PERFORMANCE ANALYSIS OF SPEED CONTROL STRATEGY FOR SWITCHED RELUCTANCE MOTOR

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ABSTRACT

Switched Reluctance Motor (SRM) has several desirable features, including simple construction, high reliability and low cost. However, it suffers from large torque ripple and large noise. In addition, highly non-uniform torque output and magnetization characteristics lead to complication of the control system. Several studies have succeeded in torque ripple reduction for SRM using Direct Torque Control (DTC) technique. A novel adaptive Takagi–Sugeno–Kang (TSK) fuzzy controller (ATSKFC) to regulate the speed of a switched reluctance motor (SRM). The proposed controller comprises two parts: a TSK-fuzzy controller and a compensated controller. The TSK-fuzzy controller is the main controller, which is used to approximate an ideal control law. This paper presents a novel approach for starting torque maximization of a five-phase 10/8 SRM with short flux path. Unlike the conventional method, this approach emphasizes maximizing the average torque of any one phase during one electrical cycle at a given speed regardless of possible instantaneous negative torque during part of the conduction interval. An on-line tuning methodology based on Lyapunov is utilized to adjust the parameters of the ATSKFC, so that the stability of the control system can be guaranteed. Three control schemes, ATSKFC, fuzzy control, and PI speed control, are verified through simulation.DTC method has many advantages such as simple algorithm, less torque ripple and instantaneous response to the torque command. In this paper, DTC of a 5 phase 10/8 SR motor is proposed. Performance of the motor is studied through the computer simulation in MATLAB/SIMULINK. The simulation results are compared to corresponding results of the same motor.

Keyword: - *Switched Reluctance Motor (SRM), Direct Torque Control (DTC) technique, Takagi–Sugeno– Kang (TSK) fuzzy and 5 phase 10/8 SR motor.*

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1. INTRODUCTION

Electric machines can be broadly classified into two categories on the basis of how they produce torque - electromagnetically or by variable reluctance. In the first category, motion is produced by the interaction of two magnetic fields, one generated by the stator and the other by the rotor. Two magnetic fields, mutually coupled, produce an electromagnetic torque tending to bring the fields into alignment [1]. The same phenomenon causes opposite poles of bar magnets to attract and like poles to repel. The vast majority of motors in commercial use today operate on this principle. These motors, which include DC and induction motors, are differentiated based on their geometries and how the magnetic fields are generated. Some of the familiar ways of generating these fields are through energized windings, with permanent magnets, and through induced electrical currents. In the second category, motion is produced as a result of the variable reluctance in the air gap between the rotor and the stator [2]. When a stator winding is energized, producing a single magnetic field, reluctance torque is produced by the tendency of the rotor to move to its minimum reluctance position. This phenomenon is analogous to the force that attracts iron or steel to permanent magnets. In those cases, reluctance is minimized when the magnet and metal come into physical contact [3]. As far as motors that operates on this principle, the switched reluctance motor (SRM) falls into this class of machines [4].

A Switched Reluctance Motor (SRM) has numerous advantages over other types of AC machines due to its simple and solid construction [5]. The rotor has a simple laminated structure with no permanent magnets or rotor windings. It rotates by using the reluctance torque, produced from magnetic saliency between stator poles and rotor poles. Thus, SRM can operate at high speeds and it is suitable for applications in high-temperature and hazardous environments [6]. In addition, SRM has enough high efficiency as compared with permanent magnet motors because it also needs no secondary windings. On the other hand, its large torque ripple and high noise level caused by its doubly salient structure restrict its wide application in the industry [7]. Additionally, the highly nonlinear magnetic characteristics of the motor make the control of the motor intricate [8]. This is further complicated by the interaction due to mutual coupling of motor phases and parameters variation of the inductance characteristics.

The proposed adaptive TSK-fuzzy controller (ATSKFC) is composed of a TSK-fuzzy controller and a compensated controller. The TSK-fuzzy controller is self-tuned and utilized to approximate an ideal control law, and then the compensated controller compensates the approximation error of the TSK-fuzzy controller [9]. Additionally, the parameters of the ATSKFC are tuned on-line based on the adaptation laws, which are derived from Lyapunov stability theory [10]. Therefore, the proposed ATSKFC not only performs well but also guarantees the stability of the control system and error convergence [11]. To confirm the effectiveness of ATSKFC, three control strategies, ATSKFC, fuzzy control, and PI speed control, are implemented separately and investigated in a practical SRM drive, to study their performances [12].

