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COMPARATIVE EVALUATION OF ASYMMETRIC HALF BRIDGE DRIVE MODES FOR SRM

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ABSTRACT

This paper discusses the mathematical model, constructional aspects, functional aspects, simulation parameters of switched reluctance motor along with its simulation. Constructional aspects include stroke angle, step angle, inductors overlap ratio and inductance versus rotor position at different angles. Functional aspects deal with mathematical expression of Switched Reluctance Motor including torque generation, calculation of flux linkage and other parameters like saturation current, base speed, electrical and mechanical motion are also discussed. These parameters are well tabulated for simulation. Once the constructional and functional parameters are defined then simulation is carried out. In this part model is tested with asymmetric half bridge converter model as power drive, three modes of operation based on applied voltage method, single pulse, soft chopping along with hard chopping are simulated at different speeds and results are demonstrated. Torque and current relationship is observed to find out which mode is suitable for smooth torque operation and have better speed control.

Keywords: *VR Motor; Switched Reluctance (SR) Drives and SRM-Switched Reluctance Motors.*

1) INTRODUCTION

Theory of switched reluctance machines cannot be said new; it is in fact much old as referring to the 19th century invention known as "electromagnetic engine". This was antecedent of today's stepper motors. The SRM have number of applications as both linear and rotary steppers and it is basically a stepper motor. SR motors are considered as an alternative to other machine drives in speed applications where variable operation is required. However, normal operation of SRMs is non-linear due to the magnetic saturation with double salient structure as well as nonsinusoidal association between flux linkage, output torques, phase current, magnetic curves and rotor angle **Error! Reference source not found.**(Byrne et al, 1985), (Krishnan, 2001).

Moreover, this motor in operation does differ from other types of motors like electronically it is always commutated and secondly it cannot be run directly as of an ac line or a dc bus source. The salient features and construction which it holds cause high nonlinear magnetic properties thus making it difficult for its analysis and control. On other hand when its comparison is done with ac and dc machines then this SR motor have its own advantages. It can achieve very high speed like 10,000 - 60,000 rev/m, because less (minimum as zero) conductors or magnets on the rotor poles. The phases which are independent magnetically, electrically and physically make this machine very reliable in industry. Now a day's one cannot deny and it is further not necessary by proving its advantages and benefits for mathematical modeling and simulation, when it is carried by keeping in mind its all necessary parameters of the systems. In short system simulation is an important feature in view of its operation and design (Soares and Costa, 2001).

When SRM and conventional DC motors are compared, such non-linearities make simulations, mathematical model and SRM's control comparatively much complex. The electrical torque generated appears to be a second (2nd) order algebraic polynomials or greater when presenting the relation of the currents in stator poles. Even in the simplest case where linear increase in inductance occurs, the electrical torque is still remaining a stator current's nonlinear function. The motor output along with input characteristics do depend upon several factors, like number of poles (stator and rotor), their arcs, machine structure, number of excited and not excited phases within one mechanical revolution with its count of repetition, magnetizing curves of laminated material, drive and converter configurations and control strategies for operation of different modes (Venkatesan et al, 2006), (Miller, 1993).

The objective and scope of the current paper is to describe by presenting the study of motor mathematical model considering constructional and functional aspects as well as simulation. Torque and current characteristics are shown, where motor is operated under various modes such as hard chopping as well as soft chopping modes and also in single pulse mode and the results are demonstrated at different speeds. The model used in this paper is same as discussed in (Ion and Nasar, 2005), based on *matlab/simulink* environment. The motor is chosen with configuration 6/4, as it is one of the most commonly used configurations. The conclusion is presented after discussing the simulation and results that phase currents in excited and de-excited stator poles are related to torque and by controlling the phase currents, ripple in torque can be reduced.

2) CONSTRUCTIONAL ASPECTS

The presence of variable reluctance in the air gap of the rotor poles and the stator poles creates motion (movement) in SRM. When a stator winding is energized, it produces a magnetic field which causes attraction of metal. Fig. 1 shows that rotor is inclined for moving towards a position where reluctance is minimized (less as equal to zero) and thus creating reluctance torque.

