Optimal Operating Parameters for Torque Ripple Minimization in Switched Reluctance Motors Based on Genetic Algorithms

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Abstract-- The paper proposes an optimization control method by adjusting the values of turn-on, turn-off and demagnetizing angles of switched reluctance motor (SRM) according to minimum torque ripple. An optimization method based on Genetic Algorithms (GA) is applied to find the best operating parameters values of SRM for minimum torque ripple. A real-coded representation is used. The optimum parameters for different operating conditions are presented.

Index Terms-- SRM, current chopping, torque ripples, SIMULINK, Genetic Algorithms.

I. INTRODUCTION

TORQUE ripple is the main drawback of switched reluctance motor to achieve high performance. It has undesirable effects to the bearing system and produce acoustic noise. Several studies have been mentioned on torque ripple reduction among these [1] presents a simple technique to minimize torque ripple based on the control of the sum of the square of the phase currents. Paper [2] proposes a Fuzzy-Logic-Based turn-off angle compensator for torque ripple reduction in a switched reluctance motor. The turn-off angle, as a complex function of motor speed and current, is automatically changed for a wide motor speed range to reduce torque ripple. Paper [3] presents an artificial neural network controller to reduce the torque ripple in SRM. The neural network is used to learn the non-linear flux linkage characteristics then provides an analytical function representing the flux linkage characteristic of the motor. The flux linkage analytical function can be operated on by co-energy and torque equations to produce forward torque estimation network. So for a desired reference torque, the controller computes the reference phase current.

Genetic Algorithms (GAs) are highly efficient and robust in searching for multi-optimal solutions in a difficult multi-dimensional solution space [4]. The optimization using GAs has been reported in several researchs such as [5] which suggests an optimization control scheme by adjusting both the turn-on and turn-off angle according to high efficiency points that are simulated by GA-Neural Networks. In [6] GAs is applied to find the best parameters of the switching power circuit (turn-on, turn-off angles and limited current in switching elements) for a SRM. The optimal parameters are found by GA with two objective functions, i.e efficiency and torque ripple. This paper introduces an optimization control method by adjusting the values of turn-on angle (θ_{on}), and turn-off angle (θ_{off}) and demagnetizing angle (θ_d) (is the angle where the phase current decays to zero when negative voltage is applied directly after turning-off) according to minimum torque ripple.

II. TORQUE RIPPLE IN SRM

Torque ripple results from motor's stepping nature and has undesirable effects to the bearing system and produce acoustic noise. It does not allow using SRM in servo applications. Excessive torque ripple, especially at low speeds is still one of the important reasons for the SRM to be unacceptable in variable speed drive market.

There are essentially two primary approaches for reducing the torque pulsations: one method is to improve the design of the motor, while the other method is to use sophisticated electronic controllers. From view of motor design, the torque pulsations may be reduced by changing stator and rotor pole structures, but only at the expense of motor performance. The electronic approach is based on selecting an optimum combination of the operating parameters, which including the supply voltage, turn-on, turn-off and demagnetizing angles, current level and the shaft load.

III. SRM DESCRIPTION AND MODELING

Figure 1 shows a typical 6/4 SRM. It is a three-phase machine and has 6 poles on the stator and 4 poles on the rotor. Here, the diametrically opposite stator pole windings are connected in series and they form one phase. Thus, the six stator poles constitute three phases. When the rotor poles are aligned with the stator poles of a particular phase, the phase is said to be in an aligned position. Similarly, if the inter-polar axis of the rotor is aligned with the stator poles of a particular phase, the phase is said to be in an unaligned position. Figure 2 shows H-bridge converter which is the most popular drive circuit for SRM.

