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FUZZY VARIABLE STRUCTURE CONTROL STRATEGY FOR STABLE NONLINEAR DYNAMIC SYSTEM

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Abstract

This paper presents a fuzzy logic controller (FLC) based on variable structure control (VSC) with sliding mode concept is used to control the speed of switched reluctance motor (SRM) drives. Since, the VSC has several attractive advantages such as high speed response, good transient performance, insensitivity to variation system parameters and external disturbances, simplicity of realization and robustness in nonlinear systems control. A sliding mode controller incorporating fuzzy control helps in achieving reduced chattering, simple rule base, and robustness against load disturbance and nonlinearities. The simulation of nonlinear model SRM using the proposed technique is carried out and the results are compared with those obtained using the conventional PI controller. Also, the experimental setup is verified, which consists of building IGBT inverter H-bridge and associative drive gate with its control circuit and interfacing between control algorithm and experimental hardware. Both simulation and experimental results with the proposed algorithm show that, the system performance is improved significantly in the presence of load disturbance and is insensitive to some parameters variations of the system. Also, the variable structure technique is used to improve the stability requirements of the dynamic system when all the Lyapunov stability condition are realized.

Keywords: Fuzzy sliding control, Lyapunov stability

1 INTRODUCTION

The switched reluctance motor (SRM) represents one of the oldest electric motor types, going back to the 19th century. Its operation principle was vented by Faraday in 1838, but it was forgotten till the beginning of 1970's due to the advent of inexpensive and high power semiconductor switching devices [1]. High power semiconductor switching devices such as thyristors, GTOs, power transistors, IGBTs, MOSFETs, micro-controllers, and microprocessors, are now used to drive and operate the SRM. These devices were not available before 1970, it was difficult at this time to drive the SRM where the SRM must be electronically commutated and thus it can not run directly from a DC supply or AC line [2].

However, the control of the SRM is not an easy task. The motor's double salient structure makes its magnetic characteristic highly nonlinear. Therefore, its mathematical model is too complex to be analytically developed. Apart from the complexity of the motor model, the SRM should be operated in a continuous phase to phase switching mode for proper motor control [3].

Variable structure systems (VSSs) theory was first proposed in the early 1950 and has been extensively developed in the beginning of 1970. The theory of VSS with sliding mode has been studied intensively by many researchers. A lot of newer results are included in both Utkin's book [4] which described identification methods used with VSSs based on sliding mode. Decarlo, Zak, and Matthews paper [5] presented, in a tutorial manner, the design of variable structure systems for a class of multivariable nonlinear time varying systems. They used the concepts of "equivalent control" and "generalized Lyapunov stability" for designing VSC.

Recently, fuzzy logic theory has been successfully applied to many engineering fields, especially in the field of control engineering. Fuzzy logic control provides a systematic procedure to transform human knowledge base into a practical automatic control strategy. Practically, fuzzy logic control shows its powerful capability in dealing with those complex systems and systems lack of knowledge of their mathematical model. Moreover it is easy to implement, as it usually needs no mathematical model of the controlled system [6].

This paper tries to discuss how some “intelligence” can be incorporated in SMC by the use of computational intelligence method. By using the similarity between fuzzy logic and variable structure with sliding mode controllers, the proposed controller is designed which is called fuzzy sliding mode controller (FSMC). Yi and Chung researches [7] employed fuzzy control to substitute the boundary layer term of a sliding mode to improve the chattering behaviour of SMC. The combination between SMC and FC theories achieves a new controller having good performance compared to that obtained by using either of them.

The aim of this paper is to present the design of an intelligent fuzzy controller incorporated in variable structure system with sliding mode. The merging between FLC and SMC is used to process the merits of both control theories and eliminates the amount of involved problems associated with them. The proposed FSMC controller is applied for controlling and regulating the speed of the switched reluctance motor theoretically and experimentally.

2 SWITCHED RELUCTANCE MOTOR

2.1 Basic of operation

The switched reluctance motor has salient poles on both stator and rotor as shown in fig. (1). The stator and rotor are usually both made of laminated silicon steel in order to eliminate eddy currents. Only the stator poles carry windings, and there are no windings or any permanent magnetic materials on the rotor. The windings on the stator are of particularly simple form, since each opposite stator pole windings are connected in series to form one phase [3, 8].