In general, a simple method such as PI speed control is often used for designing a controller to construct SRM drives [13]. Traditional control schemes, such as proportional integral (PI) control, are powerless when a precise system model is unavailable or the controlled system is too complex for modeling [14]. Although PI control is the most widely utilized solution in industry, its parameters must be tuned to perform satisfactorily when a modification is made to, or a change occurs in, the controlled system. In practice, this tuning process wastes considerable time.

2. PRINCIPLE AND OPERATION OF SRM

The SRM is the simplest of all electrical machines. Only the stator has windings. The rotor contains no conductors or permanent magnets. It consists simply of steel laminations stacked onto a shaft. It is because of this simple mechanical construction that SRMs carry the promise of low cost, which in turn has motivated a large amount of research on SRMs in the last decade. The mechanical simplicity of the device, however, comes with some limitations. Like the brushless DC motor, SRMs cannot run directly from a DC bus or an AC line, but must always be electronically commutated. Also, the saliency of the stator and rotor, necessary for the machine to produce reluctance torque, causes strong non-linear magnetic characteristics, complicating the analysis and control of the SRM. Not surprisingly, industry acceptance of SRMs has been slow.

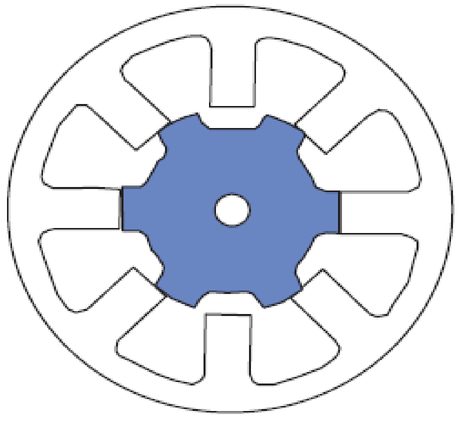

Fig - 1: Shows the 4-phase, 8 rotor poles/6 stator poles

This is due to a combination of perceived difficulties with the SRM, the lack of commercially available electronics with which to operate them, and the entrenchment of traditional AC and DC machines in the marketplace. SRMs do, however, offer some advantages along with potential low cost. For example, they can be very reliable machines since each phase of the SRM is largely independent physically, magnetically, and electrically from the other motor phases as represented in figure 1. Also, because of the lack of conductors or magnets on the rotor, very high speeds can be achieved, relative to comparable motors. Disadvantages often cited for the SRM; that they are difficult to control, that they require a shaft position sensor to operate, they tend to be noisy, and they have more torque ripple than other types of motors; have generally been overcome through a better understanding of SRM mechanical design and the development of algorithms that can compensate for these problems.

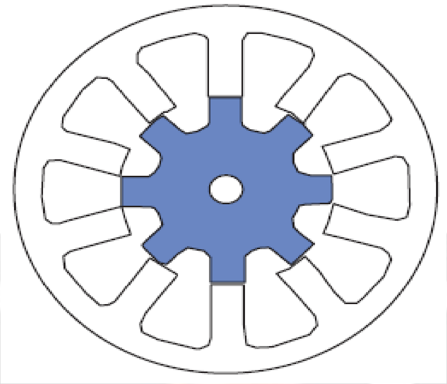

Fig – 2: Shows the 5-phase, 10 rotor poles/8 stator poles

The torque ripple in fuzzy method is 0.1 Nm that is only about 32% of the hysteresis band method with 0.31 Nm torque ripple. This is one of the most noticeable advantages of the fuzzy control method. The stator flux ripple in fuzzy method experiences a significant reduction about 50% in comparison with hysteresis band method. Since the stator flux is an electrical parameter, its ripple reduction means that the high frequency harmonics of the motor input current and hence electromagnetic inference (EMI) are reduced as shown in figure 2.

In general, voltage or current command profile is used in different aspects of SRM such as torque, speed or position control and even for torque ripple reduction. Using DTC, Jinupun [3] succeeded in torque ripple reduction of SR motors. He used a new type of winding configuration and applied the concept of short flux pattern that links two separate poles of the stator. However, the need for special motor winding configuration is both expensive and inconvenient. Cheok et. al. [4] applied DTC method to a 3-phase 6/4 SRM with a very close concept to that of conventional DTC of ac machines. They introduced a comparable theory with conventional DTC of ac machines by using motor flux and torque equations.

In this method no winding configuration changing is required. Motors with low phase number usually produce notably high torque ripple, Chan and Bolton [5]. As the number of poles increases, one can expect reduction on the developed torque ripple. At the same time, it imposes some disadvantages on other performance criteria which should be noticed. If in two SRM with different pole numbers, the iron to air ratio and excitation ampere-turn assumed to be constant, in order to achieve high inductance, flux density and total torque/weight ratio, the motor with the fewer pole number is preferable. In this work, DTC method is applied to a 5-phase 10/8 SRM, where a significant modification should be exerted on mentioned method in [4]. This occurs due to difference of poles and phases number of two 6/4 and 10/8 motors.

