MODELING AND CONTROL OF NONLINEAR SWITCHED RELUCTANCE MOTOR DRIVE

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Abstract: *This paper presents, the modelling and control of Switched Reluctance Motor (SRM) drive. Digital Signal Processor (DSP-TMS320F2812) controlled high performance SRM drive is used for experimental work. Both linear and nonlinear models of SRM are discussed and presented. Linear model of SRM is easy to simulate but it fails to generate accurate results. To meet the requirements of practical world a more accurate model of SRM is to be developed. The nonlinear model incorporates the nonlinearity of magnetization characteristics as well as torque and current profiles. The magnetic based modelling is physically motivated, and it fits to motor geometry. Experimental results of SRM drive obtained on digital platform and are compared with simulated results of both models of SRM drive. The simulated results of nonlinear model are much in line with the experimental results.*

Key words: *SRM, DSP, PID Controller, Nonlinear Modelling and Simulation.*

1. Introduction

Pioneering work of many researchers has introduced many superior features in form of Switched Reluctance Motor (SRM). They are inherently variable speed drives, which has simple construction, wide speed ranges, good energy efficiencies, high torque to inertia ratios, and high torque to power density ratios. The SRM have attracted many researchers' interests all over the world. The last decade has seen a large number of research papers and patents being filed on various aspects of SRM. It has proved to be a worthy competitor in the adjustable speed drive market and has opened up new panorama, opportunities, and challenges for the researchers in the area of machine design, power electronics, drives and digital signal processing. [1].

The SRM has the flexibility of operating as a four-quadrant drive with independent control of speed and torque over a wide speed range. Its wide torque and speed range eliminates the need for expensive and troublesome mechanical gears and transmissions. The performance of the SRM greatly depends on the applied control [4]-[5]. The SRM drive system consists of three basic components like SRM, inverter, and controller. Today, SRM drives are among the main players for important domestic, research and industrial applications. The SRM drives are vivid example of replacing complex machine geometries with smart control strategies [2], [6]-[8]. There has been worldwide interest in the uses of SRM drive.

The mathematical model of SRM has experienced three stages. First is linear model. Linear mathematic model is simple and easy of implementation, but its precision is poor. Second is quasi-linear mathematic model. In this model, the magnetic characteristic curve is piece-wise linearization. It is based on the assumption that the phase current's waveform is flat topped one. But for an actual operating performance of SRM, it is only an ideal model. Compared to linear model, quasi-linearity precision is higher, but still an approximate model. So, in order to analyze SRM precisely and quantitatively, non-linear mathematic model is the best ideal selection [5]. First this paper presents the linear and non-linear mathematic models of SRM and their control strategies. Then, the simulation of SRM models is established.

Finally the simulation results of both the PID controlled SRM drive using MATLAB/Simulink are presented. At the same time, we do DSP controlled SRM drive experiment [18]-[20]. The simulated results of SRM models have been compared with experimental results on the basis of parameters like rotor speed, phase current and phase voltage with and without load have been obtained for evaluating the performance of both schemes [11] and [14]-[16]. The simulation and experiment results show that the non-linear mathematic model based on magnetization characteristics has the advantages of high precision, high reliability and high practicability and is suitable to study the performances of SRM [21]-[23].

2. Basic Principle of operation

The SRM operation is based on the principle of the minimum reluctance, which is a corollary of the physical law of minimum energy, i.e., a movable mechanical system subject to a magnetic field tends to find a position where the energy stored in the magnetic field is minimum. At this position, the reluctance of the magnetic circuit is also a minimum, and the inductance seems by the exciting electrical circuit is a maximum. This drive system used a power electronic converter to commutate the phase currents according to the rotor position. This allowed for the full utilization of the SRM could compete with other motor and even supersede it in most application, due to high attainable torque and power per volume [19].