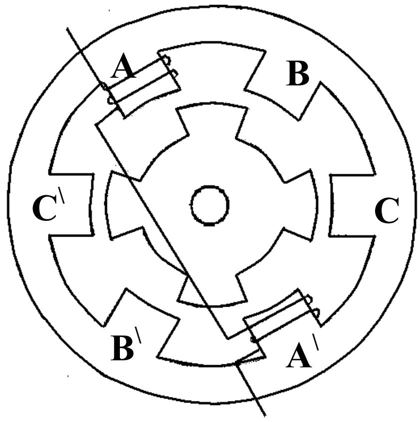


Fig. 1. A typical 6/4 SRM

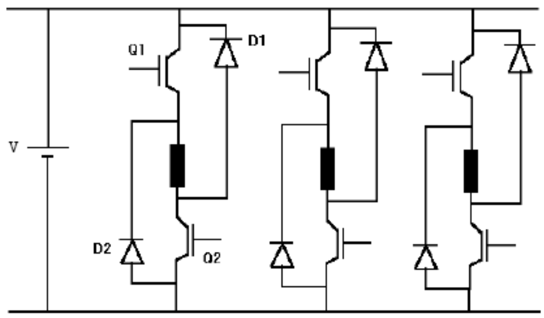


Fig. 2. *H*alf-bridge asymmetric type converter

The differential equations that represent the SRM drive when operated in linear region are:

$$\frac{d\lambda(\theta)}{dt} + Ri = V \qquad (1)$$

$$\lambda(\theta) = L(\theta)i \qquad (2)$$

$$T_{ph} = \frac{1}{2} i^2 \frac{dL}{d\theta} \qquad (3)$$

$$J\frac{d\omega}{dt} = T - T_L - \beta\omega \qquad (4)$$

$$\frac{d\theta}{dt} = \omega \qquad (5)$$

The torque ripple factor (RF) is adopted as a measure for the motor performance in each case and its value is an index for the motor ripples.

$$RF = \frac{\sqrt{\sum_{\theta=0}^{180}\left(T - T_{av}\right)^2 / n}}{T_{av}} \qquad (6)$$

Where:
L : phase inductance, H.
R : Phase resistance, Ω.
θ : Rotor position, Degree.
λ : Flux linkage.
i : Instantaneous value of phase current.
T_{ph} : Instantaneous value of phase torque.
T_L : Load torque.
β : Machine friction coefficient.
n : Number of samples.
J : Moment of inertia.
ω : Angular speed.
T_{av}: Average value of output torque.
T : Instantaneous value of output torque.
$\frac{dL}{d\theta}$:Changing rate of self inductance with respect to rotor position.

The inductance profiles of phases are given in Figure 3. The turn-on angle is considered at the middle position of the minimum inductance, for phase A of the motor this position is at zero degree.

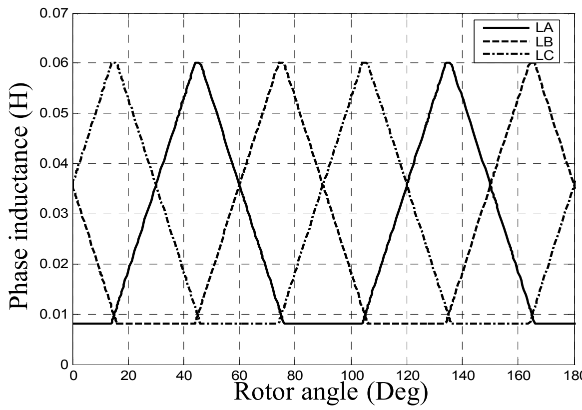


Fig. 3. Phase inductance profiles

The MATLAB/SIMULINK software package is used to set up the dynamic simulated model of 6/4 switched reluctance motor Simulation is based on equations.(1-5)[7,8]. Figure 4 shows the simulation diagram used for the SRM model using hysteresis current control. The instantaneous phase current (I_A, I_B, I_C) is compared with reference current (I_{ref}) and the error is used to chopping the phase input voltage. In the blocks (delay1, delay2, delay3), the phase voltage is chopped according to the error and the current bandwidth. Blocks (switch1, switch2, switch3) define the periods of energizing and demagnetizing voltage.

