig.4 Computed current and the torque using Method 2



i4 ,i1, i2 phase currents

t4, t1, t2 phase torques

Fig.5 Computed current and the torque using Method 3.

1. $$\frac{t}{\sum_{k=1}^{k=4} i_k} = \max\left[\frac{t}{\sum_{k=1}^{k=4} i_k}\right] \quad (7)$$

where ik the solution of the equation

$$v = i_k R + \frac{\partial \Psi_k(\theta_k, i_k)}{\partial \theta_k} \quad (8)$$

2. $[i_k]_{max} = k2$ (9)

the value of the constant k2 is equal to peak current limit

B. Solution

As this problem is quite involved, the solution is worked out using the numerical method and the equations are modified to suit the computation. The following assumptions are made

1. The speed is assumed to remain constant
2. The mutual inductance and eddy current effects are neglected.
3. The resistance of the winding is neglected.

A search algorithem is used to get solution.

The change in phase current required is required to meet the following constraint which is due to Eq. (8) and it can be expressed as,

$$\frac{di_k}{dt} = \frac{1}{\frac{\partial \Psi(\theta_k, i_k)}{\partial i_k}} * [v - i_k R - \omega \frac{\partial \Psi_k}{\partial \theta}] \quad (10)$$

The term $\frac{\partial \Psi}{\partial i}$ corresponds to the incremental inductance and it is obtained by numerically differentiating the flux-linkage characteristics with respect to phase current for any given rotor position. The back emf coefficient $\frac{\partial \Psi}{\partial \theta}$ is obtained by numerically differentiating the flux-linkage with respect to rotor position for any given phase current and these coefficients are multiplied by angular velocity to get the backemf.

The solution is obtained as follows ;

1. The required currents are obtained for every 0.2 degrees of rotor position.
2. Time required to cover 0.2 degrees is calculated for the chosen value of speed
3. For unaligned rotor position of a phase (say phase 2) the dominating phase (phase 1) is allowed to take the desired load torque and to estimate the current required a spline fit is used.
4. For any other position, the maximum and the minimum values on the phase current is calculated from Eq. (10) in difference form as follows

$$i_{1\,max}(\theta_n) = i_1(\theta_{n-1}) + \frac{v - e_{b1}(\theta_{n-1}, i_1(\theta_{n-1}))}{l(\theta_{n-1}, i_1(\theta_{n-1}))}\Delta t \quad (11)$$

$$i_{1\,min}(\theta_n) = i_1(\theta_{n-1}) - \frac{v - e_{b1}(\theta_{n-1}, i_1(\theta_{n-1}))}{l(\theta_{n-1}, i_1(\theta_{n-1}))}\Delta t \quad (12)$$

$$i_{2\,max}(\theta_n) = i_2(\theta_{n-1}) + \frac{v - e_{b2}(\theta_{n-1}, i_2(\theta_{n-1}))}{l(\theta_{n-1}, i_2(\theta_{n-1}))}\Delta t \quad (13)$$

$$i_{2\,min}(\theta_n) = i_2(\theta_{n-1}) - \frac{v - e_{b2}(\theta_{n-1}, i_2(\theta_{n-1}))}{l(\theta_{n-1}, i_2(\theta_{n-1}))}\Delta t \quad (14)$$

The maximum current of the phases are limited to peak current limit and minimum current to zero.

5. At each position, the phase in which the required torque can be obtained with minimum current is allowed to take the entire torque, if the computed current is within the current limits as obtained from Eq. 11-14. If the phase current reaches the peak current limit and if the torque produced is less than the desired torque, then the next positive torque producing phase is allowed to take the remaining torque. When the domination changes from first to the second phase, the second phase current is allowed to rise up to a value which is governed by its maximum current limit, the restriction that arises from the rate of fall of current in the other phase and the constant resultant torque condition.

6. This procedure is repeated until the unaligned position of the next phase(phase 3) is reached. At this position the solution repeats if the current in the outgoing phase(phase 1) reaches zero. If not, the dominant torque producing phase (phase 2) is called upon to compensate for the negative torque produced by the out going phase. The corrected results are used as reference for all the phases.

The computed results for a bus voltage of 560 v at 150 rpm is shown in Fig. 6. A Peak current limit of 18 A is used to obtain the solution.

C. Influence of the speed and bus voltage

As the speed changes the back emf and the time requirement to cover the angle step considered for solution changes. Therefore the upper and lower limit for the current

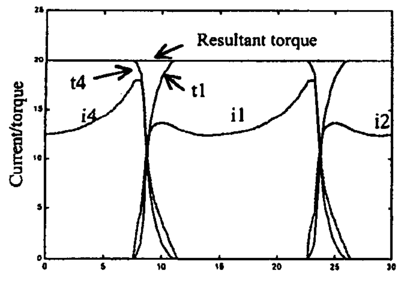


Fig. 7 Computed currents and the torque using Method 4 at 150 rpm for a bus voltage of 560V

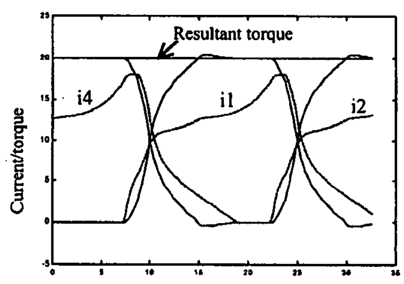


Fig. 7 Computed currents and the torque using Method 4 at 450 rpm for a bus voltage of 560V

changes as a function of speed. The computed results at 560 V and 450 rpm are shown in Fig. 7. The results shows that the current in the phase will not reach zero before 30 degrees as in the case of 150 rpm. Therefore the computations are continued till the solution repeats.

