Torque Control of Switched Reluctance Motors Using a Fuzzy Iterative Approach

R. Gobbi and N. C. Sahoo

Abstract—**This paper deals with a fundamental control issue in switched reluctance motor (SRM) drives – the torque ripple minimization. Normally, the torque ripple minimization is achieved by using a look-up table, i.e., the look-up table makes use of stored magnetic characteristics to provide reference currents for some specified torque. A number of techniques for the generation of reference current profiles have been suggested. However, because of highly nonlinear magnetic characteristics of SRM, all these schemes are not entirely successful. This work deals with a novel algorithm for generation of current waveforms by an iterative modulation of reference current pattern, using a multiplying factor. This multiplying factor is computed with help of a fuzzy system, which is well suited to compensate nonlinearities of the system. Two different schemes, i.e., one-phase-on scheme and two-phase-on scheme with torque sharing functions, are presented. The performance of the proposed strategy is verified by simulation studies.**

Index Terms—**Switched reluctance motor, torque ripple, current modulation, fuzzy system, iterative approach.**

I. Introduction

Recently, switched reluctance motor has emerged as a popular alternative to brushless DC and AC motors because of its simple and reliable structure, i.e., no magnets and windings on the rotor. It uses a unipolar power converter and can produce high torque at low speeds. However, it has limited industrial applications because of its torque ripples caused by the nonlinear torque production mechanism. The problem of torque ripple minimization has been pursued by several researchers using many approaches supported by exhaustive measurements of magnetic characteristics [1]-[3]. An analytical method using Fourier analysis and linear magnetics of SRM has also been suggested [4]. But, it produces considerable torque pulsations when used with nonlinear model. In [5], a fuzzy logic based scheme has been attempted where the initial reference current is generated as suggested in [4].

Here, an iterative method is presented, based on fuzzy logic, for determination of current waveforms so as to suppress torque ripples. Fuzzy logic is well suited to the problems with a large degree of nonlinearity and uncertainty [6], [7]. Since the torque developed by SRM is dependent on phase currents and rotor positions, the proposed fuzzy iterative approach (FIA) modulates the current waveforms from iteration to iteration by the use of a multiplying factor determined by a fuzzy rule base with two inputs, i.e., torque error and rotor position. Basically, by using the multiplying factor (which is multiplied with the torque command in the conventional current calculation using linear torque model), the SRM is asked to produce some other suitable torque profile (linear model torque calculation point of view) other than the actual commanded (desired) torque so that torque ripple is minimized with respect to the actual desired torque. This approach is adopted since the SRM does not produce the commanded torque profile with the conventional scheme. The FIA computes a correction term from iteration to iteration. This correction term is added/subtracted to/from the reference phase current of a preceding phase, in each iteration depending on the sign of the torque error (positive/negative), respectively. The corrected current is fed to the stator winding. This iterative process goes on until torque ripple is completely eliminated. All the tests are done under assumed static conditions, i.e., the computed current is assumed to be flowing instantaneously in the stator winding, and is based on a well-known nonlinear torque model of SRM. This scheme has been tested with two different excitation schemes, namely, one-phase-on scheme and two-phase-on scheme with torque sharing functions. The proposed approach can be easily used, without much computational effort, for construction of an efficient look-up table to determine reference current waveforms.

II. SRM Torque Model

The SRM has a salient pole stator with concentrated coils and also a salient pole rotor without magnets or conductors. The basic principles of SRM operation are described in [8]. A four-phase motor is used here. All the four phases are assumed to be symmetrical. In the followings, reference to a generic phase j is reflected as a subscript in the variables. Because of double saliency of the motor and magnetic saturation, the inductance of phase j ($j = 1,..,4$), L_j, is a function of both rotor position θ and current I_j. However, under the assumption of linear magnetics, inductance vs. rotor position profile for each phase can be approximated over one rotor pole pitch as shown in Fig. 1 (solid line). The significance of the sinusoidal dotted curve will be explained later. The parameters in Fig. 1 are: β_s = stator pole arc, β_r = rotor pole arc ($\beta_s < \beta_r$), α_r = rotor pole pitch ($\beta_s + \beta_r < \alpha_r$), L_a = phase inductance at aligned position, and L_u = phase inductance at unaligned position.

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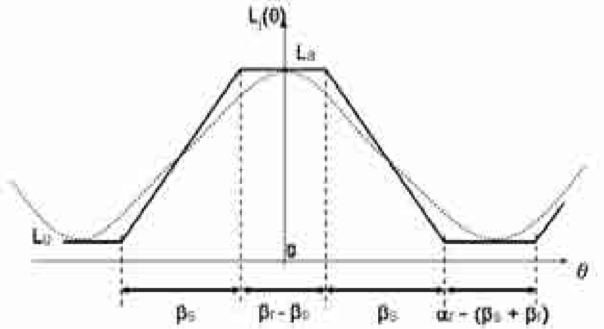

Fig. 1. Approximated inductance profile for the reference phase (phase 1 is arbitrarily chosen).