The block integrator1, 2 and 3 (*1/s*) integrate the (*V-I*R*) of each phase to find the flux linkage (λ_A, λ_B and λ_C). Then the phase flux linkage is divided by phase inductance to calculate the phase current (I_A, I_B and I_C). The phase current is the input to the blocks Torq1, 2 and 3 to calculate the phase torque. Then the total developed torque is the sum of the torque of the three phases. Block integrator 4 (*1/s*) integrate (T - T_L- $\beta\omega$)/J to find the motor speed ω then the block integrator (*1/s*) integrate ω to find rotor angle θ.

Figure 5 shows the motor characteristics for $\theta_{on} = 0^0$, $\theta_{off} = 40^0$, and a current reference of I_{ref}= 4 A and100 rpm. It is noticed that, the output torque has a great dip. Our task is to decrease this dip as possible.

Depending on linear magnetic characteristics, the model is easily designed and simulated with little computational and time efforts. The simulation results using the no

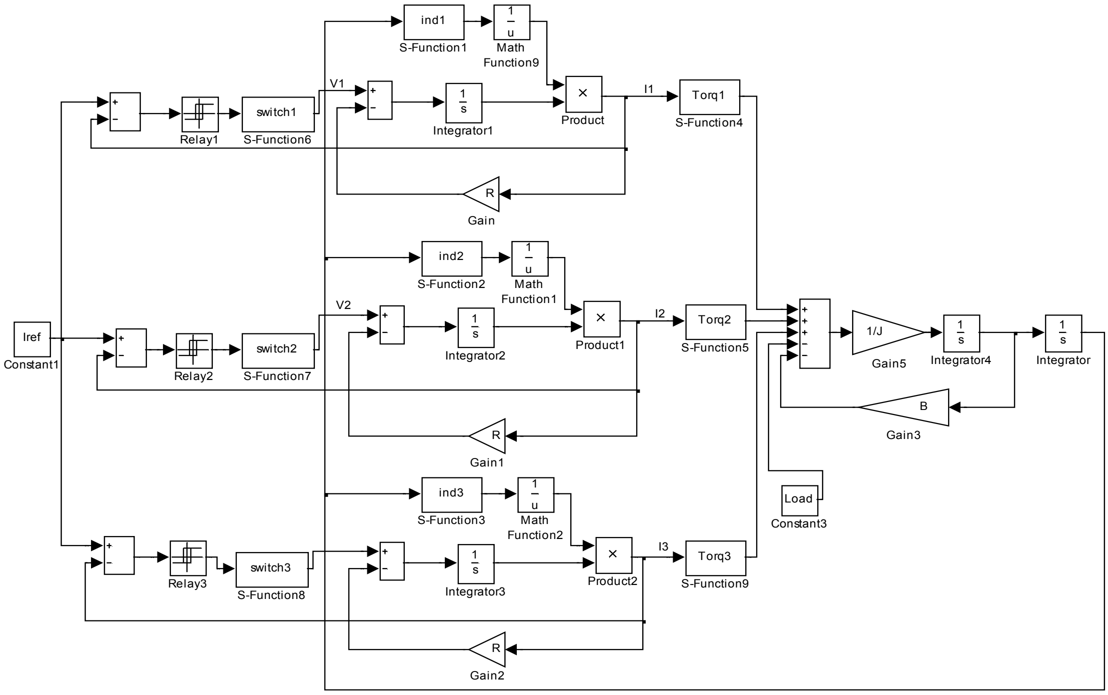


Fig. 4. Simulation of SRM model using hysteresis current control

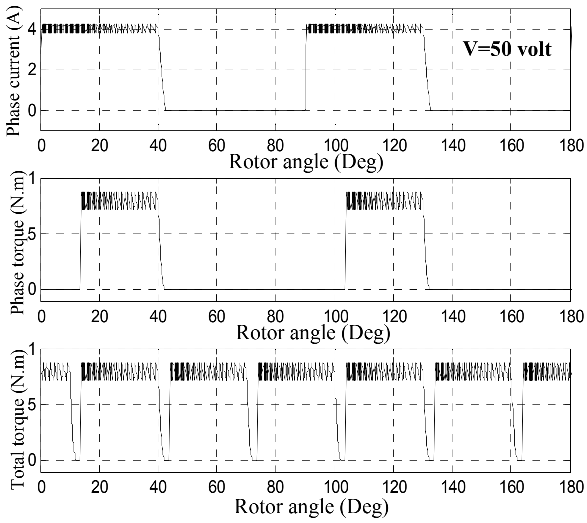


Fig. 5. The motor characteristics at $\theta_{on} = 0^0$, $\theta_{off} = 40^0$

saturated model are accepted as mentioned in [9]. When taking into account the saturation effect, the inductance curve becomes nonlinear and is a function in both the rotor position and phase current. For high precision the saturation shouldn't neglected. We are going in the near future to take the saturation effect into consideration.

IV. OPTIMIZED ANGLES FOR TORQUE RIPPLE MINIMIZATION