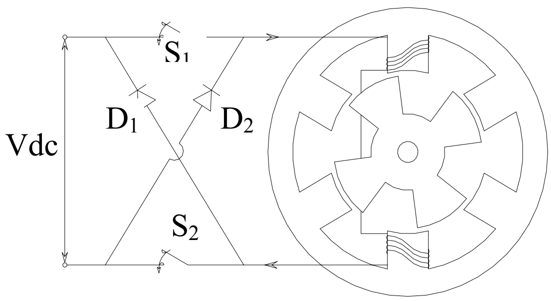

Fig.1 - 6/4 switched reluctance motor

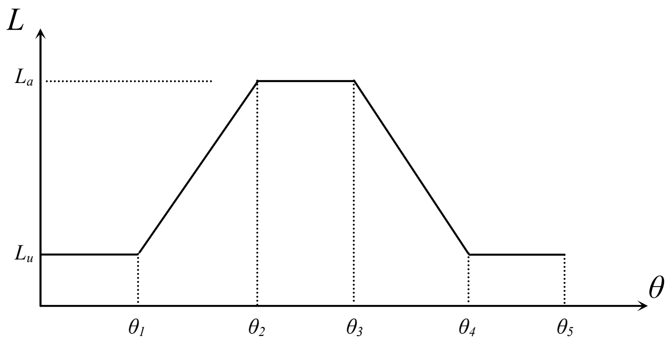

Fig.2 - Inductance profile via rotor position.

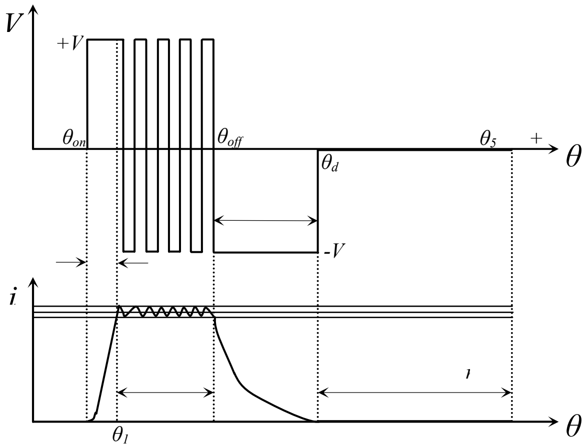

Fig.3 - Voltage, and current via rotor position.

A simplified diagram of the SRM is discussed in fig. (1), where the phase windings and the switching circuit of only one of the three stator phases. When both switches S_1 and S_2 are closed, the current passes through them from the DC supply to the phase windings causing the rotor movement. When they are open, the stored co-energy in the phase windings is returned back to the supply through the two freewheeling diodes D_2 and D_1 [9].

However, under the assumption of linear magnetism, the inductance against rotor position profile can be approximated in trapezoidal manner over one rotor pole pitch as shown in fig. (2). Where θ is the rotor position, θ_1 to θ_5. L_u and L_a are unaligned and aligned inductance respectively.

The chopping current strategy is used in the introduced work. Since this strategy is so called a hysteresis current regulator in which the power transistor are switched off and on according to whether the phase motor current is greater or less than a reference current. The error is used directly to control the states of the power transistor as shown in fig. (3) [10].

2.2 Electrical system

The SRM drive system analysis is much more complex than AC and DC motor drives because its operational region is mostly nonlinear. The nonlinearity sources are high nonlinear (B-H) characteristics of the ferromagnetic materials, nonlinearity due to switching sequences across using one dc-source to excite all motor phases, high nonlinearity characteristics due to the double saliency structure of the motor which make the phase flux linkage depends on both rotor position and current magnitude, and finally nonlinearity due to variations of the electric parameters. All nonlinearity sources affect on the torque production of the SRM, and consequently reflect on the overall performance of the motor [3].

The simulation of SRM requires solving sets of differential equations of all phases. The state of SRM phase is expressed as follows:

$$V(\theta) = \frac{d\Phi(\theta, i)}{dt} + R\, i \tag{1}$$

Where $\Phi(\theta, i)$ is the flux linkage, $V(\theta)$ is the supply voltage, R is the phase resistance, and i is the phase current.

The SRM nonlinear modelling consists of two branches. The first one is the ***modelling each phase*** operation which estimates the position angle from a fixed reference speed. The ***dynamic modelling operation*** is the second branch which calculates the position angle from the actual motor speed. The motor ***static characteristics*** data which include the flux linkage, co-energy and static torque curves. The static characteristics are used to build the simulation which carried out in last two branches discussed above [11].