A. Linear Torque Model

The inductance of phase j is given by,

$$L_j(\theta) = L_1\left[\theta - \frac{\alpha_r}{4}(j-1)\right]. \tag{1}$$

The parameters of the inductance profile are given in the Appendix.When a single phase of the SRM is energized, the torque developed, T_j , is

$$T_j(\theta_e, I_j) = N_r \frac{\partial}{\partial \theta_e} W_c(\theta_e, I_j) \tag{2}$$

where θ_e and N_r are, respectively, the electrical angle and the number of rotor poles, and $\theta_e = N_r\theta$. The co-energy, W_c , is defined as

$$W_c(\theta_e, I_j) = \int_0^{I_j} \phi_j(\theta_e, i_j)\, di_j\ , \tag{3}$$

where $\phi_j(\theta_e, I_j)$ is the flux linkage and, with assumption of linear magnetics, is expressed as:

$$\phi_j(\theta_e, I_j) = L_j(\theta_e)\, I_j(\theta_e)\ . \tag{4}$$

Hence, the final expression for the linear torque model can be obtained as

$$T(\theta_e) = \sum_{j=1}^{4} T_j = \frac{N_r}{2}\sum_{j=1}^{4}\frac{\partial L_j(\theta_e)}{\partial \theta_e} I_j^2(\theta_e)\ , \tag{5}$$

where $\partial L_j(\theta_e)/\partial\theta_e$ is the slope of the inductance profile in the zone of increasing inductance [13], [14], and for simplicity, it is assumed to be equal to a constant σ during the period when the phase is asked to produce torque. Hence, based on Fig. 1, σ is computed as,

$$\sigma = \frac{L_a - L_u}{N_r \beta_s}\ . \tag{6}$$

B. Nonlinear Torque Model

A well-established model that incorporates magnetic saturation [9] is

$$\phi_j(\theta_e, I_j) = \phi_s\left[1 - \exp(-I_j f_j(\theta_e))\right],\quad I_j \ge 0 \tag{7}$$

where ϕ_s is the saturated flux linkage and $f_j(\theta_e)$ is expressed as a strictly positive Fourier series expansion, which takes care of the periodic nature of the inductance/torque profile. However, for the degree of accuracy for the present investigation, we include the first two terms [9], [10] of the Fourier series. In this work, we obtain $f_j(\theta_e)$ by sinusoidal approximation [10] of the inductance profile $L_j(\theta_e)$ (dotted curve in Fig. 1). With this flux linkage model, the torque produced by phase j can be obtained as

$$T_j = \frac{N_r\phi_s}{f_j^2(\theta_e)}\frac{df_j(\theta_e)}{d\theta_e}\{1 - [1 + I_j f_j(\theta_e)]\exp(-I_j f_j(\theta_e))\} \tag{8}$$

The total torque, $T(\theta_e)$, produced by SRM is the summation of the individual phase torques computed by (8). This complete and more accurate nonlinear model is used for evaluation of torque profile in this study

TABLE I
SWITCHING STRATEGY FOR MOTORING TORQUE PRODUCTION IN ONE-PHASE-ON SCHEME.

	Phase 2	Phase 3	Phase 4	Phase 1	Phase 2
Rotor Position, θ_e	0 – $\frac{\pi}{6}$	$\frac{\pi}{6}$ – $\frac{\pi}{2}+\frac{\pi}{6}$	$\frac{\pi}{2}+\frac{\pi}{6}$ – $\pi+\frac{\pi}{6}$	$\pi+\frac{\pi}{6}$ – $\frac{3\pi}{2}+\frac{\pi}{6}$	$\frac{3\pi}{2}+\frac{\pi}{6}$ – 2π

III. Fuzzy Iterative Approach for Computation of Reference Current Waveforms

In this section, the proposed fuzzy iterative approach (FIA) for determination of reference current waveforms is explained. In the FIA, the basic strategy is based on an iterative modulation of the current profile(s) till the torque error goes down to zero. Basically, if motor torque is greater than the commanded torque at any rotor position, θ_e , the reference current profile of a preceding phase that produces positive (motoring) torque at $\theta_e + \pi/2$, is modulated by subtracting a correction term from it and is passed to the SRM. Similarly, if motor torque is less than the commanded torque, then the current profile of the preceding phase that produces positive (motoring) torque is modulated by adding a correction term from it and is passed to the SRM. There are broadly two different excitation schemes used in practice, i.e., one-phase-on scheme and two-phase-on scheme. As per the strategy outlined for FIA, at any rotor position, only one phase can be commanded to produce motoring torque in the one-phase-on scheme. In a similar fashion, two-phase-on scheme is defined, i.e., at any position two phases (at the most) can produce motoring torque.

A. One-Phase-On Scheme

In this scheme, only one phase of SRM produces motoring torque at specific rotor position. Each stator phase is allowed to produce motoring torque for maximum of $\pi/2$ electrical rads. Thus, four phases of the SRM complete one electrical cycle of 2π rads. The conduction sequence of the phases is determined by the physical construction of SRM and direction of rotation. For forward rotation of this SRM with motoring torque production, the switching strategy is shown in Table I This sequence is based on the nature of phase inductance profiles to produce motoring torque, i.e., a phase is energized when rotor position is in the region of increasing inductance.

In the conventional rectangular pulse excitation scheme, the desired current for a torque command T_d is computed using the linear torque model, i.e.,

$$I_j(\theta_e) = \sqrt{\frac{2T_d}{N_r\sigma}}\ . \tag{9}$$

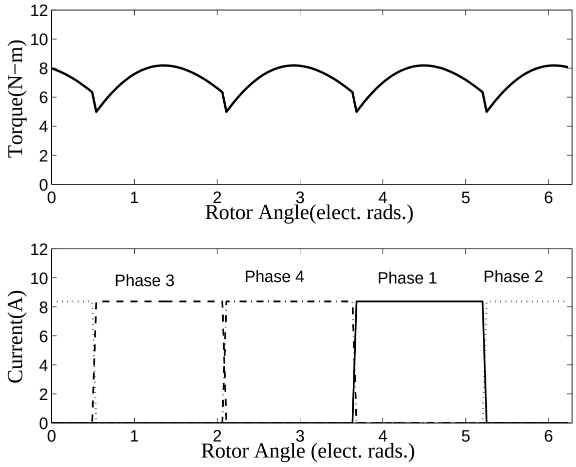

Fig. 2. Torque profile (top) and phase currents (bottom) with conventional rectangular pulse excitation scheme, T_d = 10 N-m.