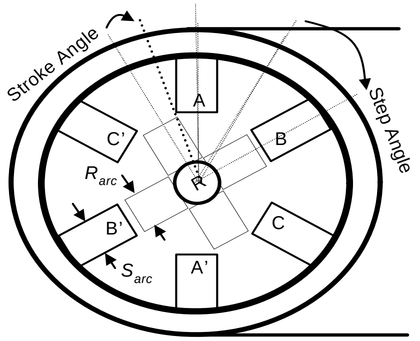

Fig. 1: A Diagram for Cross Sectional View Showing 6/4 SR Motor

This operating principal is based upon the fact that there is always a force present that causes attraction of iron or steel to permanent magnets. One can understand the importance of the air gap here that it should be minimum but it must b present. In this scenario, reluctance is going to minimize (equal to zero) as metal and magnet acquiring actual physical contacts.

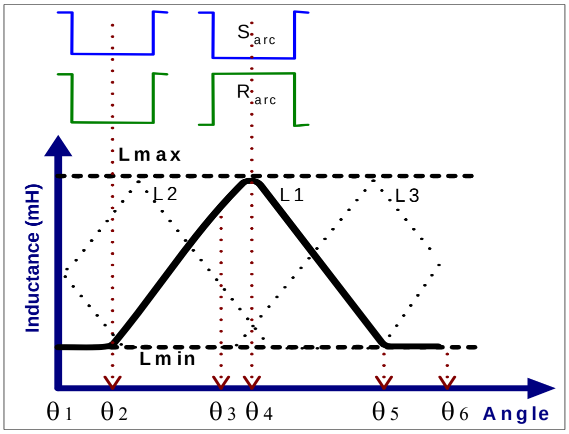

Fig. 2: The Rotor Positions with respect to Phase Inductance

The selection of number of phases, N_{Ph}, stator poles, $N_{sp,}$ and their repetition, $N_{rept,}$ within one revolution depends primarily on the application. In SR configurations rotor poles with higher values, $N_{rp,}$ causes stroke angle with low values, $\theta_{stroke,}$ and this results in the lower torque ripples. This is achieved as decreased saliency ratio's cost that is the ratio found for minimum and maximum inductance levels (aligned and unaligned rotor respectively). This decrease will lead to the decrease of torque outputs. An increase in strokes per revolution values can be used to achieve phases having high values to assuage the torques dip issue by a cost of decreased saliency ratio, hence improvement in average torque (Miller, 1993). There is a further consideration in flux linkage change rate, stator and rotor pole saliency and split ratio, available coil area, its saturation behavior, variation in reluctance and in the iron loss due to the increase of the repetition. This consideration however modifies this simple conclusion. The rotor pole arc, $R_{arc,}$ can be constructed so it is larger than arc of stator pole, S_{arc}. This will help to overcome the problem of stator fluxes at edges. Equation (2) combined with (1) defines inductance overlap ratio, K_{op}. When any one pole is kept little wider than the other, there will be a region produced called dead zone. This is produced around the aligned position where the inductance (stored energy) does not change and, thus the torque is zero at this region. The higher value of K_{op}, will cause the lower torque dip and the this will lead to the higher mean and average torque (Anwar et al, 2001), (Miller, 2002), considering:

$$\theta_{stroke} = \frac{\pi}{N_{ph} \cdot N_{rept} \cdot (N_{ph} - 1)} \qquad (1)$$

and,

$$K_{op} = \frac{\theta_{stroke}}{\min(S_{arc}, R_{arc})} \qquad (2)$$

Since the model chosen for this article is 6/4, so the motor has $N_{sp} = 6$ and $N_{rp} = 4$ and it has equal size of rotor and stator pole arcs, $R_{arc} = S_{arc}$. The step angle, θ_{step}, is the angle that explains the displacement of each phase inductance and it is given by following relation as discussed in (Soares and Costa, 2001).

$$\theta_{step} = 2\pi \left(\frac{1}{N_{rp}} - \frac{1}{N_{sp}} \right) \qquad (3)$$

Now by solving above equations for specific model gives that $\theta_{stroke} = 15^\circ$, $K_{op} = 0.5$, $\theta_s = 30^\circ$. $Kop \geq 0$ is required to have better starting torque. It also proves that minimum width of stator is required to produce torque (Anwar et al, 2001), (Miller, 2002).