Similarly the method can also be used to get the solutions at different bus voltages. (The upper and lower permissible limit for the currents will increase with increase in the bus voltage for a given speed.)

A comparison of solutions at different speed are shown in Fig 8, along with the current trajectories obtained with instantaneous commutation (here the phase currents changes instantaneously once the domination changes one phase to the other); This comparison is made to understand the influence of back-emf and the incremental inductance of the machine which restrict the rate of rise of current in the phase once that phase takes the dominance.

III COMPARISON OF METHODS

The comparison of all the schemes are studied by means of simulation. The influence of speed on the torque ripple and the average currents are studied by carrying out the simulation at two different speeds.

All the schemes will give zero torque ripple if the computed currents can be established at the desired rotor position. In practice, the current control is carried out by chopping when a constant DC bus voltage is used. The actual phase currents will have current ripple due to switching. The current ripple inturn leads to the torque ripple. To keep the switching frequency influencing the torque ripple the maximum permissible frequency limit is set to 40 kHz in all the schemes in simulation.

Figure 9 shows the simulation results in which the phase currents, the reference currents, and the resultant torque are shown at 150 rpm and at 450 rpm for all the schemes.

It is clear from Fig .9 that, the torque ripple will not vary appreciably at 150 rpm in all the methods as the actual currents can be made to follow the reference currents closely. The torque ripple increases in method 1-3 at 450 rpm. as the current cannot be forced to fall as rapidly as demanded by the reference current near the aligned rotor position. This is due to shorter time available and the increased level of back emf when compared to 150 rpm. At 450 rpm, the percentage toque ripple with respect to the average torque in Fig 9 are +5.99 and -10.39 in method 1. Method 2 gives 4.65 and -3.54. Method 3 gives 7.88 and -4.52. Method 4 gives 3.4 and -3.09. As the incremental inductance, and the back emf are accounted in method 4, the torque ripple is lesser in method 4 compared to all the other methods.

The average currents are computed from the different method at different torque levels and it is shown in Fig. 10. The average current is obtained from the reference currents. The average current with instantaneous commutation is also shown here for comparison. It is observed that at lower speeds, the average current in method 4 is appreciably lesser than in other methods for all torque levels. The average current increases in the method 4 with speed since the commutation interval increases with speed. Still the average current obtained by method 4 will be lesser than the methods 1 and 2. Appreciable difference in average currents is not observed between method 1 and 2 at lower torque levels.

A Remarks

Method 1 and Method 2 follows pre-defined torque trajectories. During commutation, a trapezoidal torque profile is used in Method 1 and sinusoidal torque profile is used Method 2. It is to be noted that, if the torque profile is fixed first, it may not be possible to establish the desired currents to meet the desired torque profile at different speeds. This is because, the currents are governed by voltage equation. In Method 3, the slope of current in

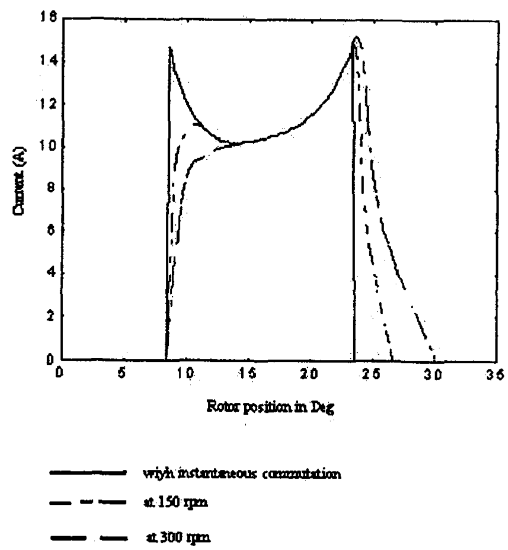


Fig. 8 Comparison of computed currents in Method 4 with the results obtained assuming instantaneous commutation.

falling and rising phases remains constant and neglects the saturation effects. As the machine is prone for saturation,it must be accounted to get better results. This point is evident from the simulation results (Tracking the falling phase reference current will not be possible as inductance keeps increasing appreciably with decrease in phase current. In other words the control demands a higher negative voltage than the available bus voltage). A closer tracking of the reference current is possible in Method 4 as it checks the feasibility of establishing the current at the time of pre-computing. A common disadvantage in all the methods other than the proposed method (Method 4) is that, the influence of bus voltage, and speed are not observable as the solutions do not depend on these factors.