2.2.1 Flux linkage current curves

Flux linkage current curves represent the relationship between the phase flux linkage and phase current at different rotor positions. It is easy to measure the flux linkage curves at aligned and unaligned rotor position experimentally. Then all intermediate curves are obtained analytically by interpolation method as shown in fig (4). Then a look up table matrix i(θ, Φ).is constructed such that the flux linkage values represent the row index, rotor position angles represent the column index, and the interior cells represent the current values

2.2.2 Static Torque Curves

A numerical integration is applied to the flux linkage current curves to compute the co-energy values. The static torque curves are obtained by differentiating numerically these co-energy values relative to rotor position angles as shown in fig. (5). By the same manner, it is easy to build a look up table matrix T(θ, i) [11].

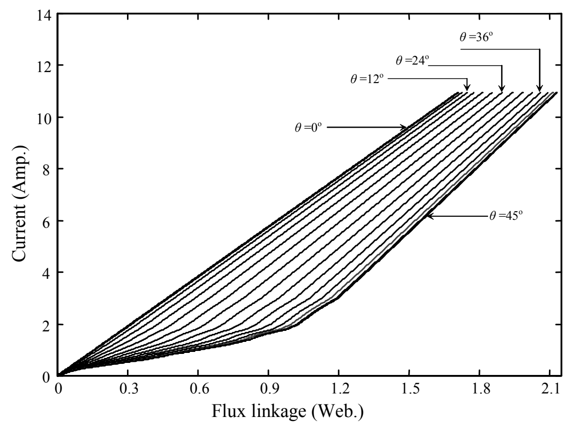

Fig.4 - Flux linkage-current curves of 6/4 SRM.

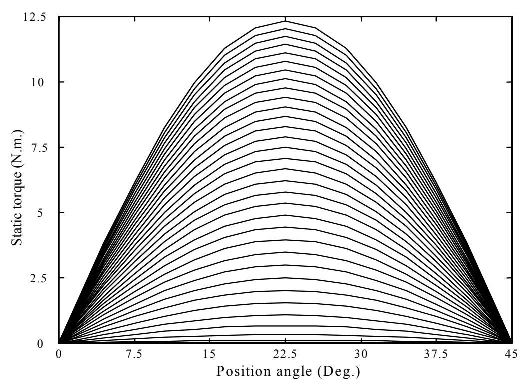

Fig.5 –Set of static torque curves characteristics.

2.3. SRM dynamic modeling

The mechanical dynamic equations must be considered in the dynamic system representation model of the SRM due to the motor torque and speed are influenced by the sudden changes of the operating points. The mechanical differential eqns. (2, 3) are[5]:

$$\frac{d\omega}{dt} = \frac{1}{J}[\sum_{j=1}^{3} \tau_j(\theta_j, i_j) - \tau_l - f\omega] \quad (2)$$

$$\frac{d\theta}{dt} = \omega \quad (3)$$

Where ω is angular rotor speed, τ_l is load torque, f is viscose fraction coefficient and J is the inertia constant respectively.

The two sets of the electrical differential eqns (1), and the mechanical differential eqns. (2, 3) are forming the complete dynamic model of the SRM. Fig. (6) shows the simulated block diagram for the dynamic operation model of three phase 6/4 SRM.

The states dynamic of SRM drives can be modelled as:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 0 & -a \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} u + \begin{bmatrix} 0 \\ -b \end{bmatrix} T_l \quad (4)$$

Where $a = f / J$, $b = 1 / J$, $x_1 = \omega_d - \omega$ is speed error, ω_d is desired reference speed and $x_2 = d\omega / dt$.

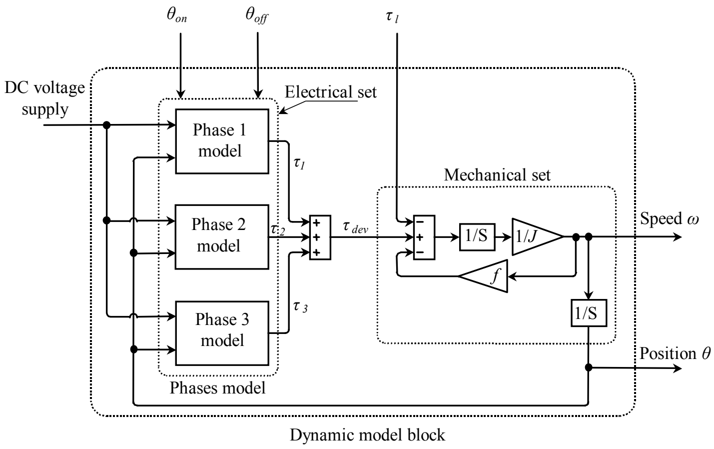

Fig.6 - Dynamic model block diagram of SRM.