Fig. 2 displays the simulation results with assumed static conditions for a torque command of 10 N-m. It is clearly observed that this scheme gives rise to very high torque ripple when tested on the nonlinear torque model (8). In addition, the average motor torque is much less compared to T_d. In essence, the motor does not produce the commanded torque, T_d, when asked to carry a current computed by (9). Thus, if the current is to be computed by (9), then the torque command T_d needs to be suitably modified such that when this modified torque command is used in the current calculation, the motor can produce the commanded torque, T_d. This task can be accomplished with a multiplying factor, K_t, which is multiplied with the actual torque command used in the current calculation. Since the torque produced by the motor is a highly nonlinear function of phase current as well as rotor position, the multiplying factor K_t should also be a nonlinear function of commanded torque and rotor position. Because of severe nonlinearity present in the SRM magnetic characteristics, it is extremely difficult to obtain an analytical expression for K_t that can be used in a straightforward way to calculate the desired current profile for the commanded torque T_d. In order to circumvent this difficulty, a fuzzy iterative approach (FIA) is used here. In this approach, the desired current profile is determined by iterative modulation (using multiplying factor) of some initial current profile that may be assumed to be as zero current for all rotor positions (and phases). Note that, Fig. 2 displays a periodic torque waveform for every $\pi/2$. Hence, the modulation can be done in two different manners depending on computational time preferred. First approach is to modulate the reference current for every electrical cycle, meaning the learning process takes place for a complete one electrical cycle before the correction term is added/subtracted to/from same phase at the next electrical cycle. Second approach is by modulating the reference current at next phase with in the same electrical cycle. Later approach is expected to reduce total computational significantly, as the learning is done only for one phase before the correction term is added/subtracted to/from the subsequent phase. With this motivation, the rest of the paper will concentrate on the second approach. The schematic of the iterative modulation of current profile is shown in Fig. 3.

TABLE II
FUZZY RULE BASE FOR DETERMINATION OF K_t

$\lvert\Delta T\rvert$ ↓ / $\theta_e^{'}$ →	VS	S	M	L	VL
VS	M	S	VS	S	S
S	M	S	VS	S	S
M	L	M	S	M	M
L	L	M	M	M	L
VL	L	M	M	M	L

In FIA, the phase current profile is computed at some suitably chosen (and sufficient) number of rotor positions in the electrical cycle by (10)–(12) without any reference to any specific phase. The superscript 'k' denotes iteration number. The index 'm' identifies rotor position. The phase is decided by the rotor position, and a complete one phase (32 samples) is equivalent to one iteration, hence, k also denotes j, i.e. assuming at $k=1$, phase corresponds to 1 ($j=1$) then for all the values of k, $j=\{REM(k,4)\}$ for k is not a factor of 4, otherwise $j=4$, where REM is mathematical remainder operator. The torque T^k is computed using the nonlinear torque model. In Fig. 3, the selector switches determine whether $\Delta I^k(m)$ will be multiplied by +1 (additive modulation) or -1 (subtractive modulation) as per (10), i.e., when the torque error is positive, the corrected current is multiplied with +1, and opposite is the case when the torque error is negative.

$$I_j^k(m) = I_{j-1}^{k-1}(m) \pm \Delta I^k(m); \quad I^k(m) \geq 0 \tag{10}$$

$$\Delta I^k(m) = \sqrt{\frac{2\left|\Delta T^k(m)\right| K_t^k(m)}{N_r \sigma}} \tag{11}$$

$$\Delta T^k(m) = T_d - T^k(m) \tag{12}$$

The multiplying factor K_t is computed heuristically by the fuzzy system (FS). The fuzzy system essentially a linguistic rule base with two inputs and one output. The inputs are absolute value of torque error ($\Delta T = T_d - T$) and rotor position $\theta_e^{'}$ $\{= REM(\theta_e, \pi/2)\}$. The output is K_t. The heuristic knowledge about the rule base is obtained by examination of simulation results (Fig. 2), where the current is computed using (9) for different torque commands, and static torque characteristics of the SRM. The fuzzy rule base is shown in Table II. The fuzzy membership functions for ΔT and $\theta_e^{'}$ are shown in Figs. 4 and 5, respectively. The linguistic labels for the fuzzy sets are: VS (Very Small), S (Small), M (Medium), L (Large), VL (Very Large). A typical rule of the rule base is interpreted as: If the torque error($|\Delta T|$) is Very Large (VL) and rotor position is in the Middle (M) of the conduction interval, then multiplying factor should be Medium (M). The crisp value of K_t is computed by the max-min rule for fuzzy inference mechanism [11], [12]. In the output space, the fuzzy sets are taken as fuzzy singletons.