The optimal values of both θ_{on} and θ_{off} for minimum torque ripple depend on the speed and the value of reference current (load). At speed 100 rpm and $I_{ref} = 4A$, the optimized values of both θ_{on} and θ_{off} and suitable θ_d can be obtained in two steps. The first at speed 100 rpm and $I_{ref} = 4A$, considering constant θ_{off} and plot the ripple factor versus turn-on angle as shown in Figure 6. It is found that, at low speed the ripple factor is not sensitive to turn-on angle. Turn-on angle must be less than 14^0 (the beginning of inductance increasing) by one degree at least (at 100 rpm) to give a chance to the current to built up and make use of the full period of inductance increasing. So the turn-on angle is chosen to be 13^0 to allow for current building at the same time not applying the current during the whole minimum inductance period, because at this period it does not produce any torque whereas it increases copper losses and consequently decreases the motor efficiency.

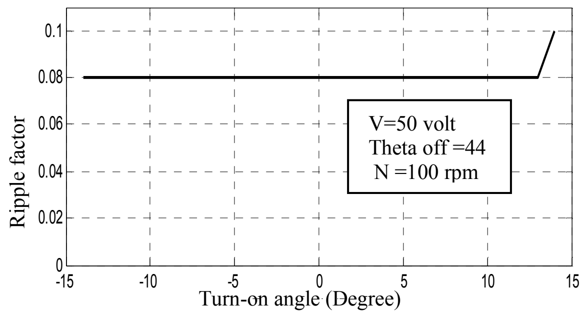


Fig. 6. Ripple factor versus Turn-on angle at 100rpm and $I_{ref} = 4A$

Then considering constant turn-on angle and the ripple factor versus turn-off angle is plotted as shown in Figure 7. The figure shows that, the ripple factor decreases with θ_{off} until it reach minimum value at $\theta_{off} = 43.5^0$ then it increases. So at constant speed 100 rpm, $I_{ref} = 4$ and constant $\theta_{on} = 0^0$, the minimum ripple factor is at $\theta_{off} = 43.5^0$.

Finally for the motor operated at 100 rpm and $I_{ref} = 4$, the optimized Turn-on and Turn-off angles for minimum torque ripple are 13^0 and 43.5^0 respectively. For these values of turn-on and turn-off the demagnetizing angle is adjusted to 46.19^0. The phase current and total torque at optimized angles are shown in Figure 8.

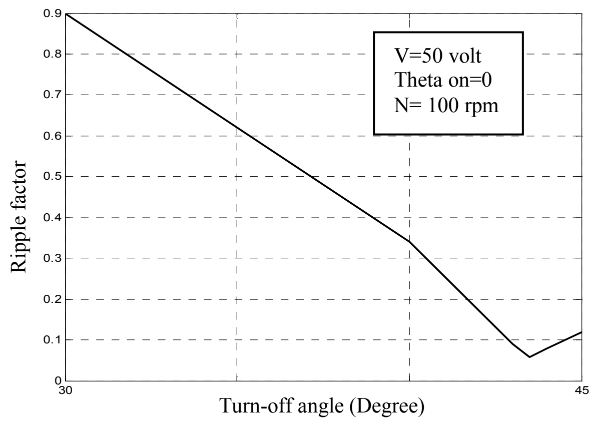


Fig. 7. Ripple factor versus Turn-off angle at 100 rpm and I_{ref} = 4 A

The high frequency ripple in the torque is due to the hysteresis current control and can be made as small as possible by reducing the hysteresis band width (B.W= 0.1) as shown in Figure 9.