The relation of inductance with respect to rotor position is clearly visible in Fig. 2. It can be observed that minimum inductance, *Lmn* is at the position which is unaligned and maximum inductance, *Lmx* is at aligned rotor stator position. The values of θ_1, θ_2, θ_4, θ_5, θ_6 are 0°, 15°, 45°, 75°, 90° respectively as shown in Fig. 2. The value of θ_3 is not decided independently. It is actually a function of different parameters like magnetizing flux properties of motor, reference driving speed, and its drive specification. Its adjustment is done by hit and trial method or it requires prior knowledge of phase current behavior (Kavanagh et al, 1991).

3) FUNCTIONAL ASPECTS

Intelligent synchronization within excitation of phases (one by one) and the rotor position produces continuous torque. When the stator poles A-A1 (A′ is represented as A1 and B′ as B1 and C′ as C1) are excited simultaneously and supposed current rotor position is as shown in Fig. 1. The magnetic field is created with presence of magnetizing phase currents in the stator poles.

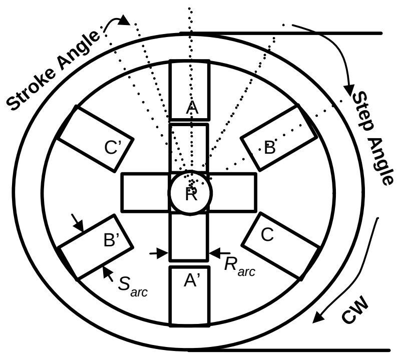

Fig. 3: Rotor is aligned w.r.t. Stator Phase A

This magnetic field attracts the associated rotor pole pair, causing its clockwise rotation towards the stator poles which are excited. During this rotational movement, the decrease in reluctance of closed flux path is obvious. Then the value of reluctance reaches to its minimum value where the rotor pole is in position which is aligned in reference to the excited stator pole. It means both pole's axis (rotor and stator) are aligned together as shown in Fig. 3. The rotation brings change in reluctance and this is the reason why the other name as variable reluctance (VR) motor is also in use for SR motors. It is obvious change in position cause the variation in the inductance of each phase. It is shown earlier that relationship between reluctance and inductance is inversely proportional. The major cause of variation in phase currents is due to this change in inductance.

Considering SRM operation, it only appears simple. It is mentioned in the end of last section that an accurate analysis considering maximum number of motor's parameters requires a complex mathematics due to its non linear structure. The instantaneous voltage of an SRM between the terminals of single phase winding is expressed with the winding's flux linkage by Faraday's law,

$$V = R_{ph} i + \frac{d\lambda}{dt} \tag{4}$$

In above equation (4),
V = terminal voltage,
i = phase current,

R_{ph} = motor resistance, and
λ = flux linkage.

In general, the flux linkage in an SRM phase can be expressed as a function of motor current (i) and rotor position (θ). Thus, Equation (4) can be more elaborated as

$$V = R_{ph} i + \frac{\partial \lambda}{\partial i} \cdot \frac{di}{dt} + \frac{\partial \lambda}{\partial \theta} \cdot \frac{d\theta}{dt} \qquad (5)$$

where, $\frac{\partial \lambda}{\partial i} = L(\theta, i)$, constant expressing the inductance and $\frac{\partial \lambda}{\partial \theta} = K_b(\theta, i)$, constant expressing the back EMF and these values are considered instantaneous in operation of SRM (Ion and Nasar, 2005),