The iterative modulation of the phase currents starts with initial zero-current profile for all the phases. Subsequently, in every iteration, the magnitude of the phase current of the selected phase is modified depending upon the magnitude

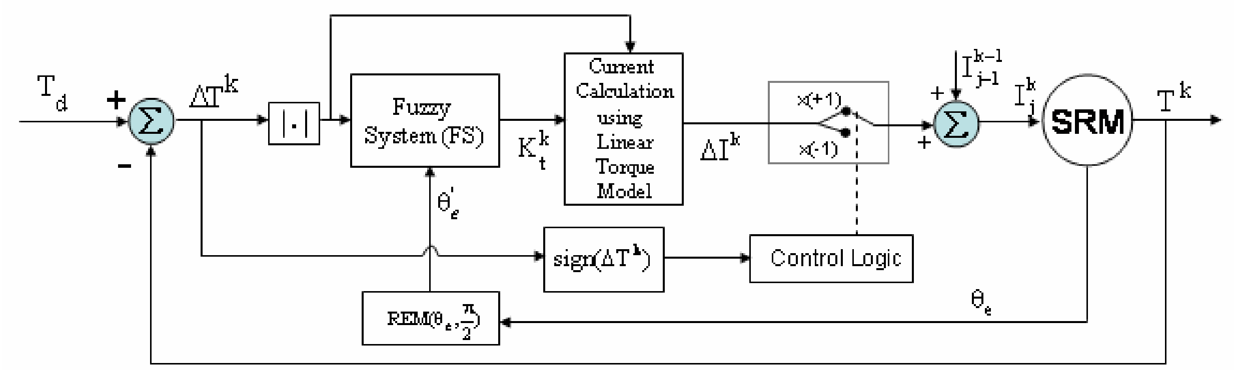

Fig. 3. Lock diagram model of the Fuzzy Iterative Approach for current calculation.

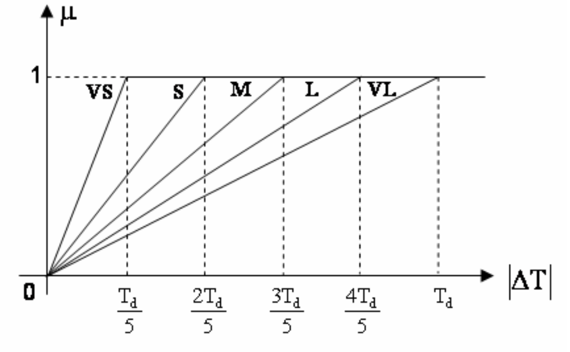

Fig. 4. Membership functions for $|\Delta T|$.

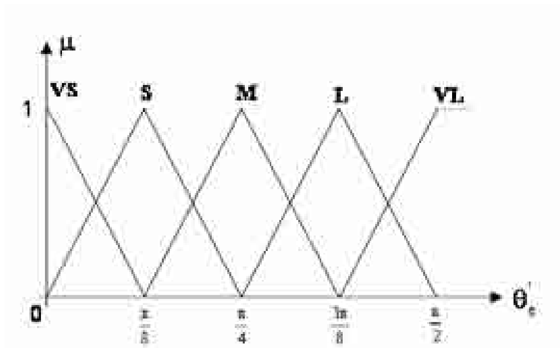

Fig. 5. Membership functions for rotor position in one-phase on scheme.

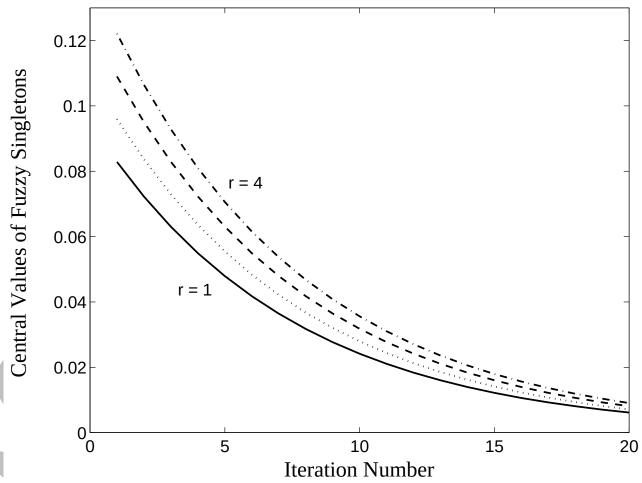

Fig. 6. Gain-scheduling for the central values of the fuzzy singletons in the output space ($a = 0.008$, $b = 0.015$, $\tau = 7.3$, $T_d = 10$ N-m).

and sign of torque error according to (10)-(12). The phase is selected depending upon the rotor position. It is important that, for any iterative computational algorithm, the amount of step size to be used for finding the solution plays an important role resulting in convergence or divergence of the algorithm. Generally, this step size is reflected as some sort of tunable gain(s) appearing in any iterative algorithm. The same is also true for our FIA and the step size, in this case, is of course ΔI . In a typical search algorithm, the step size should generally be larger during the initial phase and, as the correct solution is approached, the step size should be smaller and smaller. Since the central values of the fuzzy singletons in the output space effectively determine the step size through K_t , the gain scheduling of these central values are performed in FIA to achieve the stated objective, i.e., the output space has four fuzzy singletons whose central values are gain-scheduled, as a function of T_d , from iteration to iteration with the following empirical rule.

$$CV_r^{\ k} = (aT_d + br)\,(e^{(-k/\tau)}) \qquad (13)$$

where r is the index number of the membership function in the output space (1 ≡ VS, 2 ≡ S, 3 ≡ M, 4 ≡ L), a and b are suitably chosen constants , τ is a constant that controls the decay rate of gain scheduling and, $CV_r^{\ k}$'s are the respective central values of the fuzzy singletons of the output space. Fig. 6 shows a display of the scheduling of central values of the fuzzy singletons in the output space.

In the simulations, 32 rotor positions are selected for a complete one phase (one iteration) at regular intervals and phase current profiles are computed by FIA at these positions. Fig. 7 shows the iterative control of torque profile for $T_d = 10$ N-m along with the current profiles for phase 1 and phase 2 after torque error is reduced to zero. As stated before, these simulations are carried out under assumed static conditions. The results are quite noteworthy. In Fig. 8, the variations of K_t for $T_d = 10$ N-m are shown. It is observed that K_t becomes very small at very large number of iterations as the torque error reduces to zero and this happens because of the gain scheduling of the central values of the fuzzy singletons in the output space of the fuzzy system.