3 CONTROL AND STABILITY ANALYSIS

3.1. Sliding mode control

By tracking the motor actual speed to the desired reference speed which the difference between them is called speed error is:

$$x_1 = e = \omega_d - \omega \quad (5)$$

First, selecting the switching function (S) - the switching function is selected based on the system states as [4]:

$$s(x,t) = (\lambda e + \dot{e}) \quad (6)$$

The design parameter (λ), which is the slope of the sliding line, is selected such that ($\lambda > 0$) to ensure the asymptotic stability of the sliding mode [4, 5]. Computing the derivative of $S(x, t)$ with respect to time, we have

$$\dot{s} = \lambda \dot{x}_1 + \dot{x}_2 \quad (7)$$

Equating eqn. (7) to zero, the equivalent control law is:

$$u_{eq} = \frac{1}{b}[(\lambda + a)x_2 + c\tau_l] \tag{8}$$

Lyapunov's second method could be used to obtain the control law that would maintain this goal and a candidate function is defined as [4]:

$$V(S) = \frac{1}{2}S^2 \tag{9}$$

It is aimed that the derivative of the Lyapunov function is negative definite. An efficient condition for the stability of the system described in equation (4) can be satisfied if one can assure that [4]:

$$\frac{1}{2}\frac{d}{dt}(s^2(x,t)) \le -\eta|s|, \quad \eta \ge 0 \tag{10}$$

Inequality (10) is called the reaching condition for the sliding surface, where the system is stable and controlled in such a way that the system states always move towards the sliding surface and hits it. Thus:

$$s.\dot{s} \le -\eta.|s| \tag{11}$$

Therefore, the basic switching law of the VSC is:

$$u = u_{eq} - k\,\mathrm{sgn}(s) \tag{12}$$

Replace function *sgn*(*S*) by *sat*(*S*) in eqn. (12) to avoid the severe changes of the manipulated variable. Then:

$$u = u_{eq} - ksat(s) \tag{13}$$

3.2. Fuzzy sliding controller

VSC and FLC combination give the system their advantages and avoid their disadvantages. The proposed controller is called fuzzy sliding mode controller which is applied for controlling the speed of SRM. The control effort ***u*** is expressed as an equivalent control $\boldsymbol{u_{eq}}$ and switching control ***ksat*(*S*)**. So the proposed controller eqn (13) is divided into calculating $\boldsymbol{u_{eq}}$ from eqn. (8) and generating ***Ksat*(*S*)** with fuzzy logic to adjust for the trade off between robustness and chatter elimination.

The design of the fuzzy logic controller will follow the steps mentioned in [11]. The process input state variables are chosen as: the error signal ***e*** (error between the actual speed and the desired speed) and the change in the error signal ***Δe***. The fuzzy output variable is chosen as: the switching control signal ***Ksat*(*S*)**. The selected membership functions of the input variables and output variable are chosen seven symmetrical triangular shape with 50% overlapping and arranged regularly.

The control rules must be designed such that the actual trajectory of the states always turns toward and does not cross the sliding surface to satisfy existence condition. An example of these control rules can be expressed as:

IF the error is NB **AND** the change of error is PB **THEN** the output is Z

The min-max composition is chosen as a fuzzy inference method. Also, centre of gravity (COG) algorithm is used to perform the defuzzification process.

4 STABILITY INVESTIGATION

Concerning the stability criterion given by eqns. (5-10) and the corresponding restrictions of the switching surfaces design, we can deduce that the SRM under the effect of the proposed FSMC will be globally stable. Also the generated Lyapunov function V(S)=1/2 S*S with its time derivative will be at nearest unstable singular point of the post-fault system. From other point of view, when the system under study is affected by a sudden change in the motor speed, in this case there is a serious need for a method which can estimate the boundary of the stability domain of attraction more accurately. In this paper the Lyapunov function given in eqn. (9) and its stability regions may be generated by solving the set of nonlinear partial differential equations represents both electrical and mechanical state variables of the system illustrated in section 2.2 and 2.3 respectively. At the same time there is significant methods which may be used to derive the boundary of the regions of the overall system under study based on Bellman's concept of vector Lyapunov function. Lyapunov or energy function is generally the sum of the kinetic and potential energies of the overall post-fault system.