The SRM is an electric motor in which torque is produced by tendency of its moveable part to move to a position where inductance of the excited winding is maximized. This torque is called reluctance torque since it can be said that, it is out of a tendency to decrease the reluctance to its minimum. The motion may be rotary or linear, and rotor may be interior or exterior. Generally the movable part is a simple component made of soft magnetic iron, shape in such a way as to maximize the variation of inductance with position. The geometrical simplicity is one of the main attractive features of SRM. There are no windings or permanent magnets being used, the manufacturing cost appears to be lower than for other type of motors, while the reliability and robustness appear to be improved [9], [14].

The SRM does not mean that the reluctance itself is switched in motor, but refers to the switching of phase currents, which is an essential aspect of the operation. It is generally necessary to control the current waveforms electronically, otherwise the efficiency, noise level, and the utilization of converter volt-amperes can be disappointing.

In this paper, the SRM is a 4-phase, 0.75KW, 8:6 structures. The cross-section of SRM is shown in Fig. 1[5] and [9].

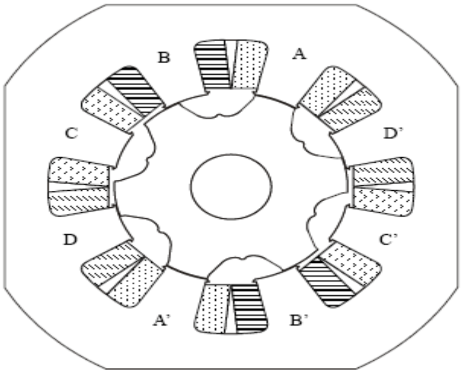

Fig. 1. Structure of 4 phase 8/6 SR Motor

3. Magnetization Characteristics

The double salient structure of SRM causes highly nonlinear characteristics of the motor. The nonlinear characteristic of the SRM lies between the relationship of flux linkage with stator currents and rotor angles. Therefore, it is essential to develop a model based on magnetization characteristics, which show the nonlinear behaviors of the SRM [9]. In general, the nonlinear magnetic characteristics of an SRM can be appropriately modeled by equations defining the nonlinear flux–current–angle and torque–flux–angle characteristics. Even in the linear flux region, the torque produced is non-linear function of the stator current thereby making its control challenging [4]. The torque contour follows a particular path depending on the level of excitation current and the torque produced is a function of the change in co-energy of the rotor which in turn is a function of flux linkage, excitation current and rotor position. Thus the rotor angle has to be known accurately [2], [24].

4. Modeling of SRM Drive

The purpose of the model is to capture the functioning of some system. The construction of a model can be viewed as a process in which a collection of objects called the variables and parameters of the model are related by some other objects called the connectives or operators of the model. The variables used in the model correspond to some characteristics of the system being modeled [9]. Different parts of the drive system are modeled separately and integrated to obtain the complete model.

In the proposed scheme, the motor speed is compared with reference speed and is fed through PID speed controller to get reference current (I^*_{abc}). Now machine current I_{abc} is compared with I^*_{abc} and the error signal generated is used to get proper phase voltages while keeping the stator current regulated within hysteresis band around the reference current. Same values of phase voltages are used by the VSI for the switching of the phases on the basis of rotor position obtained from the motor speed. But sign command plays an important role during the switching of phases for the forward and reverse operation of the SRM. This section briefly describes the linear model of SRM, modeling of inductance profile, PID speed controller, Hysteresis current controller, inverter and switching angle. The block diagram of the close loop drive scheme is shown in Fig. 3.

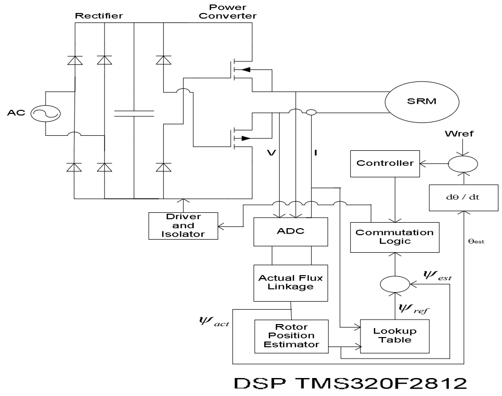

Fig. 2. SRM Drive modeling scheme

A. Modelling of SRM

The mathematical model of SRM is a set of differential equations obtained by dynamic electric machine theory.