The simulation results clearly establish the elegance of the proposed approach for determination of reference current waveforms for torque ripple minimization. With regard to the nature of current waveforms, it is seen that the phase currents have sharp rising and falling edges. Also, the relative magnitudes of the currents are also high. This is expected because of the very nature of the excitation scheme, i.e., one-phase-on scheme where one phase is instantly asked to produce some high motoring torque. As a

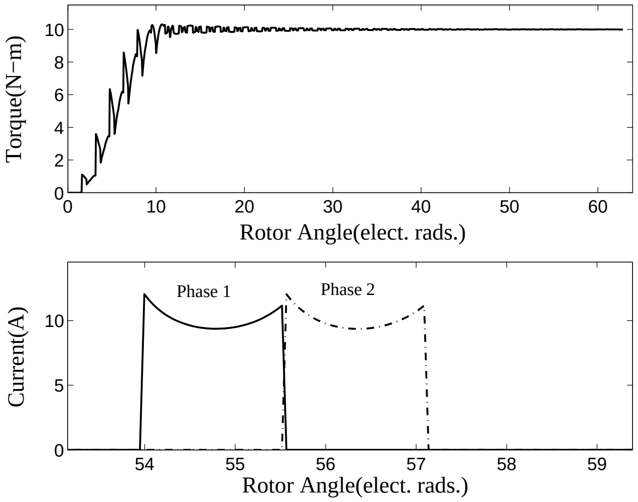

Fig. 7. Iterative torque control for $T_d = 10$ N-m in one-phase-on scheme (top), Phase 1 and phase 2 current waveforms in an electrical cycle for zero torque error (bottom).

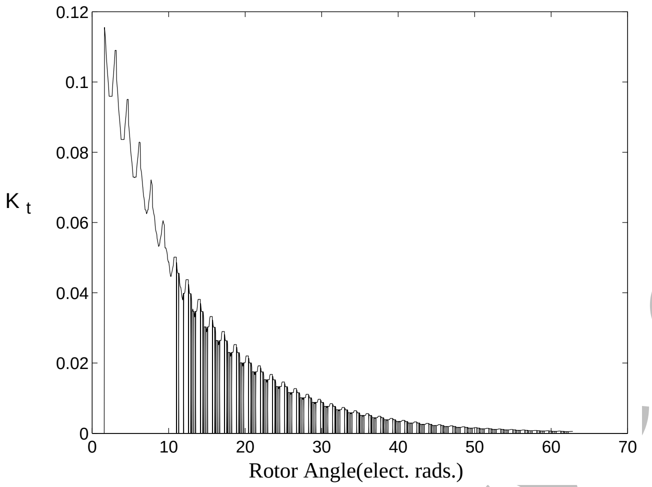

Fig. 8. Variations of Kt for $T_d = 10$ N-m.

result of this, the phase current waveforms contain a lot of harmonic components which the stator circuit of the SRM may find difficult to track because of inherent bandwidth limitations. For the sake of illustration, the amplitude spectrum of the phase current profile (as obtained from FIA) for T_d = 10 N-m is shown in Fig. 9 for a motor speed of 1500 rpm. In order to achieve both the objectives, i.e., relatively less magnitude of current and less harmonic components, it is necessary to go for two-phase-on scheme where there is a phase overlap region in which two phases can produce motoring torque. Moreover, by suitable design, it is possible to shape the torque command profile for every phase such that a phase is never asked to produce a high torque instantly. The details of this scheme are described in the next section.

B. Two-Phase-On Scheme with Torque Sharing Functions

In this scheme, at the most, two phases are allowed to produce motoring torque at any rotor position. Moreover, the commanded torque profile for a phase is smoothened by torque sharing functions (TSFs). The TSFs are designed in such a way that the TSF for a phase has overlap and non-overlap periods. In the overlap period, two adjacent phases conduct and, in the non-overlap period, only one phase can conduct. The advantages are: relatively less

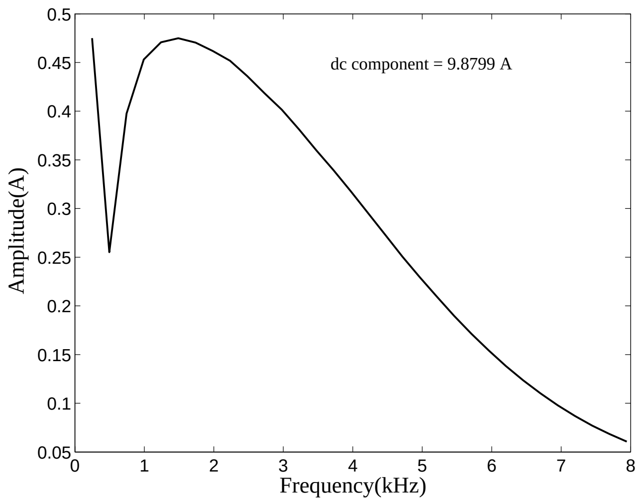

Fig 9. Amplitude spectrum of the phase current profile; $T_d = 10$ N-m, one-phase-on scheme, motor speed = 1500 rpm.

magnitudes of currents are required in the overlap period because of TSFs and, due to intentional choice of smoother TSFs, the phase current profile does not contain much higher order harmonics.