IV CONCLUSION

A comparative study of different torque ripple minimisation schemes are studied in this paper. The results show that the torque ripple will not appreciably differ in all the schemes at low speed (150 rpm) although their average currents differ. At slightly higher speed (450 rpm) ,the torque ripple is higher in all other methods compared to the proposed method [Method 4]. The proposed method also gives lesser average currents and permits the use of peak current limit. It also helps in quantifying the factors influencing the torque ripple.

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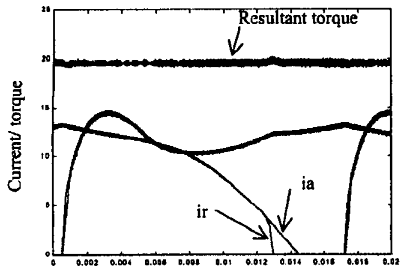
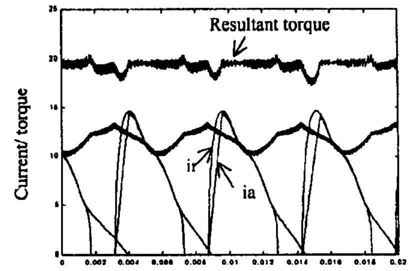
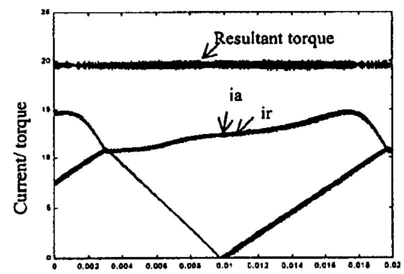


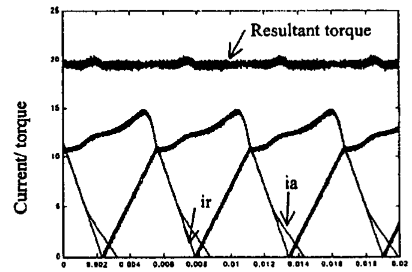
Method 1 at 150 rpm



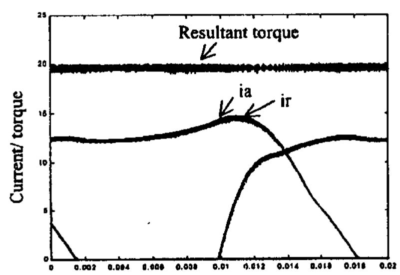
Method 1 at 450 rpm



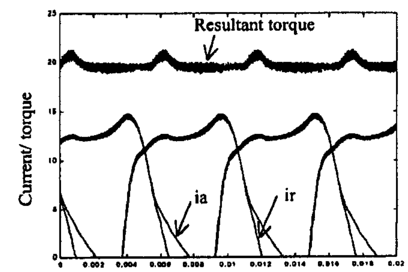
Method 2 at 150 rpm



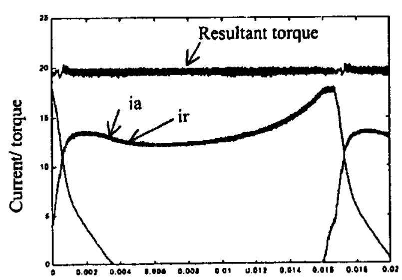
Method 2 at 450 rpm



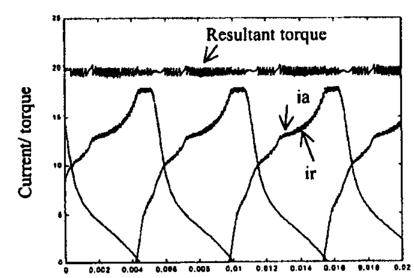
Method 3 at 150 rpm



Method 3 at 450 rpm



Method 4 at 150 rpm



Method 4 at 450 rpm

Fig. 9 Simulation results showing actual phase currents, reference currents and the resultant torque in different methods.

ia : actual phase current

ir : reference phase current

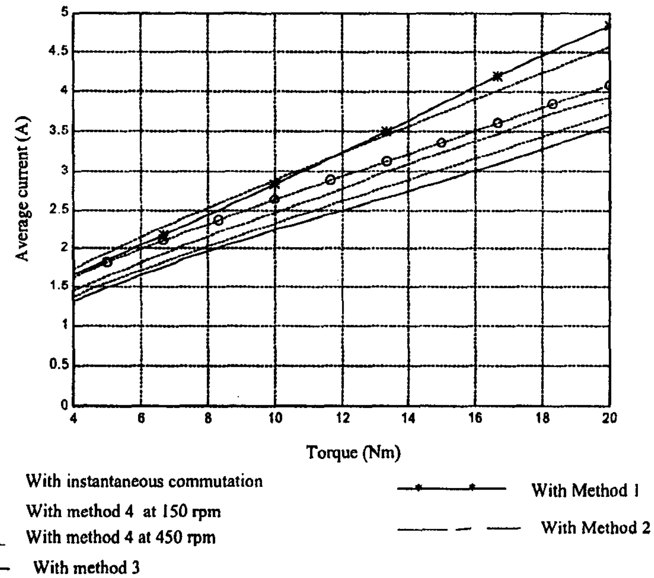


Fig 10 Comparison of average currents