i. Linear Modeling of Switched Reluctance Motor

Switched reluctance motor is nonlinear in nature, therefore it's important to develop a relevant mathematical model of the machine. A simple linear model of the SRM is presented here. The electrical equation for each phase could be written as

$$\frac{d\psi_i}{dt} = V_i - I_i R \tag{1}$$

But the flux in each phase is given by the linear equation

$$\psi_i(\theta, I_i) = L(\theta) I_i \tag{2}$$

The mechanical equation could be given by

$$J\frac{d\omega}{dt} = T - T_l - F\omega \tag{3}$$

$$\frac{d\theta}{dt} = \omega \tag{4}$$

$$T = \frac{1}{2}\sum_{i=1}^{3}\frac{dLI_i^2}{d\theta} \tag{5}$$

Where V_i is the applied voltage across the SRM stator winding, I_i is the current in the winding, ψ_i is the flux linkage, R is the resistance of each phase winding, J is the rotational inertia constant, F is the frictional coefficient, T is the total torque developed by all the phases, T_l is the applied load torque, ω is the rotor speed and θ is the rotor position angle.

Due to the negligible magnetic coupling between the adjacent phases of the SRM the flux linkage is assumed to be unaffected by the currents in the other phases and is defined as a function of the current *i(t)* and the rotor angle.

ii. Inductance Calculation

The magnetization characteristics of SRM is non linear in nature but it is convenient if the SRM is operated completely in the linear region of its flux linkage characteristics because this is the simplest case. Now flux and current relation is linear in nature. A triangular inductance profile is used here due to the simplicity offered in inductance calculation. Equation (2) used for inductance calculation according to rotor position (θ) .

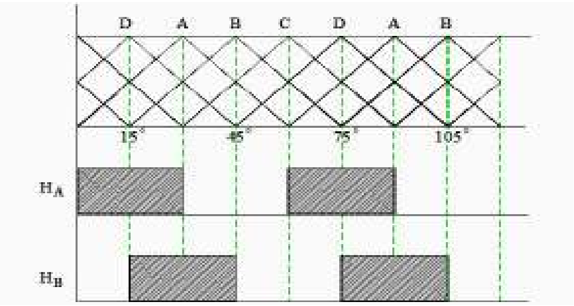

Fig.3. Inductance Profile and Rotor position

B. Nonlinear Modeling of SRM

The mathematical model of the SRM consists of a set of differential equations obtained using dynamic electric machine theory. The mathematical description of controller includes the modeling of converter, commutation logic, current controller and speed sensors. The integrated model of the SRM plant, thus, forms the basis for the nonlinear control problem addressed in this paper [9]. The simplicity in construction and relatively easy working belies the complexity of the mathematical modeling for the performance prediction, when a narrow air gap for improved energy conversion efficiency is used. The high degree of difficulties in modeling of the SRM is due to the nonlinear electrical phase equation, which is represented in several ways:

$$\frac{d\psi(i,\theta)}{dt} = v - Ri(\psi,\theta) \tag{6}$$

$$\frac{di(\psi,\theta)}{dt} = \left(\left[\frac{d\psi}{dt}\right]^{-1}\right)\left(v - iR - w\frac{d\psi}{d\theta}\right) \tag{7}$$

$$\frac{di}{dt} = \left[\frac{1}{l}\right]\left(v - iR - iw\frac{\delta L}{\delta\theta}\right) \tag{8}$$

$$\frac{di}{d\theta} = \frac{1}{w}\left(1 + \left[\frac{\delta\psi}{\delta i}\right]\right)\left(v - iR - w\left[\frac{\delta\psi}{\delta\theta}\right]\right) \tag{9}$$

$$\frac{d\psi}{dt} = g\left(i - f\left(\psi(t)\right)\right) \tag{10}$$

where

$W^{'}$ *(θ, i)* = Co-energy function, l = Incremental Inductance, L = Slope of line from origin to instantaneous flux, g = a function of current and flux linkage, f = a function of flux linkage

It is obvious that the above equations have no analytical solution as the flux linkage is a nonlinear function of current and rotor angle and the equations have two unknowns ψ and *i.* The attempts to model SRMs basically differ on the variable chosen for solution and hence the requirement of different data sets.