As proposed in [13], TSFs based on cubic segments (CS) are used. The cubic segment is a cubic polynomial of θ_e and is characterized by four arbitrary parameters. Each TSF is periodic with electrical cycle and has a rising segment, a constant segment and a falling segment. In the overlap interval, one new phase comes into conduction (incoming interval of a phase) and another phase goes out of conduction (outgoing interval of a phase). The non-overlap interval is same as one-phase-on scheme, so it can be called as ON interval. The general mathematical description of the TSF follows. The subscripts, 'r' and 'f', stand for rising and falling segments, respectively. Since FIA operates over torque error from iteration to iteration, the TSFs are defined accordingly.

θ_{ov} = phase overlap angle,
ΔT_d = incremental desired torque,
ΔT_{jd} = incremental desired torque of phase j
$\theta^r_{e,j0}$ = angle at which a TSF has a zero value for the rising segment
$\theta^f_{e,j0}$ = angle at which a TSF has a full value for the falling segment

In FIA, the incremental desired torque ΔT_d is chosen to equal to torque error ΔT in each iteration. The mathematical expressions for the different segments are defined as given below.

Rising Segment

$$\Delta T_{jd} = A_r + B_r(\theta_e - \theta^r_{e,j0}) + C_r(\theta_e - \theta^r_{e,j0})^2 + D_r(\theta_e - \theta^r_{e,j0})^3 \quad (14)$$

Constant Segment

$$\Delta T_{jd} = \Delta T_d \quad (15)$$

Falling Segment

$$\Delta T_{jd} = A_f + B_f(\theta_e - \theta^f_{e,j0}) + C_f(\theta_e - \theta^f_{e,j0})^2 + D_f(\theta_e - \theta^f_{e,j0})^3 \quad (16)$$

where the constants A's, B's, C's, and D's are chosen so as

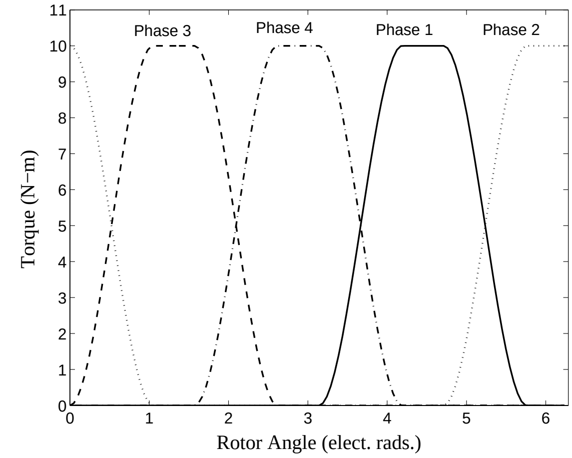

Fig. 10. Examples of torque sharing functions with cubic segments for desired torque of 10 N-m

TABLE III
SWITCHING STRATEGY FOR MOTORING TORQUE PRODUCTION IN TWO-PHASE-ON SCHEME

Rotor Position, θ_e	Phase
0 – $\frac{\pi}{6}-\frac{\theta_{ov}}{2}$	Phase 2
$\frac{\pi}{6}-\frac{\theta_{ov}}{2}$ – $\frac{\pi}{6}+\frac{\theta_{ov}}{2}$	Phase 2 Phase 3
$\frac{\pi}{6}+\frac{\theta_{ov}}{2}$ – $\frac{2\pi}{3}-\frac{\theta_{ov}}{2}$	Phase 3
$\frac{2\pi}{3}-\frac{\theta_{ov}}{2}$ – $\frac{2\pi}{3}+\frac{\theta_{ov}}{2}$	Phase 3 Phase 4
$\frac{2\pi}{3}+\frac{\theta_{ov}}{2}$ – $\frac{7\pi}{6}-\frac{\theta_{ov}}{2}$	Phase 4
$\frac{7\pi}{6}-\frac{\theta_{ov}}{2}$ – $\frac{7\pi}{6}+\frac{\theta_{ov}}{2}$	Phase 4 Phase 1
$\frac{7\pi}{6}+\frac{\theta_{ov}}{2}$ – $2\pi-\theta_{ov}$	Phase 1
$2\pi-\theta_{ov}$ – 2π	Phase 1 Phase 2

to satisfy the constraints. The four constraints for the rising segment are:

$$\Delta T_{jd} = \begin{cases} 0 & \text{at } \theta_e = \theta^r_{e,j0} \\ \Delta T_d & \text{at } \theta_e = \theta^r_{e,j0} + \theta_{ov} \end{cases},$$
$$\frac{d\,\Delta T_{jd}}{d\,\theta_e} = \begin{cases} 0 & \text{at } \theta_e = \theta^r_{e,j0} \\ 0 & \text{at } \theta_e = \theta^r_{e,j0} + \theta_{ov} \end{cases} \quad (17)$$

Similar constraints are used for the falling segment. Hence, the various constants can be derived as:

$$A_r = 0\,;\ B_r = 0;\ C_r = \frac{3\Delta T_d}{\theta_{ov}^2};\ D_r = -\frac{2\Delta T_d}{\theta_{ov}^3} \quad (18)$$
$$A_f = \Delta T_d\,;\ B_f = 0;\ C_f = -C_r\,;\ D_f = -D_r$$

All the phases are allocated equal slots for conduction. The overlap periods are chosen to be symmetrical about $\pi/6$, $(\pi/2+\pi/6)$, $(\pi+\pi/6)$ and so on. The overlap angle is chosen to be $\pi/3$. Thus, each phase is allowed to conduct for an interval of $(\pi/2+\pi/3)=\{\theta_{cond}=\text{conduction angle}\}$. The switching strategy for motoring torque production under this scheme is displayed in Table III. In Fig. 10, the TSFs for (incremental) desired torque of 10 N-m is shown. Fig. 11 displays the simulation results with assumed static conditions for $T_d = 10$ N-m with conventional current calculation using linear torque model and TSFs. Note that the torque ripple is much less compared to one-phase-on scheme (Fig. 2) due to TSFs. Nevertheless, the torque ripple is still substantial.