$$V(X)= Vke+Vpe \tag{14}$$

The critical value of the Lyapunov function given in eq. (14), Vcr, is evaluated as the lowest energy value of the SRM represented by eqn. (4) at its unstable equilibrium point, u.e.p,

$$Vcr = V(X1uep , X2uep) \tag{15}$$

Vcr is denoted as the value of Lyapunov function (9) at the boundary of the region of attraction for the SRM. From the stability point of view it should be noted that the proposed hybrid fuzzy-sliding mode controller applied to regulate the fluctuation in the speed the switched reluctance motor presents some significant advantages as: its ability to improve remarkably the stability region estimation as well as decreasing the effect of any expected external variable on the motor speed. The suggested algorithm opens a new horizon to estimate more accurate switching surfaces and offers a bright future for the dynamic operation of the SRM which will be more suitable for on line industrial application.

5 SYSTEM VERIFICATION

In order to verify the control strategy as discussed above, the simulation study of the total system as shown in fig. (7) was implemented using matlab/simulink soft ware packages. The three phase 6/4 SRM drive parameters are stated in reference [11].

The simulation is carried out by fixing the reference speed at 1000 rpm and the motor load. The speed responses are shown in fig. (8) when using FSMC and PI controller. It is clear that the speed traces the reference when using FSMC withoutbany overshoot and settles faster compared with PI controller. Figures (9) and (10) present the motor developed torque and the controllers outputs respectively.

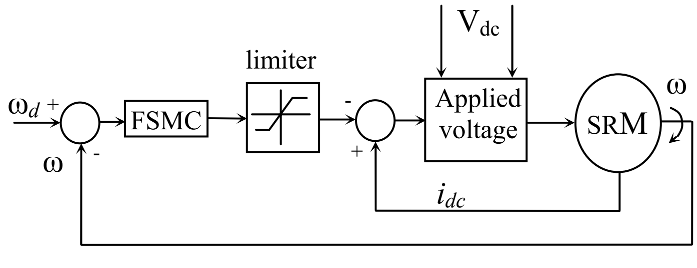

Fig.7 - Closed loop of SRM using proposed FSMC

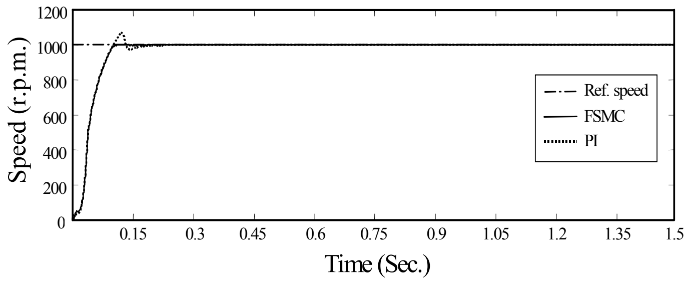

Fig.8 - Speed responses with reference speed 1000 rpm.

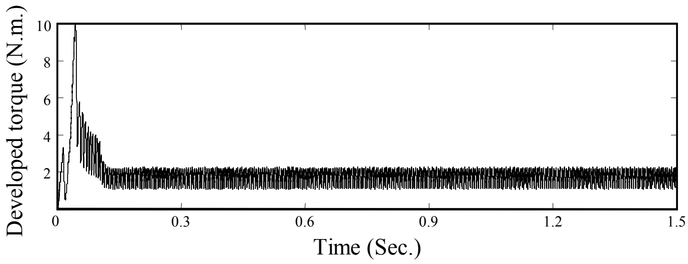

Fig.9 - Developed instantaneous motor torque.

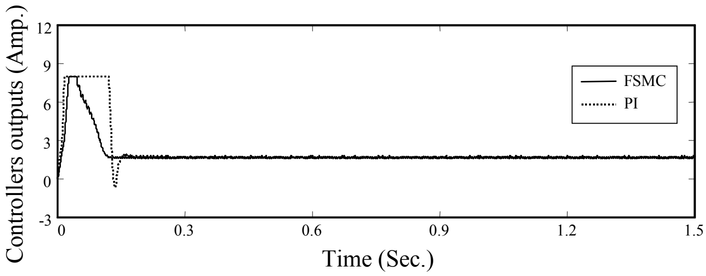

Fig.10 - Controllers outputs.