The static characteristic equations are

$$w'(\theta,\ i) = \int_0^i \psi(\theta,i)\,di \qquad \text{where } \theta = \text{constant} \tag{11}$$

$$T(\theta,\ i) = \frac{\delta W'(\theta,\ i)}{\delta\theta} \qquad \text{where } i = \text{constant} \tag{12}$$

We take the magnetic saturation and non-linearity into account by considering the experimental $\psi - I$ characteristic data as shown in Fig. 3. For discrete rotor positions θ and $T-\theta$ characteristic data with current varying as shown in the Fig. 4. The lookup tables used here offer practical performance indices and linear interpolation techniques are used to find the intermediate parameter values. The Fig. 3 is used to find the value of current for a given value of flux and rotor position. This value of current obtained is then used in Fig. 4 to find the torque developed by the motor [9], [14], [24].

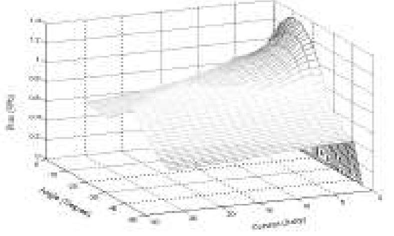

Fig. 4. Experimental flux- current characteristics

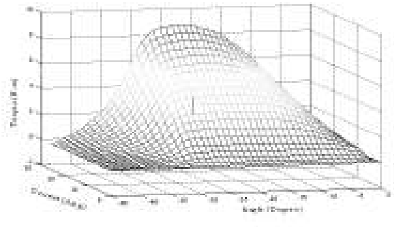

Fig. 5. Experimental torque- angle characteristics

The Fig. 4 and 5 have been used by curve fitting analytical approximations method in dynamic simulation and control of SRM drive.

C. Modeling of PID Controller

The discrete time equivalent expression for PID controller is given as follow

$$u(k) = K_p e(k) + K_i T_s \sum_{i=1}^{n} e(k) + \frac{K_d}{T_s} \Delta e(k) \tag{13}$$

Here, u(k) is the control signal, e(k) is the error between the reference and the process output, T_s is the sampling period for the controller, and

$$\Delta e(k) \equiv e(k) - e(k-1) \tag{14}$$

The parameters of the PID controller K_p, K_i, and K_d can be manipulated to produce various response curves from a given process.

D. Modeling of Hysteresis Current Controller

Basically a current controller is used to follow the current command in some apparatus. The current control technique plays an important role in the inverter. There are various techniques available for the current controller. Considering easy implementation, quick response, maximum current limit and insensitivity to load parameter variation, the hysteresis controller is a popular option [18].

Following equations are used for firing the inverter.

$$I_a^* = I_{ref} - I_a \tag{15}$$

If $I_a^* >= h$

$$Ea = V\max \tag{16}$$

If $I_a^* <= -h$

$$Ea = 0 \tag{17}$$

Where h is the width of the hysteresis band, Ea = Phase voltage, Vmax = Maximum voltage. Similar equations can be obtained for all three phases using Ib*and Ic*. Here Ia, Ib, and Ic are the three phase stator currents.

E. Modeling of Inverter Circuit

Excitation of the stator windings of the SRM is provided by the converter circuit. According the rotor position, the applied voltage across stator winding of each phase becomes positive, negative and zero and the sequence of switching is decided by the sign signal. The excitation pattern of the converter devices is governed by the following equations

$\theta_{on} <= \theta <= \theta_{off}$

$$Va = Ea \tag{18}$$

$\theta_{off} <= \theta <= \theta_q$

$$Va = -V\max \tag{19}$$

$\theta > \theta_q$

$$Va = 0 \tag{20}$$

Here θ_{on} and θ_{off} are the rotor positions at which the corresponding phase excitations are turned on and off. It is seen that both angles are such that they occur in the rising inductance profile region so that positive torque is produced to move the rotor in the forward direction. In similar pattern, it can be written for the other phases.