The FIA is now introduced in the same manner as discussed in previous section. A schematic block diagram of the FIA with TSFs is shown in Fig. 12. The earlier membership functions for rotor position (Fig. 5) are adjusted with the inclusion of an overlap angle, θ_{ov}, and are shown in Fig. 13. The membership functions for phase

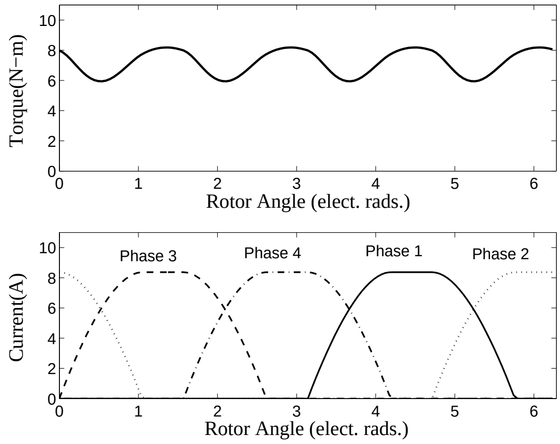

Fig. 11. Torque profile and phase currents with two-phase-on scheme calculation) with TSF for $T_d = 10$ N-m and conventional current calculation; (top) torque profile (bottom) phase currents.

torque error are exactly similar to those in Fig. 4. The magnitude of the phase current of the selected phase is computed using equations similar to (10)-(12). But, as discussed earlier, the TSFs are first calculated using equations (14)-(18) by taking torque error ΔT^k into account. The design of the fuzzy system is same as before. Similar to one-phase-on scheme, in (10), $\Delta I_j^k(m)$ is added/subtracted depending upon the sign of the torque error (positive/negative, respectively).

The central values of the fuzzy singletons in the output space of the fuzzy system are calculated in exactly the same manner as before. However, the values of the constants a, b, and τ are suitably chosen for this scheme $(a = 0.005,\ b = 0.02,\ \tau = 7.3)$. Fig. 14 shows the iterative control of torque profile under assumed static conditions for $T_d = 10$ N-m. Note the difference compared to one-phase-on scheme. For motoring torque production regions, the currents of two adjacent phases are shared to produce the desired total torque. The rise of the incoming phase current and fall of outgoing phase current are significantly smoother than one-phase-on scheme. As an additional illustration, the simulation results for $T_d = 30$ N-m are shown in Fig. 15.

The test results with two-phase-on scheme based on TSFs are found to be suitable for high performance applications as the high frequency components of the phase current profile are almost negligible. To highlight this point, the amplitude spectrum of the phase current waveform for $T_d = 10$ N-m is shown in Fig. 16, assuming the speed of the motor to be 1500 rpm. The current profile contains significantly less high frequency components compared to one-phase-on scheme (Fig. 9) where high frequency components are notably present. The torque ripple is generally sensitive to the harmonics in the current. Thus, in reference current waveform generation, one has to consider this aspect for successful reduction of torque ripple. From this perspective, the two-phase-on scheme with TSFs produces fairly smoother current waveforms suitable for faithful tracking by the stator circuit resulting in lower torque ripple.

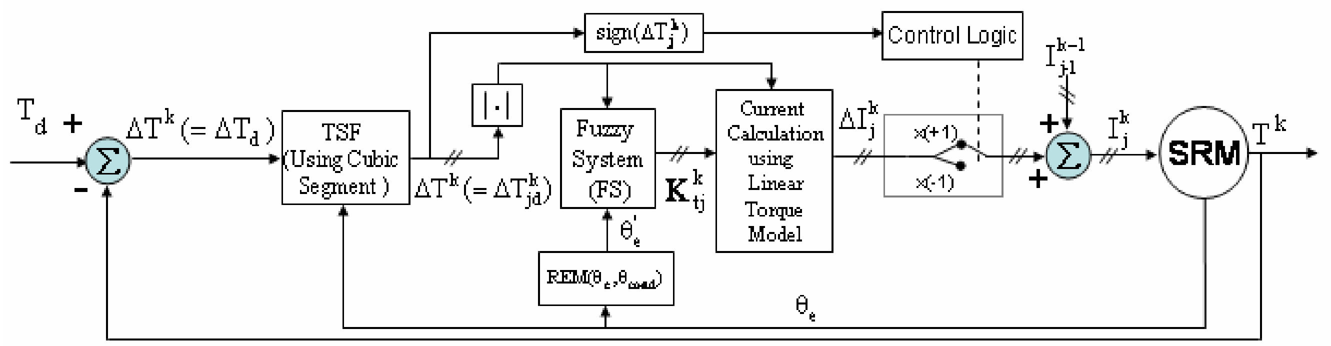

Fig. 12. Block diagram model of the Fuzzy Iterative Approach for current calculation with TSF.

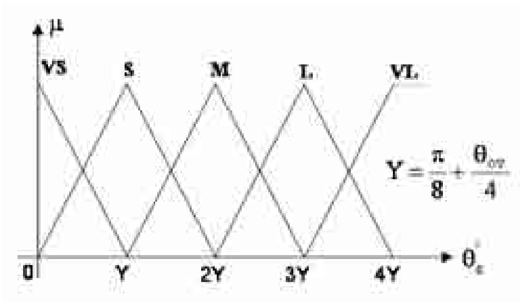

Fig. 13. Membership functions for rotor positions for two-phase-on scheme { $\theta_e' = REM\,(\theta_e, \theta_{cond})$ }.