The phase 1 excitation voltage and the instantaneous profiles of dc-link currents for the three phases via rotor position angle are shown in figures (11) and (12) respectively, when using FSMC. Fig. (12) Shows that the motor dc-link phases currents are almost flatten toped, which reduce the torque ripples and consequent the speed of the motor. Also, the instantaneous three phases torques via rotor position angle developed by the motor phases are shown in fig. (13).

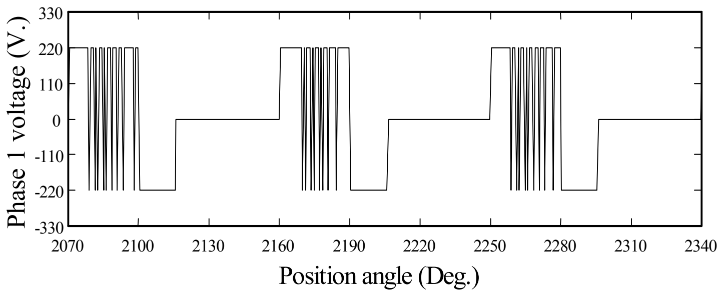

Fig.11 - The voltage excitation of phase 1.

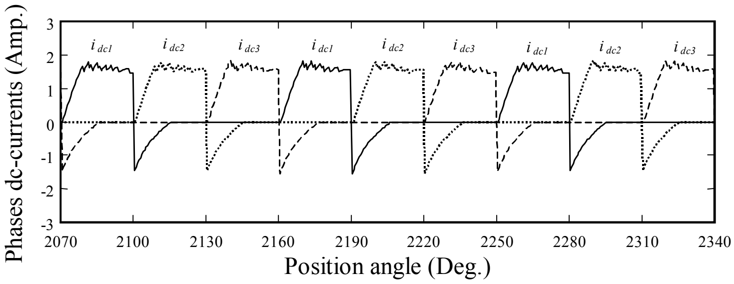

Fig.12 - Instantaneous dc-link 3- phases currents.

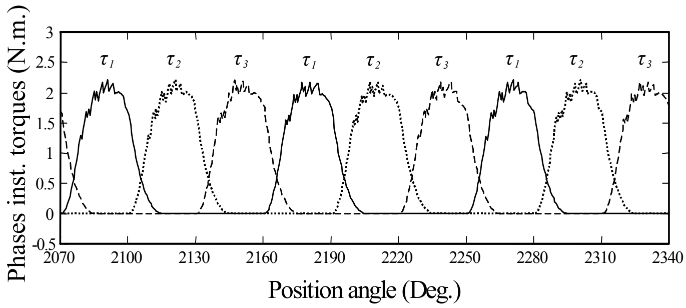

Fig.13 - The three phases instantaneous torques.

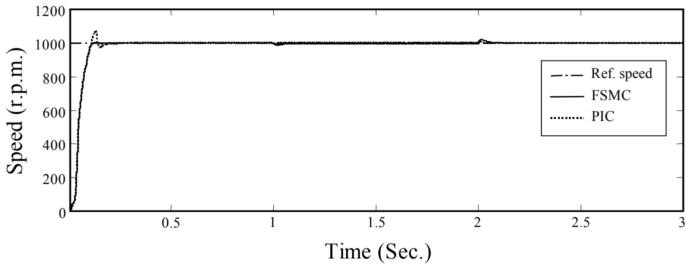

Fig.14 - Speed responses with reference speed 600 rpm when changing the load disturbance .

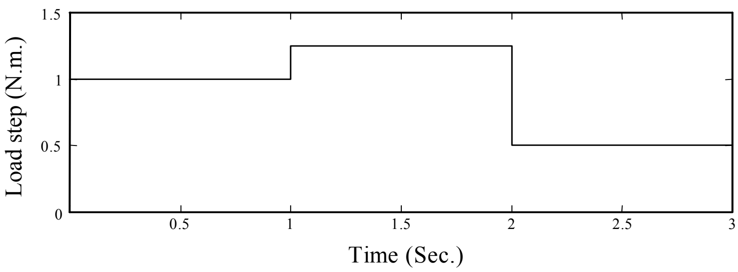

Fig.15 - Changing step load disturbance.