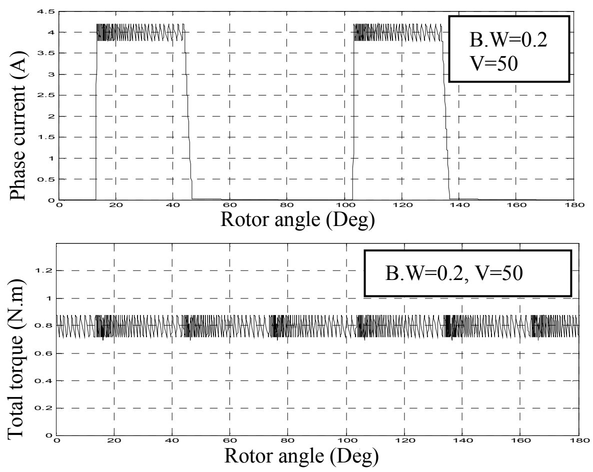


Fig. 8. The motor characteristics at $\theta_{on}=13^0$, $\theta_{off}=43.5^0$

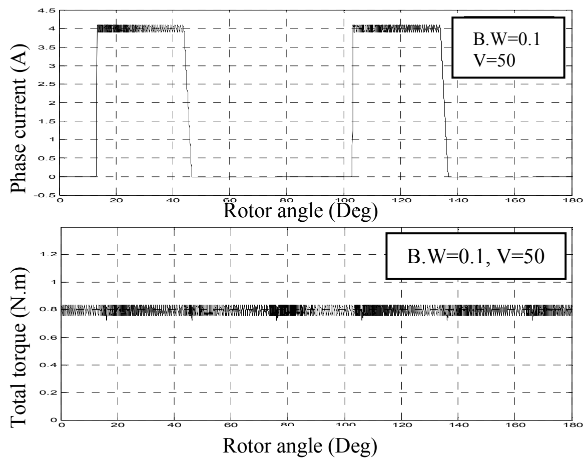


Fig. 9.The motor characteristics at Band-width =0.1

The motor characteristics with optimized θ_{on} and θ_{off} at speeds 100, 400 and 800 rpm are studied. Figure 10.shows the phase current at I_{ref} =4 A at the three speeds. It noticed that the switching frequency decreases with speed increasing so it is expected that the high frequency ripples increase with speed. Also the current take a long period to reach zero with the speed increasing so the phase negative torque also increases as shown in Figure 11. Consequently the torque dip increases with increasing of speed and the torque ripple increases as shown in Figure 12. The minimum ripple factor is 0.058, 0.097 and 0.16 at speeds 100, 400 and 800 rpm respectively.