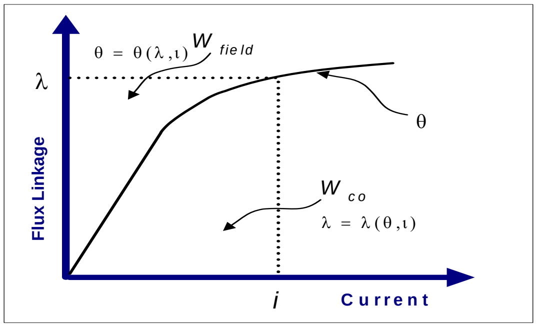

Fig. 4: Graphical explanation of W_{co} *and* W_{field} *on Energy Diagram*

Now for power and torque calculation, power conservation is considered. If power is conserved then electrical power must be converted in to ohmic losses, $R_{ph}.i^2$, instantaneous field power, dW_{field}/dt in an inductor and instantaneous mechanical power out, dW_{mech}/dt as expressed in (6), (7). Power itself is the energy with rate of change in time, so W_{field} and W_{mech} are referred as field energy and mechanical energy respectively. Mechanical energy can be expressed as torque and in common practice the torque is expressed in co-energy, W_{co}.

$$Vi = R_{ph} i^2 + \frac{d\lambda}{dt} i \qquad (6)$$

It proves that

$$i\frac{d\lambda}{dt} = \frac{dW_{field}}{dt} + \frac{dW_{mech}}{dt} \qquad (7)$$

Fig. 4 shows the relationship of stored field energy with stored field co-energy. It is obvious from Fig. 4 that W_{co} can be expressed as in (8) and $i\lambda$ as in (9). Later using the fact that mechanical power W_{mech} is the product of torque and speed, instantaneous torque per phase $T_{ins/ph}$ can be expressed as in (10), providing the current is constant (Ion and Nasar, 2005),

$$W_{co} = \int_0^i \lambda(\theta, i).di \qquad (8)$$

and

$$i\lambda = W_{field} + W_{co} \qquad (9)$$

It can be shown:

$$T_{\frac{ins}{ph}} = \frac{\partial W_{co}}{\partial \theta}, i = constant \qquad (10)$$

Total instantaneous torque is

$$T_{ins} = \sum_{i=1}^{N_{ph}} T_{\frac{ins}{ph}}(i) \qquad (11)$$

and in case of no saturation, familiar equation of torque is

$$T_{ins} = \sum_{i=1}^{N_{ph}} \frac{i^2}{2}.\frac{dL}{d\theta} \qquad (12)$$

4) MODELING PARAMETERS

In this section those parameters of SR motor and its drive are elaborated. These are essential parameter as far as operation of the SRM is considered. There is always a mutual flux present between the stator phases. If it is neglected then the torque profile $\lambda(\theta,i)$ is a non-linear function of both parameters θ and i. This is obtained by finding maximum and minimum value of torque profile given as λmax, and λmin. For a given switched reluctance motor (known $\lambda(\theta,i)$ profile), the current profile of currents in each phase is controlled to achieve the control over torque. This mainly depends upon rotor position (θ). Referring to Fig. 2, $\theta_1 - \theta_4$ can be named as dwell angle θ_{dwell}, for which phase 1 should be energized. Similarly after this same phase 1 should be de-energized to cut the negative torque and simultaneously next about to aligned phase should be energized for continuous operation. Instantaneous angle of motor, θ_m is the current angle of specific phase. The base speed of motor, ω_b corresponds to the maximum θ_{dwell} ($\theta_{dwell(max)}=\theta_m=\pi/N_{rp}$) with λ_{max}*(depends on machine design),* supply voltage, V_{drv}*(drive supply voltage*), where as current in saturation is denoted as i_s. Now for the simulation of the model presented in (Ion and Nasar, 2005), some parameters are given in Table I, where few of them relate to motor constructional aspects, some with SR drive and others are found by following expressions:

$$\lambda_{min} = i_{max} \cdot L_{min} \quad (13)$$

and,

$$\lambda_{max} = i_{max} \cdot L_{max} \quad (14)$$

where, i_{max} is the maximum current at zero speed and in other expression at constant speed, ω_r

$$\lambda_{max} = \int_0^t V_{drv} \, . dt = V_{drv} \frac{\theta_{dwell}}{\omega_r} \quad (15)$$

Now, since motor normally is operated at specific speed so well known mechanical motion equation (no friction) is as follows:

$$J . \frac{d\omega_r}{dt} = T_{ins} - T_{load} \quad (16)$$

Where, J is motor inertia and T_{load} is constant load torque applied on motor externally.