5. Experimental Setup

A DSP based SRM drive system is made up of several distinct subsystems includes DSP development tool board (TMS320F2812), personal computer, H-bridge converter, Hall current sensors, eddy current load and 8/6 pole SRM. This setup has been used for obtaining experimental results [11]-[12]. The block diagram of experimental setup and photograph of DSP controlled SRM drives are shown in Fig. 5. and Fig. 6.

Fig. 5. Block diagram of DSP controlled SRM drive

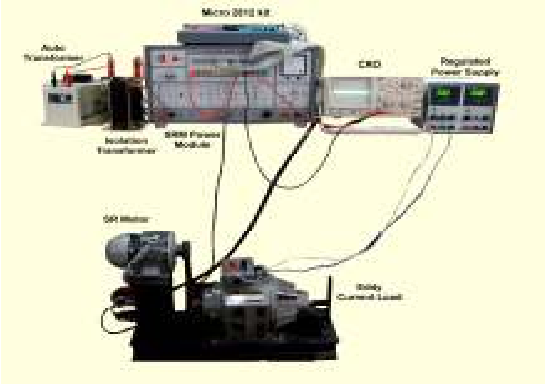

Fig. 6. Photograph of experimental setup of DSP controlled SRM drive

The DSP controlled four phase SRM drive is used in laboratory for experimental work. The high speed, dual bus and programmable Harvard architecture of DSP is used for controlling the operation of SRM drive [7], [12], [13]. The torque in SRM is independent of the excitation current polarity. The H-Bridge converter is used for experimental setup. The H-Bridge power converter circuit is shown in Fig. 7 [10], [17].

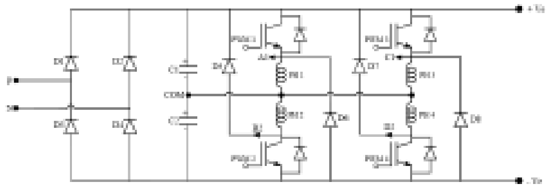

Fig. 7. H-Bridge power converter circuit

The opto-isolator provides the isolation in term of impedance. For sensing current by Hall sensors are used for feedback action in practical setup. The DC operated eddy current load is used according to the experimental need, which is shown in Fig. 8.

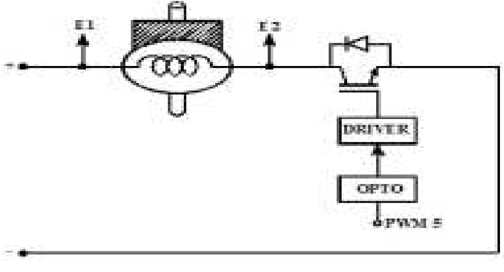

Fig. 8. Block diagram of DSP controlled SRM drive

6. Results and Discussions

To prove the functionality of PID speed controlled linear and nonlinear models of SRM drive with the DSP controlled SRM drive scheme under load or no load conditions. The performance of the MATLAB simulated SRM drive models have been observed in terms of outputs i.e. rotor speed, phase current, and phase voltage. The linear model fails to produce simulated results for practical systems because its modeling based on certain assumptions. The other model is a practical or nonlinear model of drive suitable for handling real world problems. Its simulated results based on magnetization characteristics, which matched with experimental results of same type drive. These results prove the suitability of nonlinear scheme for high performance SRM drive.