6 PRACTICAL REALIZATION

The control system of SRM consists of two loops. The inner current limiting control loop, and the outer speed control loop. The proposed FSMC is used for outer speed control loop. By comparing the estimated actual rotor speed with the command reference speed 900 rpm. The full switching signal patterns are generated by measuring the position rotor angle as shown in ig. (16).

The dc-link current of the motor is compared with the current command produced from FSMC to give the current error. This current error is passed through a PWM circuit which is compared with a triangular carrier having a frequency 3.3 KHz to give the required PWM trains of pulses as shown in Fig. (17).

The full switching signal patterns and PWM train of pulses are passed through AND gate circuit to produce the chopped phases gate pulses. The chopped voltage, which is applied to on phase of the motor, produced from the inverter is described in Fig. (18). The corresponding chopped phase current is shown in fig. (19). Finally, the measured speed response of the motor is shown in fig. (20) when using the proposed FSMC.

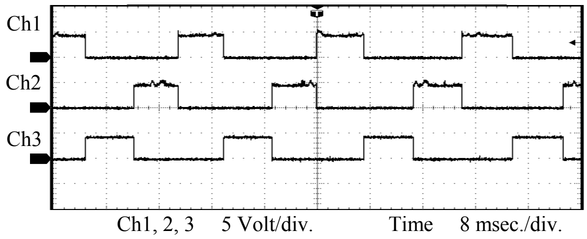

Fig.16 - The full switching signals pattern.

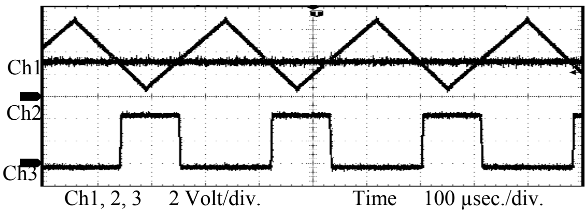

Fig.17 - Practical output of the PWM circuit.

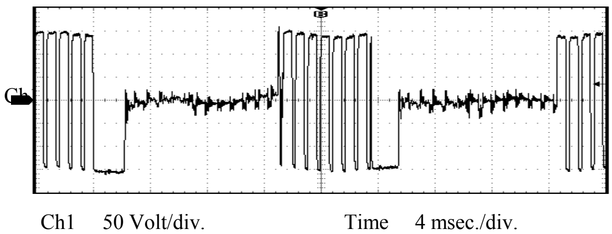

Fig.18 - Practical chopped phase voltage.

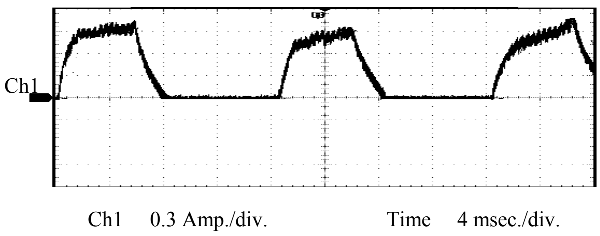

Fig.19 - Chopped phase current waveform.

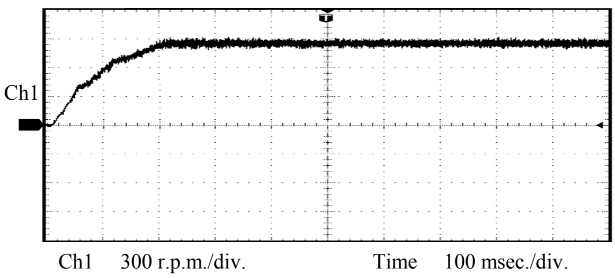

Fig.20 - Measured speed response of the motor.

7 CONCLUSION

This paper presents a design approach for fuzzy sliding mode controller used to switched reluctance motor speed regulation theoretically and experimentally. The combination between fuzzy logic control theory and variable structure control technique based on sliding mode is achieved to include their merits and eliminate their disadvantages. The proposed approach is used to implement fuzzy sliding mode controller by using Lyapunov function. The results have been simulated through the Matlab–Simulink toolbox show that using the proposed controller in the speed loop gives best and robust responses

The dynamic responses of the proposed FSMC when applied to 6/4 SRM speed regulator give a good performances. The overshoot in transient state is ignored, also torque chattering is decreased. So the proposed controller gives a good smoothing speed tracking with minimizing its ripples to guarantee a robust command control action when all Lyapunov stability requirements are taken into consideration.

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