Design of Speed Controlled SRM Drive for Electric Vehicle using Flexible Takagi-Sugeno-Kang Fuzzy Controller

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Abstract- *Switched Reluctance motors are now becoming popular in electric vehicle applications because of its simple construction and advantages. This paper presents a control method for Switched Reluctance motor drive fed by half bridge asymmetrical converter. A SRM drive requires an highly efficient fuzzy or neural based control technique as they are non linear and time varying systems. A novel flexible Takagi-Sugeno-kang (FTSK) fuzzy controller is used to control the speed of the proposed SRM drive system. The performance of the proposed system is verified based on the experimental and simulation results.*

Keywords- half bridge asymmetrical converter, Switched Reluctance Motor (SRM), Takagi-Sugeno-Kang (TSK) fuzzy controller, speed control

I. INTRODUCTION

The Switched Reluctance motors are mainly used in electric traction systems and home applications. Due to the environmental concerns and impact of CO2 emission, the electric vehicles and hybrid electric vehicles are gaining its importance in recent days [1]-[5]. In electric vehicle drives, the Switched Reluctance motor drives are gaining its importance over the other motor drive systems due its advantages such as simple construction, fault tolerant operation, high efficiency and wide operating speed. The simple construction of the Switched Reluctance motor is because of the absence of coils, brushes and permanent magnets. The wide speed range of SRM depends upon the geometry, topology of power converter, and also depends on the control methodology of the motor [6]. Figure1. shows the simple construction of the Switched Reluctance Motor.

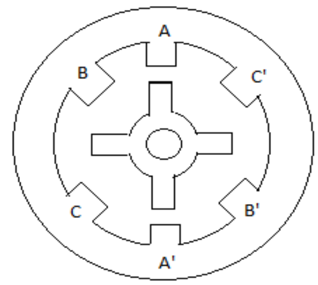

Figure 1. Switched Reluctance Motor

The Switched Reluctance Motor drive comprises of three components namely a converter, Switched Reluctance Motor and a controller as shown in Figure 2. There are various converter topologies available for SRM drive. Asymmetrical converter topology is most widely used for Switched Reluctance motor in electric vehicle as it is optimum for high voltage. Asymmetrical converter topology consists of two power switches and two diodes per phase. To control the non linear SRM drive, non linear control techniques such as artificial neural network, fuzzy logic, sliding mode control, finite element analysis, and gain tuning PI controllers are most widely used [7]. A.Rajendran and S. Padma in [8] employed H-infinity control technique and concluded that H-infinity controller has higher performance efficiency when compared to traditional PI controller and fuzzy based controller by reducing the robustness. In [9], Luis Oscar de Araujo Porto Henriques, Luıs Guilherme Barbosa Rolim, Walter Issamu Suemitsu, J. A. Dente, and P. J. Costa Branco, employed a neuro fuzzy based technique to estimate the rotor position by integrating the rotor speed. In [10] an artificial neural network is proposed. The neural network based control technique requires an extra computing processor to ensure its control performance. The complexity of system deals with its control performance. In [11] fuzzy based model is described. In this paper, Mamdani type fuzzy controller is proposed which provided an efficient result. However it has certain drawbacks such that it requires large number of fuzzy sets and rules. These fuzzy sets and rules should be tuned by the designer for better performance which reduces the applicability of fuzzy schemes. Takagi–Sugeno–Kang control is another fuzzy based control scheme which is used for non-linear relations using a reduced number of fuzzy sets and rules [12]-[16]. In Takagi–Sugeno–Kang fuzzy controller, the fuzzy sets are furnished with functional- type importance which are tuned by designing proper adaptation rule without the designers sense to obtain an efficient performance. The system stability of the system can be improved because of the designed adaptation rules. Owing to these advantages of the TSK fuzzy controller, they are suited for non linear application and provide a high performance in terms of speed control.