A. Simulation Results of SRM drive

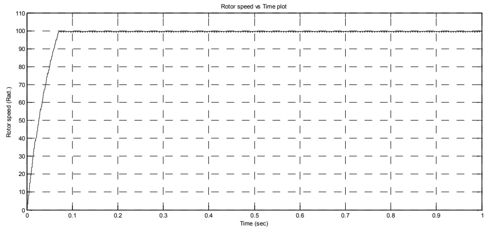

Fig. 9.1. Rotor speed vs. time with linear model

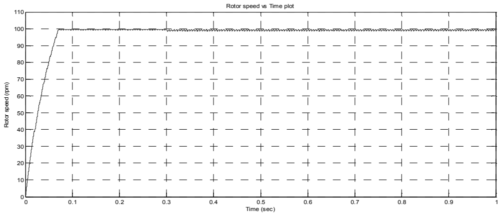

Fig. 9.2. Rotor speed vs. time with nonlinear model

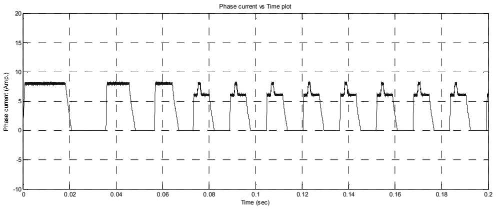

Fig. 9.3. Phase current vs time with linear model

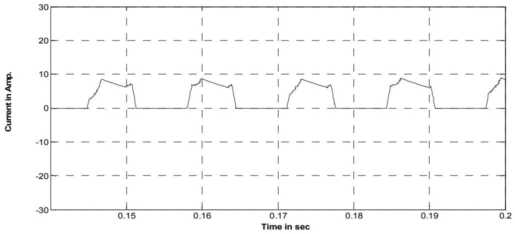

Fig. 9.4. Phase current vs time with nonlinear model

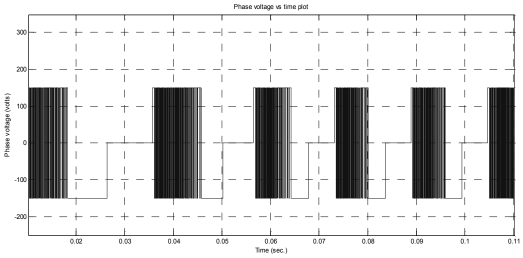

Fig. 9.5. Phase voltage vs. time with linear model

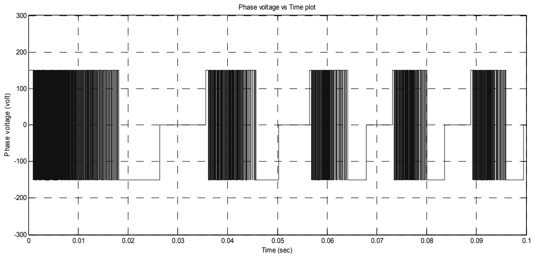

Fig. 9.6. Phase voltage vs. time with nonlinear model

The transient inductance and torque pulses for linear model are shown in Fig. 9.7. The torque pulses of linear and nonlinear model of SRM drive has been shown in Fig. 9.8-9.9.

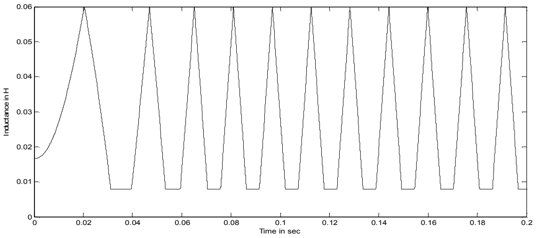

Fig.9.7.Inductance vs. time with linear model

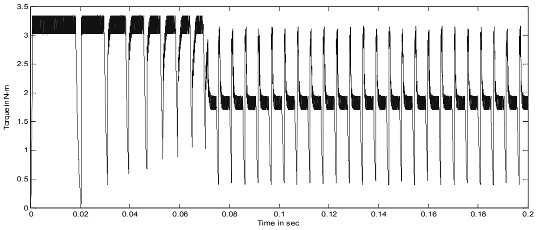

Fig. 9.8.Torque vs. time with linear model

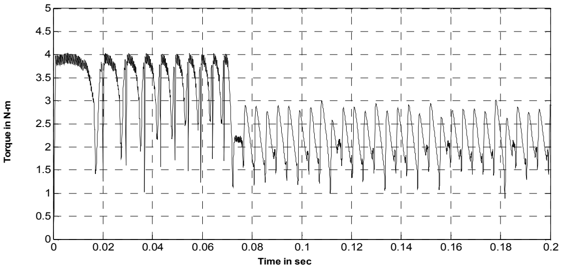

Fig. 9.9. Torque vs. time with nonlinear model

At low speed the effect of saturation in linear and nonlinear model of SRM drive has very small. At high speed the saturation play its role in the simulation results of linear has less but more in nonlinear model have been shown in Fig. 9.3-9.4. The SRM nonlinear model results have been very close to experimental results.