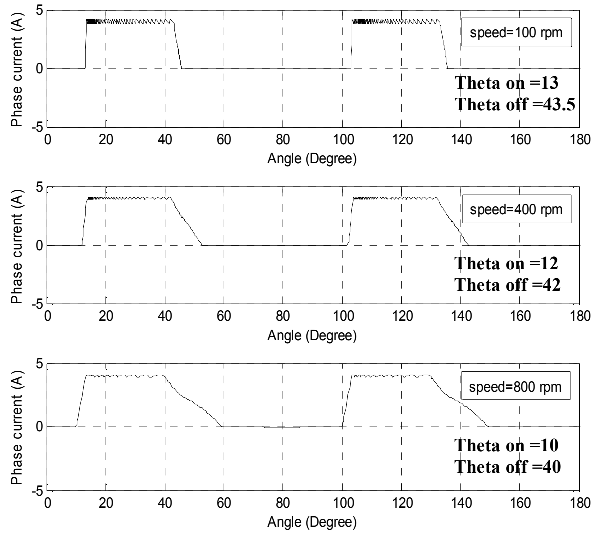


Fig. 10. Phase current at optimal θ_{on} and θ_{off} at different speeds

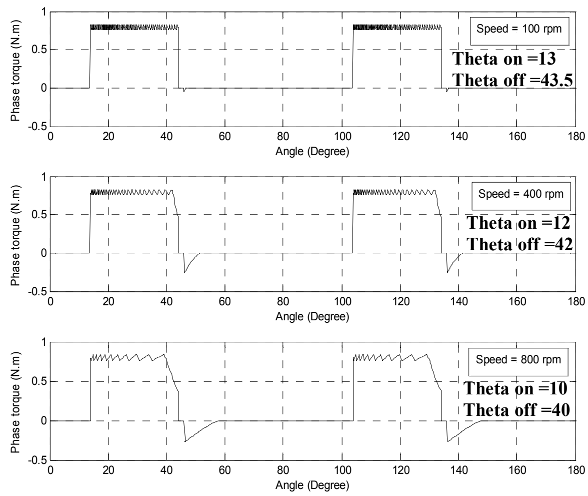


Fig. 11. Phase torque at optimal θ_{on} and θ_{off} at different speeds

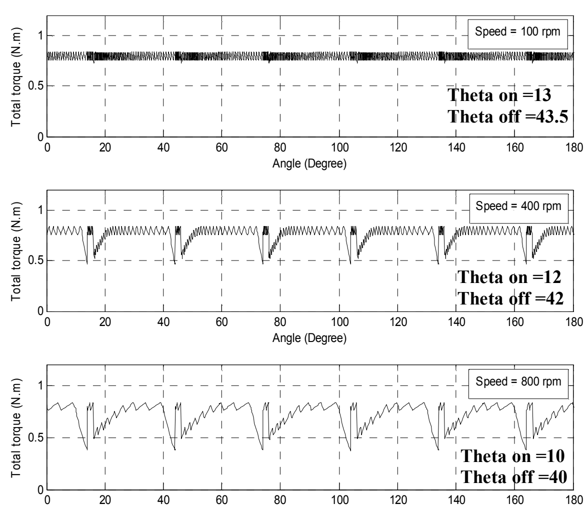


Fig. 12. Total torque at optimal θ_{on} and θ_{off}at different speeds

This optimization method can, however, be automated in a more computerized way by using Genetic algorithms (GAs).

V. GENETIC ALGORITHMS

Genetic algorithms (GAs) are numerical optimization algorithms inspired by natural selection and natural genetics. GAs techniques differ from more traditional search algorithms in that they work with a number of candidate solutions rather than just one candidate solution. Each candidate solution of a problem is represented by a data structure known as an individual. A group of individuals collectively comprise what is known as a population. GAs are initialized with a population of random guesses .Then GAs use three operators, selection, crossover, mutation to direct the population towards convergence to the global optimum. If the population size is too large, the GA tends to takes longer to converge upon a solution. However, if the population size is too small, the GA is in danger of premature convergence upon a sub optimal solution. To overcome this problem, different trials are made to choose the best size of population and number of generations to reach the global minimum with less time.

The GA software used for optimal control settings reported in this work is a commercially available (MATLAB toolbox, GOAT). Both SIMULINK and GA are under MATLAB environment, so that it's easy to call the SIMULINK model within the GA program. A code called (sim ' file name') is used to run the model within the GA program. A real-coded representation is used. The problem in the genetic algorithm tool can be defined in a M-file. It contains the cost function which is used to determine the fitness of an individual (the function that wanted to be optimized), and the numbers of independent variables for the cost function in our case:

Cost function= ripple factor (R.F)
Variables:

$\theta_{on} \in (0^0 - 14^0)$
$\theta_{off} \in (30^0 - 45^0)$
$\theta_d \in (31^0 - 90^0)$

Genetic algorithm is used to find the optimum values of turn-on, turn-off and demagnetizing angles corresponding to minimum torque ripple as follow:

1- Initial population forming: For each individual, GA randomly chooses values for turn-on, turn-off and demagnetizing angles (chromosome) within their defined ranges. The simulation program is called to calculate the ripple factor corresponding to this chromosome. This process is repeated 20 times until the initial population is completed.