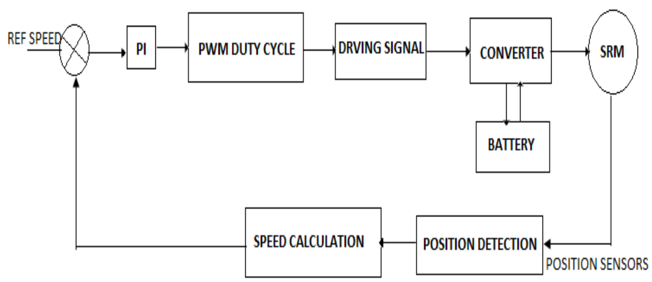

Figure 2. Block Diagram of Switched Reluctance motor Drive

In this paper, a flexible Takagi–Sugeno–Kang fuzzy controller is proposed. This proposed controller has two controllers they are, TSK fuzzy based controller and a compensated controller. This controller not only to regulate the speed of SRM drive it also insures the stability of the system.

II. SWITCHED RELUCTANCE MOTOR

SRM is special type of motor that it runs with the help of the reluctance torque. The structure of the SRM is simple and it encloses laminated stator and rotor. The stator of the SRM comprises of copper phase windings. The rotor tries gets the minimum reluctance path by aligning itself with stator windings. The rotor always tries to rotate along the minimum reluctance path along the rotating magnetic field. The rotor of the SRM can be controlled by exciting the stator phase windings in a specific sequence. By making use of the variation of the phase induction with rotor position, the torque is produced. When the inductance increases along the direction of the rotation in the presence of the phase current produces a positive torque. Whereas, the negative torque is produced due to the decrease in inductance along the direction of the rotation in the presence of phase current.

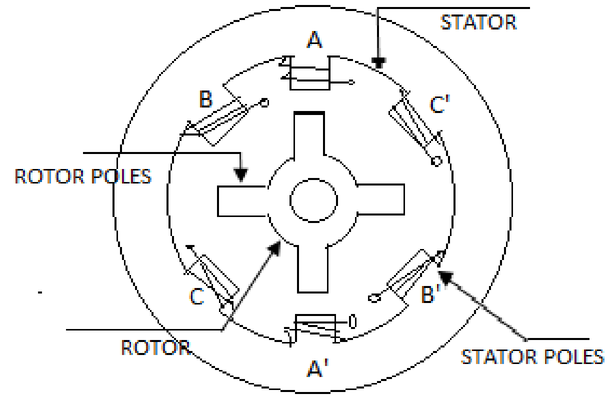

Figure 3. Stator and Rotor of Switched Reluctance Motor

III. ASYMMETRICAL HALF BRIDGE CONVERTER

The asymmetrical converter topology is mostly used in SRM dives for various applications because of its advantages such as simple control and structure. The proposed asymmetrical converter consists of six active power switches and six power diodes. The diodes cannot be integrated with power switches due to the connections in the circuit. The phase voltage and current are controlled independently through asymmetrical converter topology. The asymmetrical converter topology provides three switching states to control the phase currents they are, 1.Magnetising stage; 2.Demagnetising stage; 3.Freewheeling stage. In the magnetising stage, the phase current is energised from the power supply by turning ON both the switches in a leg of a phase. Whereas in demagnetising phase, both the switches in the leg are turned OFF, phase current commutate to the diode and decays rapidly. In the freewheeling stage, only one of the switch s turned ON or OFF the phase current decays slowly when the voltage across the winding is near zero.