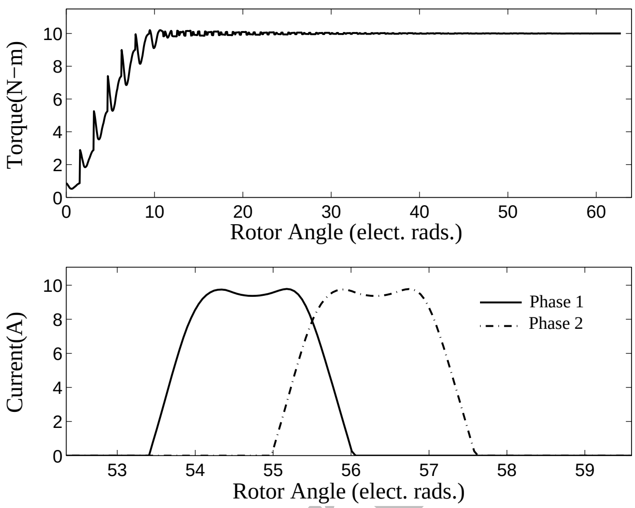

Fig. 14. Iterative torque control for $T_d = 10$ N-m in two-phase-on scheme with TSFs (top), phase 1 and 2 current waveforms in an electrical cycle for zero torque error (bottom).

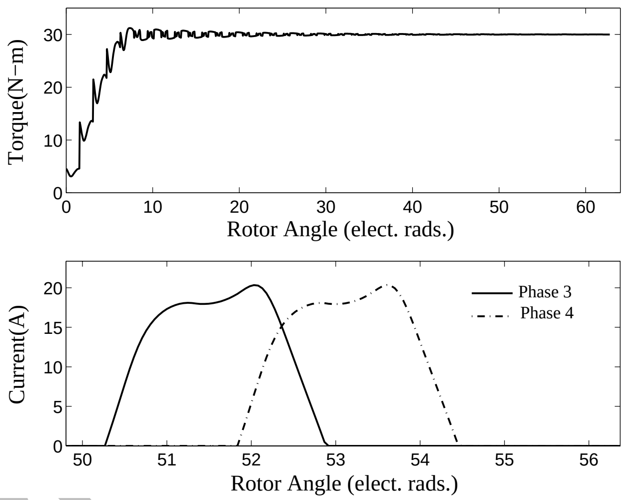

Fig. 15. Iterative torque control for $T_d = 30$ N-m in two-phase-on scheme with TSFs (top), phase 3 and 4 current waveforms in an electrical cycle for zero torque error (bottom).

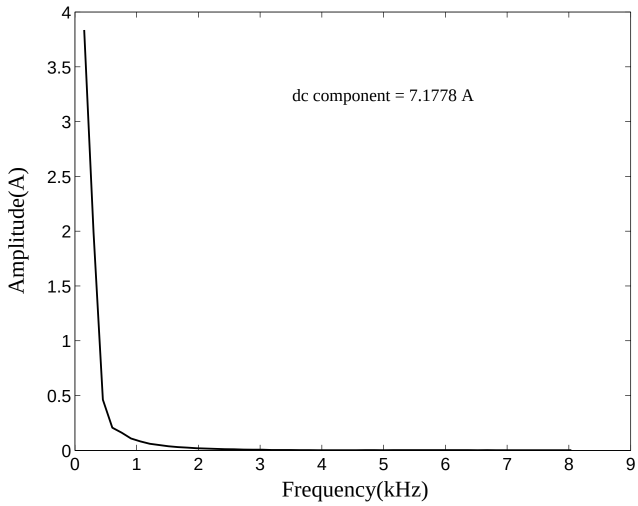

Fig 16. . Amplitude spectrum of the current profile for $T_d = 10$ N-m in two-phase-on scheme with TSFs (motor speed = 1500 rpm).

IV. CONCLUSION

A fuzzy iterative compensation scheme has been proposed for determination of desired phase current waveforms in two different excitation schemes, i.e., one-phase-on and two-phase-on with TSFs, so as to minimize the torque ripples in SRM. The approach operates by the use of a multiplying factor in the conventional current calculation based on linear torque model and a fuzzy rule base determines this factor by heuristic judgment. Based on the torque error from iteration to iteration, the torque ripple is minimized by the iterative process. The positive/negative torque errors are minimized by additive/subtractive modulation of phase current of a phase producing positive torque from iteration to iteration. The simulation results of two-phase-on scheme with TSFs, under assumed static conditions, are satisfactory for high performance applications with regard to faithful tracking of reference currents by stator circuit of SRM. There are several other issues that need further investigations into this approach. For example, it is a fact that the phase current profile under dynamic conditions is highly dependent on speed of the motor. Thus, for high performance applications, the reference current profile should be computed taking into account the speed of the motor. In other words, in this fuzzy iterative approach, the TSF should be modified as a function of motor speed and rotor position for satisfactory dynamic response.

APPENDIX

Motor Parameters: The SRM parameters are taken from [14]. Output power =7.5 kW, Rated speed =1900 rpm, Number of phases =4, Number of stator poles $(N_s) = 8$, Number of rotor poles $(N_r) = 6$, $L_a = 10$ mH, $L_u = 110$, $\alpha_r = 1.05$ rad, $\beta_s = 0.35$ rad, $\beta_r = 0.42$ rad, $\phi_s = 1.2$ Wb.

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