2- The chromosomes in the population are ranked in ascending order from lowest to the highest ripple factor.

3- The top ten chromosomes are kept for mating and the rest are discarded to make room for the new offsprings.

4- Then two parents are randomly selected for mating from the selected ten chromosomes to produce two offspring that contain traits from each parent.

5- GA introduces probabilistic random changes, mutation, to the two offsprings to avoid the local minimum problem. For each new offspring simulation program is called to calculate the ripple factor corresponding to each individual.

6- Offsprings are added to the rest of parents to form a new population.

7- The process described from step 2 above is iterated until the first generation is completed. The last population is used as starting population for the next generation until the solution corresponding to the minimum ripple factor is found. The number of generations is 50.

It's known that one drawback of random search methods like GA is its long search time. In our method, GA is run off line for each operating condition. So that computational time is not a matter. Results of GA are suggested to be used to train an ANN to adapt the switching angle according to each loading case.

The results of optimization by GAs at speeds 100, 400 and 800 rpm with different I_{ref} are introduced and compared with that obtained from trial method in the following tables (I – III).

It is noticed from the comparison between the optimized firing angles from trial optimization method and that from GAs that, the values are to close. So the GAs is a good method for obtaining the optimized angles corresponding to minimum ripple at desired speed and load.

The motor under study has the following parameters:
3 ph, 6/4 SRM, 150 volt
R = 1.3 Ohm
L_{max} = 60 mH
L_{min} = 8 mH
Friction Coefficient = 0.0183 N.m.sec/rad
J = 0.0013 N.m.sec^2/rad

TABLE I
OPTIMAL VALUES OF θ_{ON} AND θ_{OFF} BY TRIAL METHOD AND GAS AT 100 RPM

Speed (rpm)	I_{ref} (A)	Trial Optimization Method				Genetic Algorithms			
		θ_{on}	θ_{off}	θ_d	Rf	θ_{on}	θ_{off}	θ_d	Rf
100	2	14^0	44^0	46.34^0	0.115	13.79^0	43.99^0	45.56^0	0.113
100	4	13^0	43.5^0	46.19^0	0.058	12.89^0	43.65^0	46.30^0	0.058
100	8	13^0	43^0	47.15^0	0.054	12.91^0	42.88^0	47.24^0	0.050

TABLE II

OPTIMAL VALUES OF θ_{ON} AND θ_{OFF} BY TRIAL METHOD AND GAS AT 400 RPM

Speed (rpm)	I_{ref} (A)	Trial Optimization Method				Genetic Algorithms			
		θ_{on}	θ_{off}	θ_d	Rf	θ_{on}	θ_{off}	θ_d	Rf
400	2	13^0	43^0	48.7^0	0.12	13.08^0	43.02^0	48.53^0	0.122
400	4	12^0	42^0	52.47^0	0.11	12.29^0	42.28^0	51.96^0	0.109
400	8	10^0	40^0	58.35^0	0.15	9.94^0	40.39^0	58.33^0	0.149