3. MOTOR TORQUE – SPEED CHARACTERISTICS

The basic operating principle of the SRM is quite simple; as current is passed through one of the stator windings, torque is generated by the tendency of the rotor to align with the excited stator pole. The direction of torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flow through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase's excitation with the rotor position. By varying the number of phases, the number of stator poles, and the number of rotor poles, many different SRM geometries can be realized. Generally, increasing the number of SRM phases reduces the torque ripple, but at the expense of requiring more electronics with which to operate the SRM. At least two phases are required to guarantee starting, and at least three phases are required to insure the starting direction. The number of rotor poles and stator poles must also differ to insure starting.

The torque-speed operating point of an SRM is essentially programmable and determined almost entirely by the control. This is one of the features that make the SRM an attractive solution. The envelope of operating possibilities, of course, is limited by physical constraints such as the supply voltage and the allowable temperature rise of the motor under increasing load. In general, this envelope is described by figure 3.

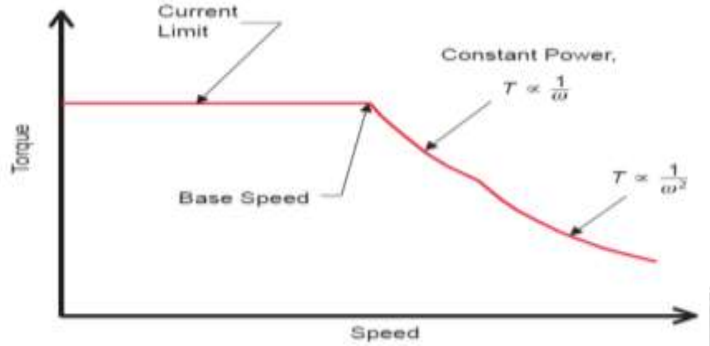

Fig – 3: SRM Torque-Speed Characteristics

Like other motors, torque is limited by maximum allowed current, and speed by the available bus voltage. With increasing shaft speed, a current limit region persists until the rotor reaches a speed where the back-EMF of the motor is such that, given the DC bus voltage limitation we can get no more current in the winding—thus no more torque from the motor. At this point, called the base speed, and beyond, the shaft output power remains constant, and at its maximum. At still higher speeds, the back-EMF increases and the shaft output power begins to drop. This region is characterized by the product of torque and the square of speed remaining constant.

4. DESIGN OF THE ATSKFC

The fundamentals of the TSK-fuzzy system are introduced. Then, the parameter variations and the external load of the SRM drive are considered along with the uncertainties for developing the proposed ATSKFC. Finally, an improved compensating control strategy is adopted to reduce the fluctuation of ut . The details are discussed as follows.

4.1 TSK – FUZZY SYSTEM

Typically, a TSKFC system comprises four main parts: the fuzzification, inference mechanism, knowledge base, and defuzzification, as shown in figure 4. The knowledge base stores all needed information, which includes linguistic variables of input signals, membership function of each linguistic variable, and a collection of TSK-fuzzy IF–THEN rules.

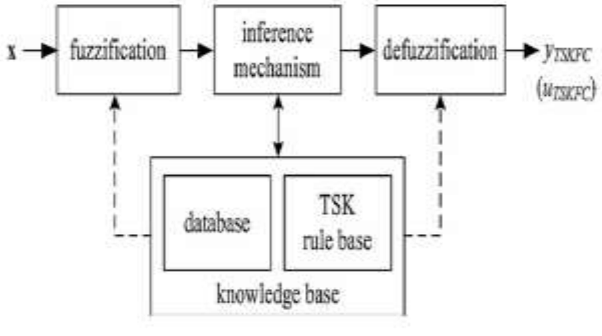

Fig – 4: Basic configuration of the TSK-fuzzy system

The fuzzy basis function vector defined as

$$\varphi_i = \frac{v_i[1 \quad \mathbf{x}^T]^T}{\sum_{i=1}^{N_r} v_i} \qquad (1)$$

In this study, the input variables of the TSKFC are speed error *e* and the change of speed error Δ*e*. The output of the TSKFC is designed to yield a control law *u*TSKFC. As to the adjustable parameters, the parameters ***θT*** will be adjusted using adaptive rules that are derived from Lyapunov stability theory and described in the following section. In addition, each parameter is initialized to zero before being adjusted.