Table 1: List of SRM Model Parameters and how these are selected

Parameter	Value	Selection
R_{ph}	4.1 Ω	Motor parameter
L_{max}	180 mH	Motor parameter
L_{min}	60 mH	Motor parameter
i_s	2A	Motor parameter
I_{max}	10 A	Motor/Drive
V_{drv}	240 V	Drive parameter
λ_{max}	1.8 Wb	(14)
λ_{min}	0.6 Wb	(13)
J	.002 kgm^2	Motor parameter
ω_b	104 rad/s	(15) where $\omega_r = \omega_b$
ω_{ref}	50, 100, 150 rad/s	Simulation parameter
$S_{arc,}$, R_{arc}	30˚, 30˚	Motor parameter
Θ_{dwell}	45˚	Motor parameter
T_{load}	2 Nm	Simulation Parameter

Table 1 shows the parameters, their values and how these parameters are selected in right most column that even mentions the mathematical expression if used to calculate the value. Motor parameters are selected from SRM available in Laboratory by measuring practically like, R_{ph}, L_{max}, L_{min}. Some parameters mentioned earlier in Section II are not repeated in this table.

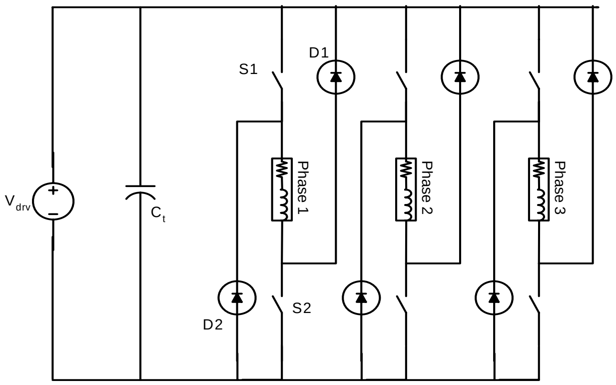

Fig. 5: Asymmetric Half Bridge Converter

Model of drive used for simulation consists of two switches *S1, S2* and two diodes *D1, D2* per SRM phase as shown in Fig. 5, only phase 1 is labeled completely. Three operating modes single voltage pulse, soft chopping and hard chopping mentioned in (Venkatesan et al, 2006) are used to compare the current and torque behavior at different speeds.

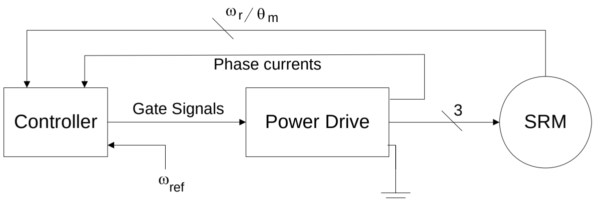

Fig. 6: Simulation Block of SRM and its Drive

In single voltage pulse both *S1, S2* are kept on for $\theta_{dwell,}$ causing positive rise in voltage and then both are simultaneously turned off, so energy is transferred to dc source by freewheeling diodes (negative voltage due to phase conductor). In soft chopping mode *S1* is turned on and off with *S2* continuously on till θ_{dwell}, and then both are turned off as end of first mode. In hard chopping mode both *S1, S2* are turned on and off till $\theta_{dwell,}$ then both are turned off simultaneously. The difference between these modes will become clear in subsequent section where results of simulation are elaborated. Fig. 6 shows the conventional simulation block with its power drive and controller showing feedback parameters required for smooth operation of SRM (Wong et al, 2007).

5) SIMULATION AND RESULTS

In this section simulation is carried out. First mode of operation will be single voltage pulse and speed of motor is varied by varying $\boldsymbol{\omega}_{ref}$ in three steps 50, 100, 150 rad/s at 0.1, 0.2 and 0.3 seconds on time scale respectively. First simulated model was run with drive model running in Single Pulse mode, where voltage pulse is applied for duration of dwell angle and then both switches *S1, S2* are turned off, voltage become negative.