TABLE III

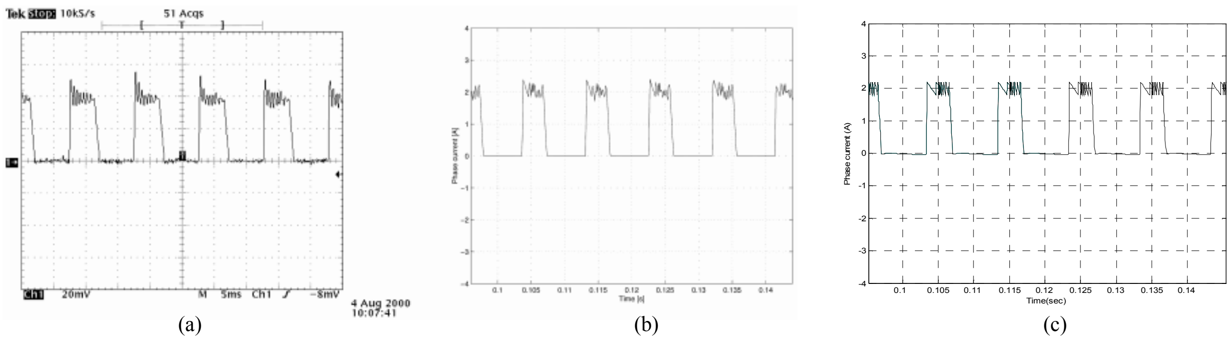
OPTIMAL VALUES OF θ_{ON} AND θ_{OFF} BY TRIAL METHOD AND GAS AT 800 RPM

Speed (rpm)	I_{ref} (A)	Trial Optimization Method				Genetic Algorithms			
		θ_{on}	θ_{off}	θ_d	Rf	θ_{on}	θ_{off}	θ_d	Rf
800	2	12^0	41^0	51.54^0	0.16	12.84^0	41.21^0	52.04^0	0.157
800	4	10^0	40^0	59.89^0	0.17	9.72^0	40.24^0	59.64^0	0.170

VI. EXPERIMENTAL VERIFICATION

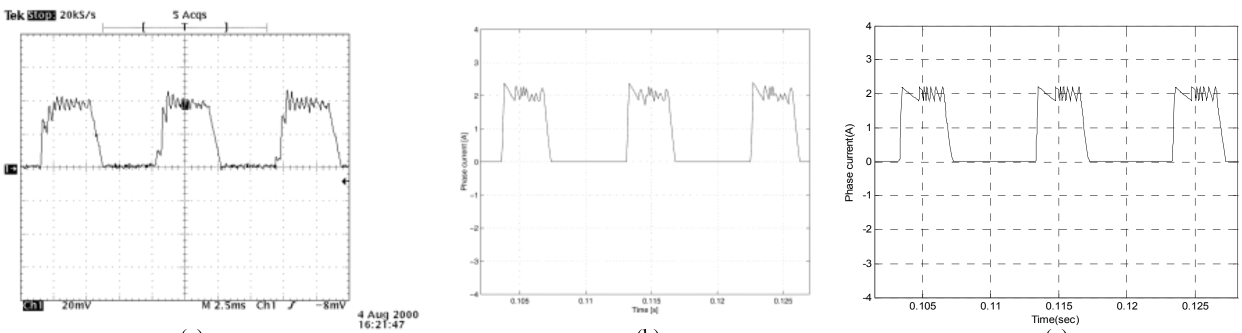
In order to validate the proposed SRM model, the simulation results are compared with the simulated and experimental results with the same motor parameters in [10]. Figures (13, 14) show the comparison between simulated, the measured data of phase current [10] and the simulated from proposed model at supply voltage 150v and 100v respectively.

It is clear from figures that the proposed simulation model matches the experimental and simulated results in the mentioned paper



(a) (b) (c)

Fig. 13. Comparison of measured (a), simulated (b) giving by [10] and simulated from proposed model(c) of phase current at 150 volt



(a) (b) (c)

Fig. 14. Comparison of measured (a), simulated (b) giving by [10] and simulated from proposed model(c) of phase current at 100 volt

VII. CONCLUSIONS

This paper suggests an optimization method by adjusting the turn-on, turn-off and demagnetizing angle of 6/4 switched reluctance motor according to minimum torque ripple.

Genetic algorithms (GAs) are used for obtaining the optimized angles. GAs are successfully applied for optimal design of a SRM operating angles.

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