4.2 STABILITY ANALYSIS AND DESIGN OF ATSKFC

The mechanical equation for SRM drives can be obtained as equation 2 & 3 is 4

$$T_e = \frac{1}{2} i_s^2 \frac{dL_{jj}}{d\theta_r} = \frac{1}{2}\left(\frac{dL_{jj}}{d\theta_r} i_s\right), \quad i_s = K_t(\theta_r, i_s) i_s \qquad (2)$$

$$T_e = J_m \dot{\omega}_r + B_m \omega_r + T_L \qquad (3)$$

Where J_m is the moment of inertia, B_m is the viscous frictional coefficient, ω_r is the rotor speed, and T_L is the external load.

$$\dot{\omega}_r = -\frac{B_m}{J_m}\omega_r + \frac{K_t}{J_m} i_s^* - \frac{1}{J_m} T_L = A_s \omega_r + B_s u_t + C_s T_L \qquad (4)$$

The Lyapunov function candidate

$$V(t) = \frac{1}{2} e^2 + \frac{1}{2\alpha} \tilde{\theta}^T \tilde{\theta} \qquad (5)$$

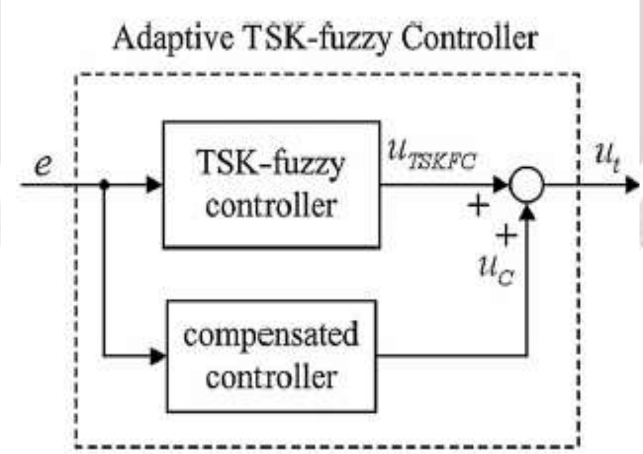

Fig – 5: Configuration of the proposed ATSKFC

The stator flux and the motor total torque levels are controlled within two separate hysteresis bands, so when the instantaneous torque and flux cross the related band limits, they need to increase or decrease in order to remain inside the bands as illustrated in figure 5.