B. Experimental Results SRM Drive

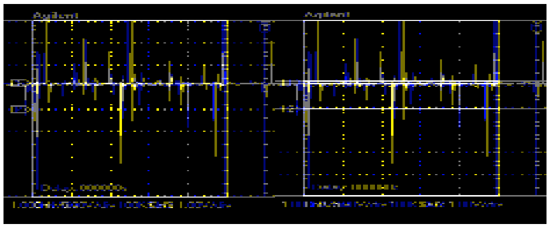

Fig.`9.10. Rotor speed vs. time

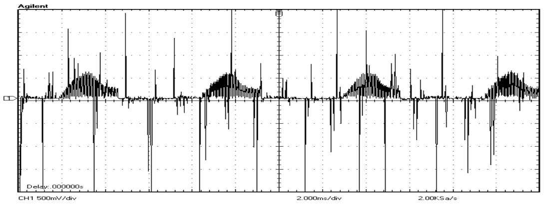

Fig. 9.11. Phase current vs. time

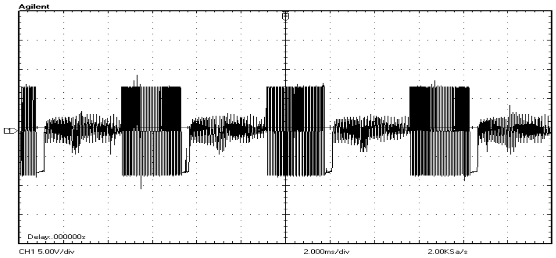

Fig. 9.12. Phase voltage vs. time

Both simulated as well as experimental results are shown in Fig. 9.1-9.9. It is observed that the results obtained from non linear model are very much close to the experimental results as compare to linear model. Another interesting observation is that though there is difference between the speed behavior of the drive with these two models but this not so large and hence can be concluded that linear model can be used where no precise motion control is required.

Conclusions

Different modeling techniques for SRMs are discussed in this paper. These modeling techniques have been simulated using MATAB/Simulink software. This paper has performed a thorough evaluation of the simple and effective PID based linear and nonlinear models of SRM drives and DSP controlled SRM drive experimental setup. The PID speed controlled linear model of SRM drive is a theoretical model based on certain assumptions, it does not fulfill the requirement of practical systems. Then, consider another PID based nonlinear model for drive is a practical model to deal various real world problems. The simulated results of nonlinear SRM model are compared with experimental results of DSP controlled SRM drive with or without load in terms of rotor speed, phase current, and phase voltage.

Appendix

DC bus voltage: 300V, Rated Power: 0.75 kw, Base speed: 1000 rpm; No. of stator poles: 8; No. of rotor poles: 6; No. of phases: 4; Stator pole arc: 30degree; Rotor pole arc: 30degree; Unaligned phase inductance: .0008 H; Aligned phase inductance: .006 H; Phase resistance (R): 1.3 ohm; Inertial co efficient (J): .0013; $\theta_{on} : 0^{o}$; $\theta_{off} : 40^{o}$; $\theta_{q} : 60^{o}$.