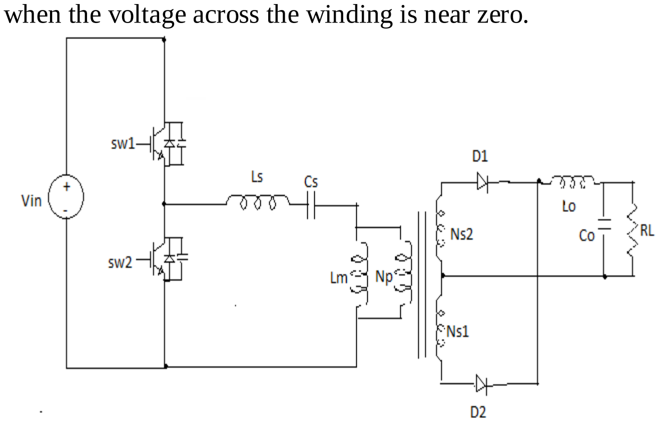

Figure 4. Circuit Diagram of Asymmetric Half Bridge Converter

IV. DESIGN AND ANALYSIS OF FUZZY CONTROLLER

A. STABILITY ANALYSIS OF TAKAGI–SUGENO–KANG FUZZY CONTROLLER

The Takagi–Sugeno–Kang fuzzy controller mainly used to reduce the number of fuzzy sets rules required for the computation. The proposed control technique is used for complex and high dimensional problems. This controller develops a systematic approach to generate the fuzzy rules from the given input and output data sets. There are four main components which a Takagi–Sugeno–Kang fuzzy controller comprises are fuzzification, knowledge base, inference mechanism and defuzzification. The linguistic variable signals, membership functions of each linguistic variable, collection of Takagi–Sugeno–Kang fuzzy IF-THEN rules are stored in knowledge base.

The nth fuzzy rules can be described as given below

$$Q(n): IF\ a1 = Fn1\ and\ a2 = Fn2, THEN\ Xn = bn0 + bn1a1 + bn2a2 = \Phi nT[1\ AT]T \tag{1}$$

Where Fin are fuzzy sets, i=1, 2, AT= [a1 a2] are input vectors, ϕnT = [bn0 bn1 bn2] vectors of adjustable parameters, and the scalar output is X n

The central average defuzzifier and product interpretation is used and the output of the Takagi–Sugeno–Kang fuzzy controller X_{TSKFC} is given as

$$X_{TSKFC} = \frac{\alpha_1 x^1 + \alpha_2 x^2 + \cdots + \alpha_{K_j} x^{K_j}}{\alpha_1 + \alpha_2 + \cdots + \alpha_{K_j}} = \frac{\sum_{n=1}^{K_j} \alpha_n x^n}{\sum_{n=1}^{K_j} \alpha_n} = \frac{\sum_{n=1}^{K_j} \alpha_n \phi_n{}^T [1\ A^T]^T}{\sum_{i=1}^{K_j} \alpha_n} \tag{2}$$

Where the total number of fuzzy rules is denoted by K_j, $\alpha_n = \pi_i^2 = 1 \upsilon_{F_i^n(a_i)}$, the membership value of the fuzzy sets F_i^n is denoted by $\upsilon_{F_i^n}$.

The above equation (2) can be rewritten as

$$X_{TSKFC} = \phi^T \rho \tag{3}$$

Where, aggregated vectors of the adjustable parameter vector is $\phi^T = \phi_1^T + \phi_2^T \ldots + \phi_{K_j}^T$ and fuzzy basic functions is $\rho^T = [\rho_1^T\ \rho_2^T \ldots \rho_{K_j}^T]$ and is defined as

$$\rho_n = \frac{\alpha_n [1\ A^T]^T}{\sum_{n=1}^{K_j} \alpha_n} \tag{4}$$

The speed error E and the change of speed error ΔE are given as the input variables to Takagi-Sugeno-Kang fuzzy controller. A control law U_{TSKFC} is returned as the output of the Takagi-Sugeno-Kang fuzzy controller. The adaptive rules which are derived from Lyapunov stability theory is used to tunet the adjustable parameters ϕ^T. Each and every parameter of the Takagi-Sugeno-Kang fuzzy controller parameters are initialized to zero before tuning.

B. DESIGN OF FLEXIBLE TAKAGI-SUGENO-KANG FUZZY CONTROLLER

The flexible Takagi-Sugeno-Kang fuzzy controller has two components, one is Takagi-Sugeno-Kang fuzzy controller and the other is the Compensated controller.

The mechanical equation of the SRM drives can be obtained by using FTSKFC is

$$\dot{\varphi_r} = -\frac{B_m}{J_m}\varphi_r + \frac{C_t}{J_m} j_g^+ - \frac{1}{J_m} T_L = P_g \varphi_r + Q_g \varphi U_t + R_g T_L \tag{5}$$

Where current command is given by j_g, $P_g = -B_m/J_m$, $Q_g = C_t/J_m$ and $R_g = -1/J_m$.

Then () can be written as,

$$\varphi = \bar{P}\dot{\varphi_r} + \bar{Q} U_t + S \tag{6}$$

The nominal parameters of P, Q, R are given as $\bar{P}$, $\bar{Q}$, $\bar{R}$ and their corresponding parameter variation are given as ΔP, ΔQ and ΔR. The systems uncertainty is given by S.