5. SIMULATION RESULTS

Here the simulation is carried by two different cases,

1. Proposed 8/6 SRM converter by using ATSKFC, fuzzy and PI controller
2. Five phase 10/8 SRM ATSKFC controller

5.1 PROPOSED 8/6 SRM UNDER DIFFERENT CONTROLLERS

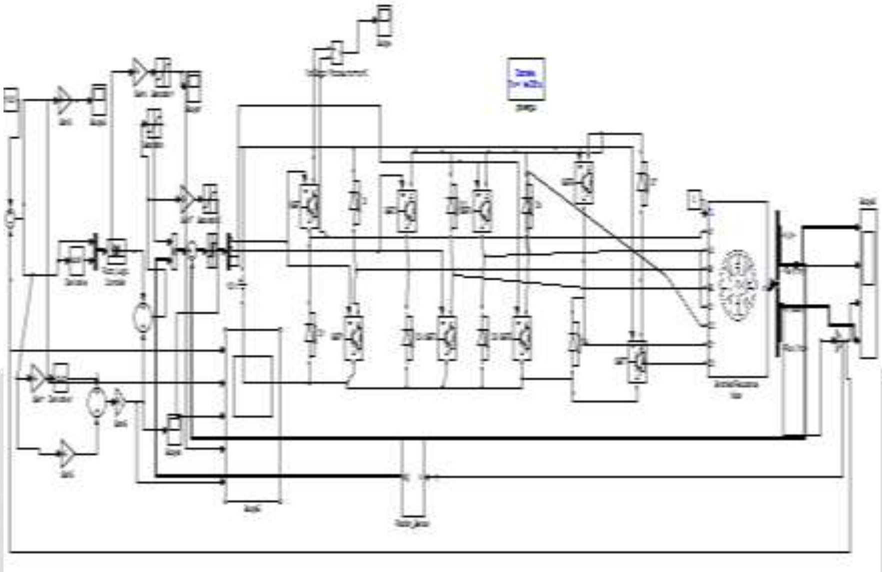

Fig – 6: MATLAB/SIMULINK model of proposed converter

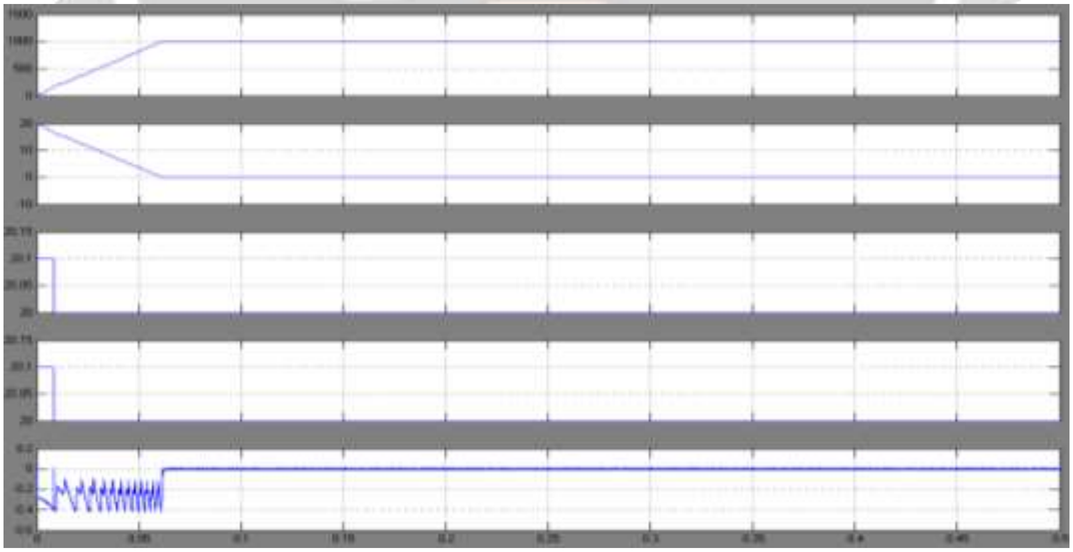

Fig – 7: Simulation results of the ATSKFC for the SRM drive $\delta = 0.1$

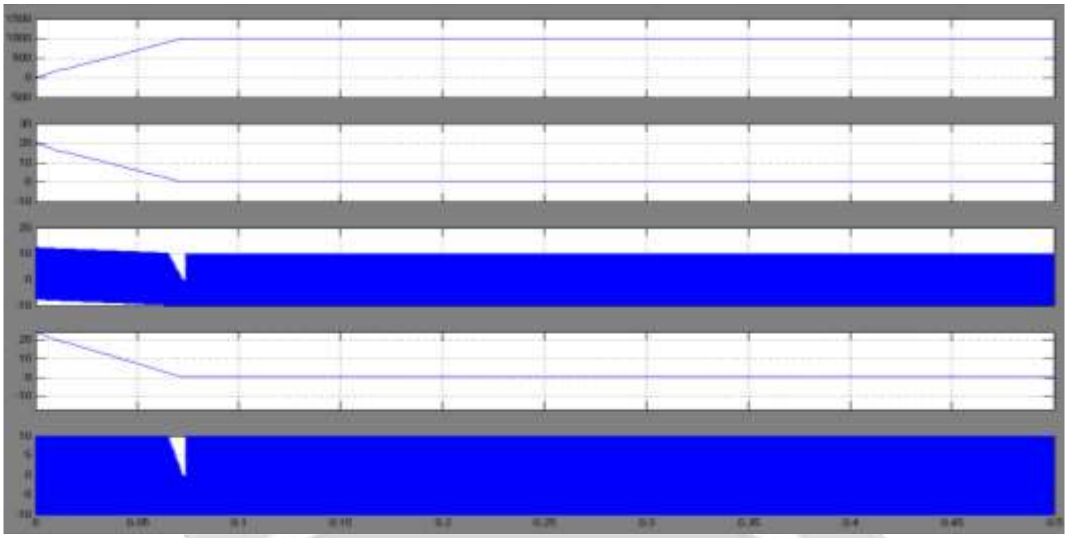

Fig – 8: Simulation results of the ATSKFC for the SRM drive δ =10

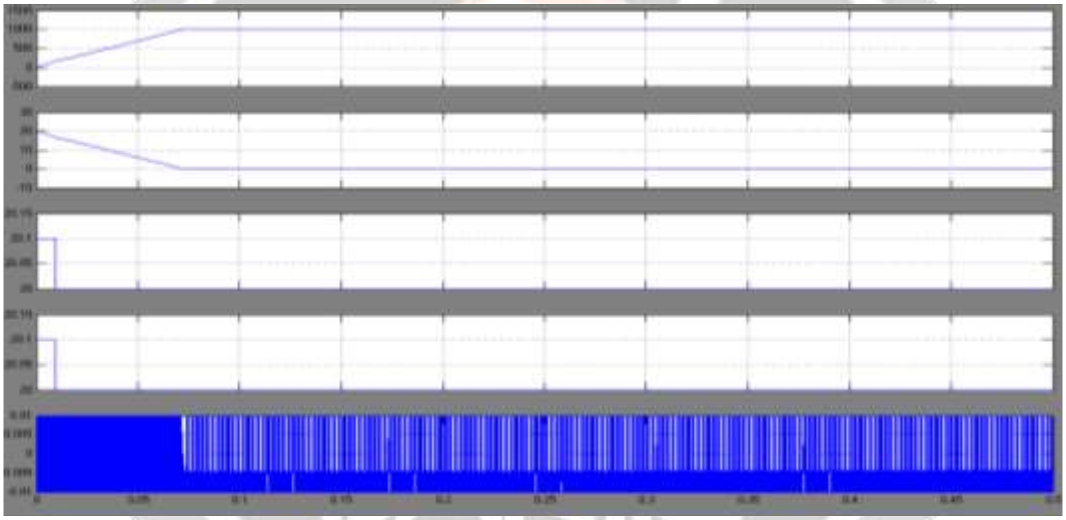

Fig – 9: Improved compensated controller with δ = 0.1

In above Figures 6, 7, 8 and 9 demonstrates that the speed error was approximately1.28 r/min when the SRM drive system is in the steady state. The small δ caused a small compensation and resulted in a huge speed error around70.99 r/min in the transient stage. In Figure 8, the maximum transient state error is clearly lower because δ = 10 caused a larger compensation. However, the larger compensation also caused undesired chattering phenomena and was associated with a larger steady-state error. From these two simulation tests, a fixed compensation is difficult to have the satisfactory performance. Fig. 9 plots the results of simulating the proposed ATSKFC with the improved compensated controller (25) and δ =0.1. The figure indicates that the improved compensated controller provides more compensation in the transient stage and maintains a small compensation in the steady state of the SRM drive system. This improved compensation enables the proposed ATSKFC to perform well in not only transient but also steady state of the system.