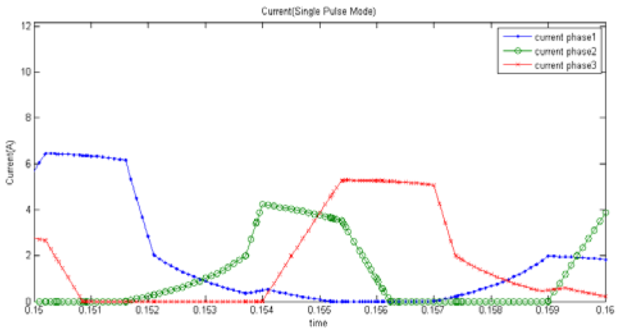

Fig. 7: Phase Currents in Single Voltage Pulse Mode

Fig. 7, Fig. 8 and Fig. 9 show Current, Speed and Torque respectively. It can be observed that when motor is below base speed, $\boldsymbol{\omega_b}$ the speed of motor fluctuates around *50* rad/s and as motor moves to high speed it become more stable, because in this mode at low speed, value of current in between phases is low as less than 2A and causes fluctuations in speed and also high torque ripple as can be observed in Fig. 9. According to the behavior of phase currents shown in Fig. 7, this mode is not suitable at low speed, on the other hand current and torque value is high as *6A* and *15 Nm* respectively in this region.