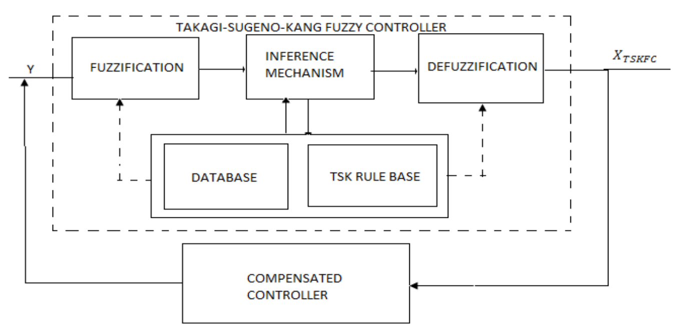

Figure 5. Block Diagram of FTSKFC

The speed error is given as the difference between the rotor speed (φ^+) and the predefined speed of the rotor (φ_r).

$$E = \varphi^+ - \varphi_r \tag{7}$$

The ideal control law can be defined as below, when the system anxiety and the nominal parameters of the SRM are known.

$$U^{+} = \frac{-F_g \varphi_r - S + c_1 E}{B_g} \qquad (8)$$

Where c_1 is the constant

The error dynamics is given by

$$\dot{E} + c_1 E = 0 \qquad (9)$$

The above equation implies that the pre defined trajectories are asymptotically tracked by the rotor speed. The realized control law cannot be directly implemented in practice. An FTSKFC is proposed to approximate the ideal control law and it can be expressed as follows

$$U_t = U_{TSKFC} + U_C \qquad (10)$$

From (8),(9) and (10), the error equation obtained is

$$\dot{E} = -c_1 E + Q_g (U^{+} - U_{TSKFC} - U_C) \qquad (11)$$

The error μ can be defined with minimum approximation error as follows

$$\mu = U^{+} - \phi^{+^T} \rho \qquad (12)$$

The error equation (11) can be represented as

$$\dot{E} = -c_1 E + \bar{Q}_g [\mu - \tilde{\phi}^T \rho - U_C] \qquad (13)$$

Where $\tilde{\phi} = \phi - \phi^{+}$

The Lyapunov functions is given by

$$v(t) = \frac{1}{2} E^2 + \frac{1}{2\beta} \tilde{\phi}^T \phi \qquad (14)$$

Where β>0 is denoted as adaptation gain.

By differentiating the Lyapunov function with respect to time, it yields

$$\dot{v}(t) = -c_1 E^2 + E \bar{Q}_g [\mu - \tilde{\phi}^T \rho - U_C] + \frac{1}{\beta} \tilde{\phi}^T \dot{\phi} \qquad (15)$$

On further simplification,

$$\dot{v}(t) \le -c_1 E^2 \le 0 \qquad (16)$$

Let the function Ξ (t) =$c_1 E^2 \le$ -v(t). Integrating with respect to time

$$\int_0^t \Xi(\gamma)\, d\gamma \le v(0) - v(t) \qquad (17)$$

$$\lim_{t \to \infty} \int_0^t \Xi(\gamma)\, d\gamma < \infty \qquad (18)$$

From the above equation, the stability of the proposed FTSKFC is guaranteed.

V. SIMULATION AND RESULT

In this paper asymmetrical converter fed SRM drive is proposed. Asymmetrical converter is most commonly used converter topology due to its various advantages. By giving the proper gating signals to the proposed converter the rotation of the motor can be controlled. The TMS320F240 DSP controller is used to produce the gating signal for switching the converter switches. The gating signals for the proposed converter are shown in the Fig.6.