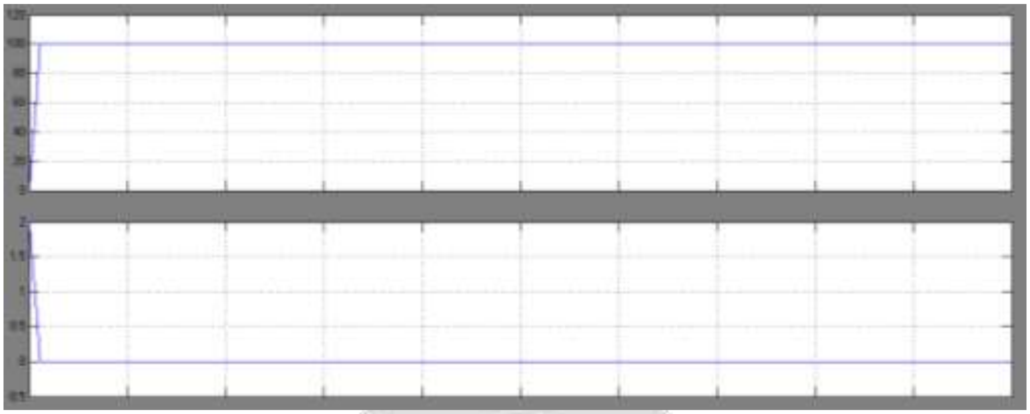

Fig – 10: Simulation results of the ATSKFC under speed at 100 sin(*t*) r/min

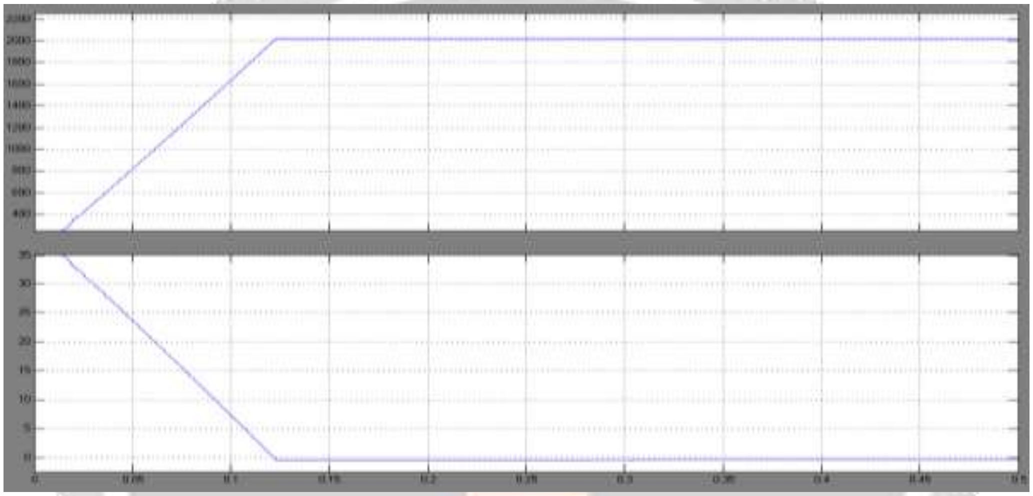

Fig – 11: Simulation results of the ATSKFC under speed at 2000 sin(*t*) r/min

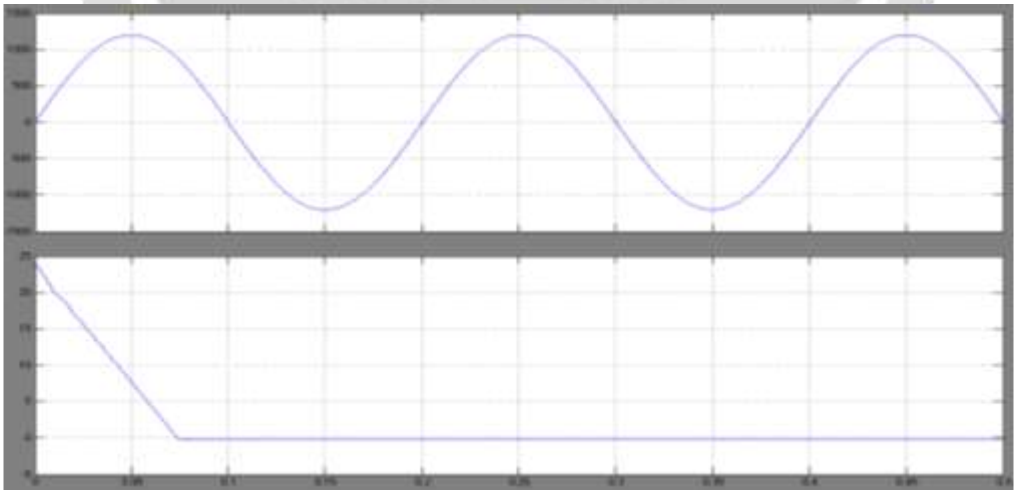

Fig – 12: Simulation results of the ATSKFC under speed at 1200 sin(*t*) r/min.

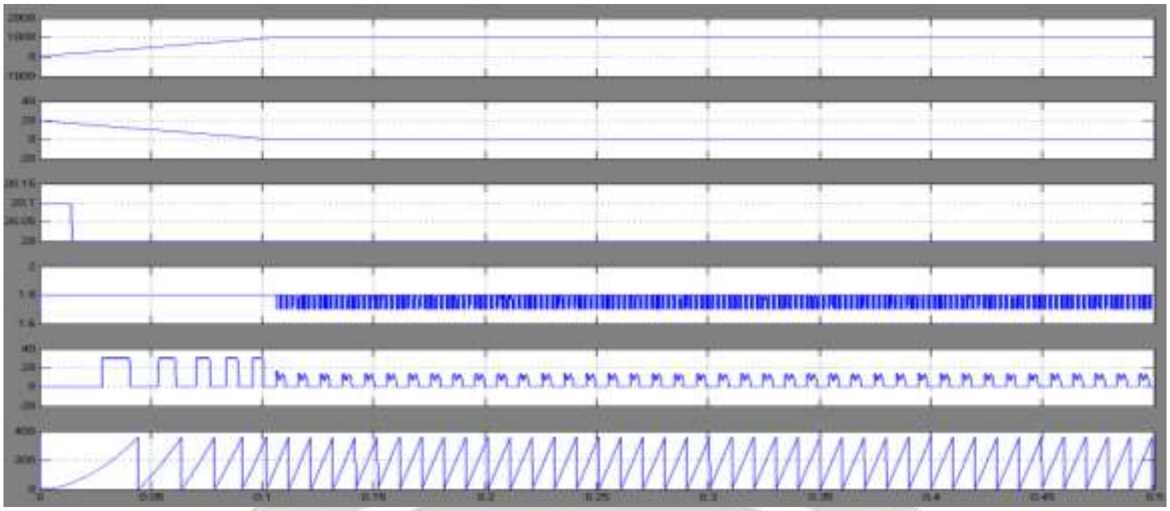

Fig – 13: Simulation results under full-load condition. Speed response, speed error, and control effort, Torque output, phase current and rotor angle.1000 rpm using ATSKFC