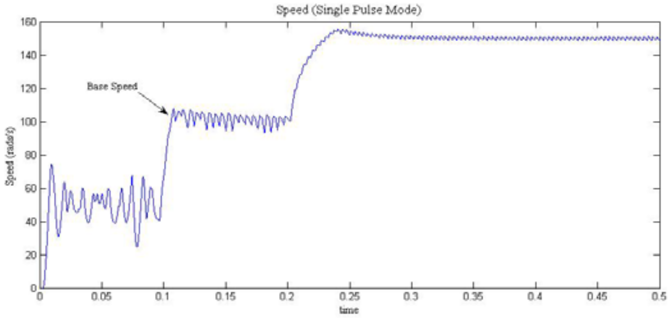

Fig. 8: Speed in Single Voltage Pulse Mode

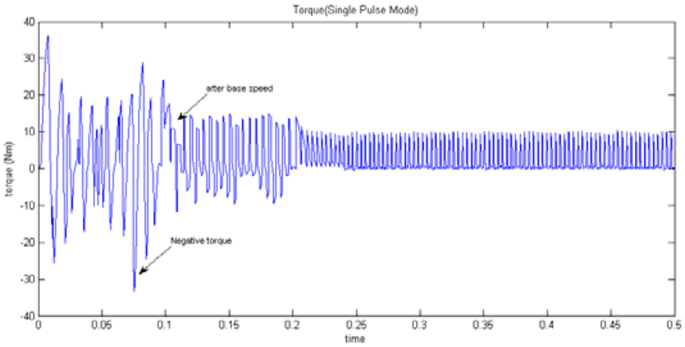

Fig. 9: Torque in Single Voltage Pulse Mode

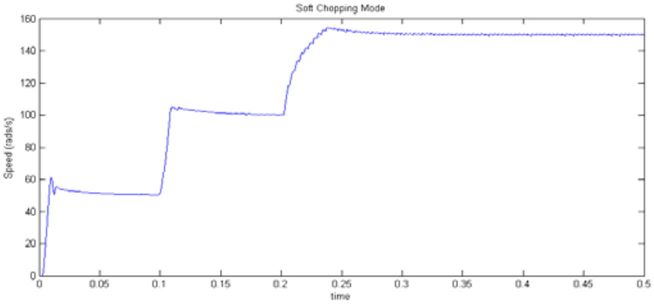

Fig. 10: Speed in Soft Chopping Mode

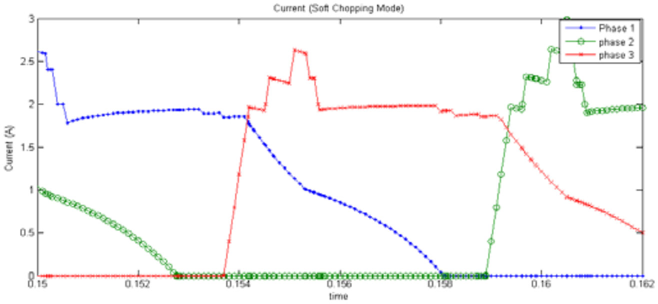

Fig. 11: Phase Currents in Soft Chopping Mode

The speed control in soft chopping mode below and above the base speed is an improvement, Fig. 10 clearly showing this fact. Figure 11 shows that flat top of current is changed to small fluctuations due to on/off of switch *S1*, therefore average value of current and torque is less than of that in

Single Pulse Mode but improvement can be seen in torque Fig. 12, which is smoother and have higher average value of 7-8 Nm.

In Hard Chopping Mode the graph of speed does not have any major difference. This can be explained by observing the current waveform in Fig. 13, value of current and its rise and fall are similar in both modes, so the speed control. The difference is present initially where speed in soft chopping mode shoot up to 60 rad/s then slowly settled at 50 rad/s and in hard chopping mode speed smoothly followed the ω_{ref} in all regions.

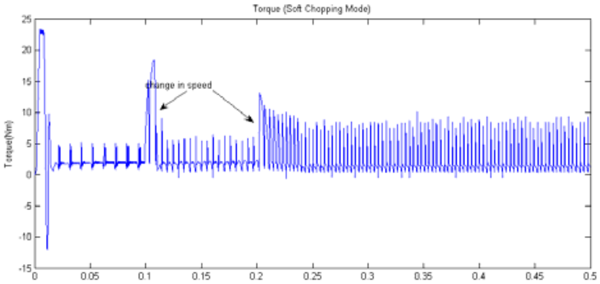

Fig. 12: Torque in Soft Chopping Mode

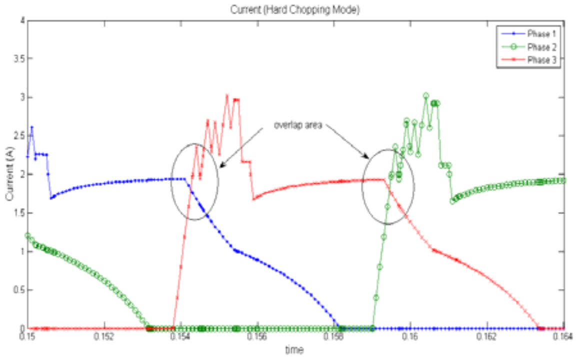

Fig. 13: Phase Currents in Hard Chopping Mode

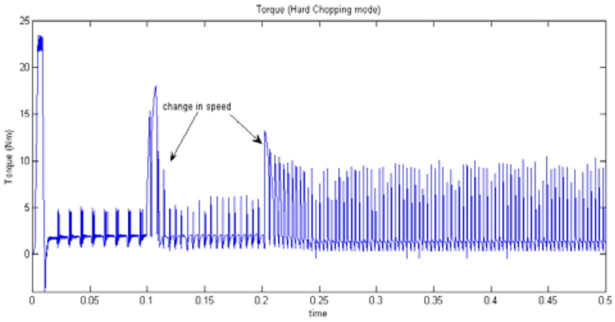

Fig. 14: Torque in Hard Chopping Mode

Comparing current shapes in Fig. 11 and 14, it is evident that in hard chopping mode current is smother than soft chopping mode, therefore, average value of torque is better in this case. Speed control is more precise but takes longer to reach reference speed.

6) CONCLUSION

Detailed study of motor mathematical model is presented in this paper. SRM's important parameters such as torque, flux linkage, phase commutation and base speed are evaluated for asymmetric half bridge converter in three classical modes and results are discussed in detail. It is shown that Single Voltage Pulse Mode is not suitable for low speeds, and its advantages include high torque and phase currents. SRM running in other two modes slightly differs from each other in term of smooth phase currents and smooth initial start, where hard chopping mode proved to be a batter choice.

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