References

1. R. Kumar, R. A. Gupta and S. K. Bishnoi, “Converter Topologies for Switched Reluctance Motor Drives”, *International Review of Electrical Engineering, Vol. 3, No. 2* , March-April 2008, pp. 289-299.
2. M. Ehsani, “Switched Reluctance Motor Drives - Recent Advances**”,** *Sadhana, Vol. 22, Part 6*, December 1997, pp. 821-836.
3. B. Fahimi, “Design of Adjustable Speed Switched Reluctance Motor Drives”, *IEEE International Conference Industrial Electronics Society IECON’01*, 2001, pp. 1577-1582.
4. Mehrdad Eshani, Iqbal Husain, Sailendra Mahajan and K. R. Ramani, “New Modulation Encoding Techniques for Indirect Position Sensing in Switched Reluctance Motors”, *IEEE Trans. Industry Applications, Vol. 30, No. 1*, January/February 1994, pp. 85-91.
5. Buju G. S., Menis Roberto and Valla Maria. J, “Variable structure control of an SRM drives”, *IEEE Trans. on Industrial Electronics,Vol. 1*, Feb 1993, pp 56-63.
6. Sayeed Mir, “Classification of SRM Converter Topologies for Automotive Applications*” SAE 2000, World Congress. Detroit, Michigan,* March 6-9, 2000.
7. M. Ehasni, I. Husain, S. Mahajan, and K. R. Ramani, “New Modulation Encoding Techniques for Indirect Rotor Position Sensing in Switched Reluctance Motors, *IEEE Trans. on Ind. Applicat., Vol. 30, No.1*, January/ February 1994, pp. 85-91.
8. TMS320F2812 Datasheet, *Texas Instruments*, 2002.
9. C. Mademlis and I. Kioskeridis, “Four-Quadrant Smooth Torque Controlled Switched Reluctance Machine Drives”, *IEEE International Conference*, 2008, pp.1216-1222.
10. R. Krishnan, “*Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design, and Applications*”, CRC Press, 2001.
11. G. Baoming and Z. Nan, “DSP- based Discrete-Time Reaching Law Control of Switched Reluctance Motor”, *IEEE International conference IPEMC*, 2006, pp. 1-5.

12. H. P. Huang, M. L. Roan and J. C. Jeng, "On-Line Adaptive Tuning for PID Controllers", *IEE Proc. Contr. Theory Applicant., Vol. 149, No. 1*, January 2002*,* pp. 60-67.
13. T. J. E. Miller. "*Electronic control of switched reluctance motors"*. Newnes Power Engineering Series Oxford, UK, 2001.
14. F.Soares, P.J.Costa Branco, "Simulation of a 6/4 Switched Reluctance Motor Based on Matlab/Simulink Environment," *IEEE Trans. on Aerospace and Electronic System, vol. 37, no. 3,* pp. 989-1009, July 2001.
15. S. Mir, I. Husain, and M. E. Elbuluk, "Switched Reluctance Motors Modeling with on-Line Parameter Identification", *IEEE Trans. on Industry Applications, Vol. 34, No. 4,* July/ August 1998, pp.776-783.
16. S Mir., I.Husain, M.E Elbuluk,., "Energy-Efficient C-Dump Converters for Switched Reluctance Motors," *IEEE Transactions on Power electronics, Vol.12, Issue 5*, Sept. 1997*,* pp. 912-921.
17. Mehrdad Eshani, Iqbal Husain and Ashok B. Kulkarni, "Elimination of Discrete Position Sensor and Current Sensor in Switched Reluctance Motor Drives", *IEEE Trans. Industry Applications, Vol. 28, No. 1*, January/February 1992, pp. 128-135.
18. T Lachman., T.R Mohamad., and C.H Fong., "Nonlinear Modeling of Switched Reluctance Motors using Artificial Intelligence Techniques", *IEE Proc.-Electr. Power Appl., Vol. 151, No.1*, January 2004, pp. 53-60.
19. Ramasamy G., Rajandran R.V., Sahoo N.C., "Modeling of Switched Reluctance Motor drive System using Matlab/Simulink for Performance Analysis of Current Controllers", *IEEE PEDS*, 2005, pp. 892-897.
20. V.Vladan and N.V. Slobodan, "A Simple Nonlinear Model of the Switched Reluctance Motors", *IEEE Trans. on Energy Conv., Vol. 15, No. 4*, December 2000, pp. 395-400.
21. G. Venkatesan, R. Arumugam, S. Vasudevan, S. Paramasivam and S. Vijan, "Modeling and Simulation of a Novel Switched Reluctance Motor Drive System with Power Factor Improvement", *American Journal of Applied Sciences 3(1)*, 2006, pp. 1649-1654.
22. S. Zhou and H. Lin., "Modeling and Simulation of Switched Reluctance Motor Double Closed Loop Control System", *6th World Congress on Intelligent Control and Automation*, June 21-23, 2006, pp. 6151-6155.