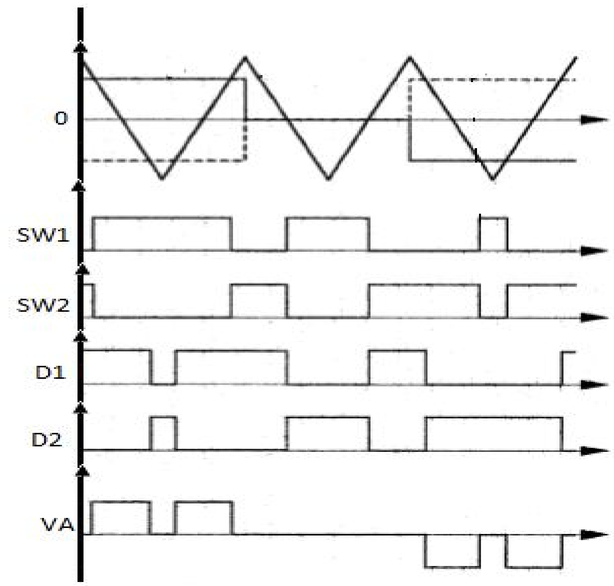

Figure 6. Gate Signals for Symmetric Half Bridge Converter

The experimental study was carried out to confirm the feasibility, efficiency and the tracking capability of the SRM drive. In the proposed SRM drive there are two controllers namely the current controller and the speed controller. The proposed flexible Takagi-Sugeno-Kang fuzzy based controller is used as an speed controller where as PI controller is used as an inner current controller. To obtain the acceptable current response the control parameters of the PI current controller were obtained by trail and error methods. In the proposed FTSKFC system there are only 4 rules and 12 adjustable parameters is proposed as each input variable was assigned with only 2 fuzzy sets. The speed error and the change of the speed error is given as the input for the fuzzy controller. Some simulations were done to track the capabilities of the FTSKFC and to check the efficiency of the parameter variations of the system. To confirm and regulate the speed tracking capabilities at various speed commands such as 200 rpm, 1500 rpm and sinusoidal speed capability, the proposed FTSKFC control technique is adopted. The PI parameters are tuned to obtain the satisfactory performance results. Fig.. shows the simulation results under various speed commands. The speed command in the simulation were 200rpm, 2500 rpm and 1500 sin(t) rpm. From this it is clear that the proposed technology not only performs well on constant speed but also tracks the sinusoidal speed command.

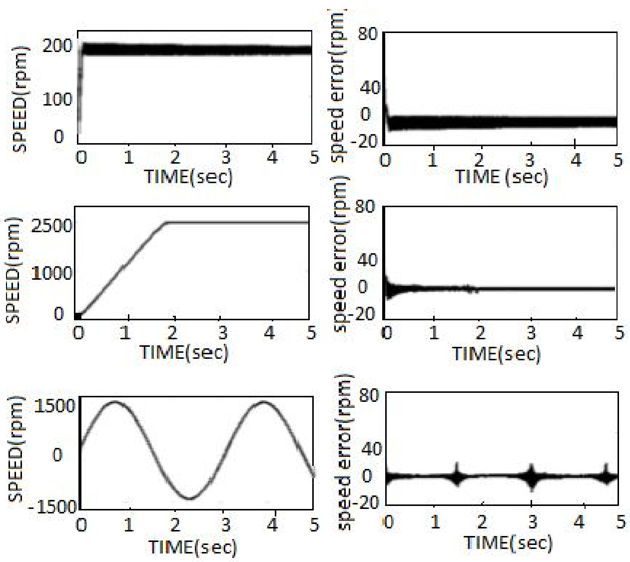

Figure 7. Speed and sped error of various speed conditions (a) at 200 rpm (b) at 2500 rpm (c) at varying sinusoidal signal with 1500 sin(t) as its rpm.

VI. CONCLUSION

This paper develops a Flexible Takagi-Sugeno-Kang Fuzzy based controller technology for asymmetrical converter fed SRM drive. The Lyapunov stability theory is proposed to enhance the stability of the drive system. When compared to all the other techniques, the propose flexible Takagi-Sugeno-Kang fuzzy based controller better performance efficiency and tracking capability thus enhances the reliability of the system. Based on the experimental results, the overall efficiency of the system is enhanced by the adopted controller not only under constant speed condition but also at sinusoidal speed command conditions. The FTSKFC system tracks the various speed references with reliable performance efficiency. The proposed system performs well on both transient and steady state operating conditions. Apart from this proposed fuzzy based control methodology, the asymmetrical converter converter should be properly triggered which also enhances the overall performance of the system. The DSP controller TMS320F240 is used to control asymmetrical controller switching circuit. Thus the asymmetrical converter fed switched reluctance motor's performance efficiency under various speed commands is increased by proposed Flexible Takagi-Sugeno-Kang fuzzy based controller.

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