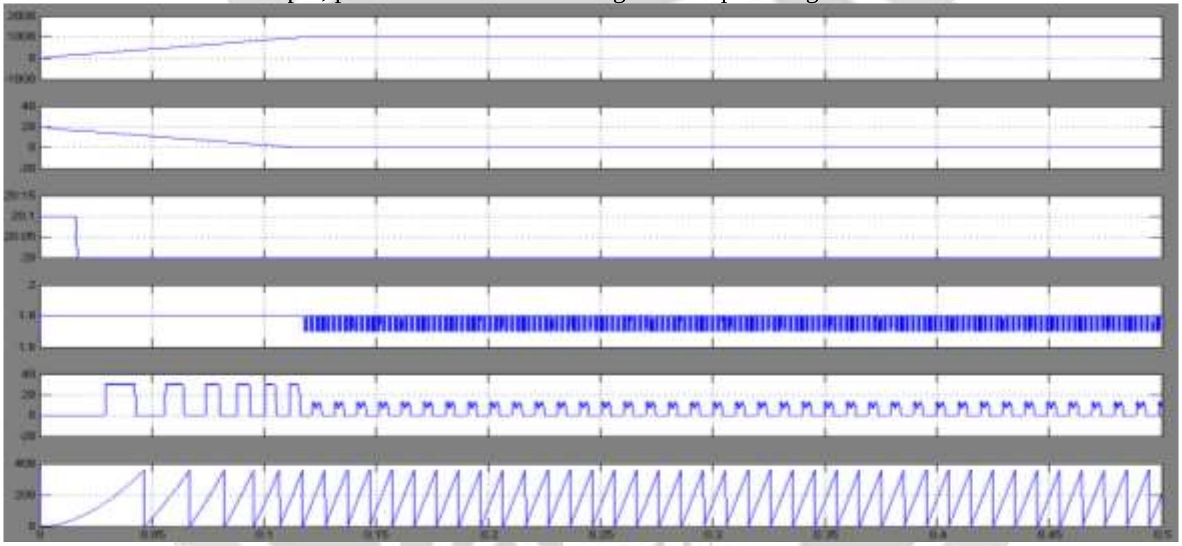

Fig – 14: Simulation results under full-load condition. Speed response, speed error, and control effort, Torque output, phase current and rotor angle.1000 rpm using fuzzy controller

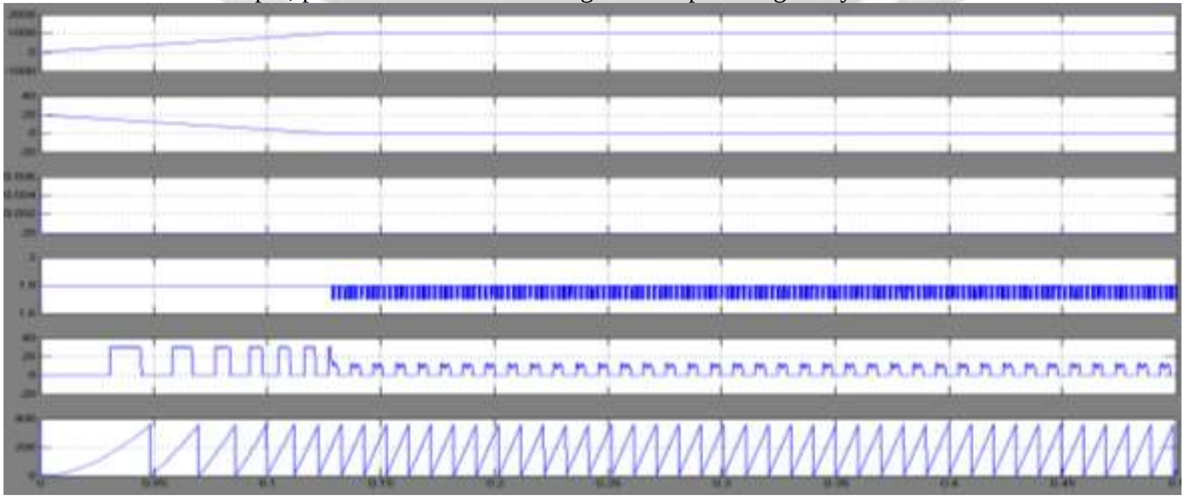

Fig – 15: Simulation results under full-load condition. Speed response, speed error, and control effort, Torque output, phase current and rotor angle.1000 rpm using PI control

5.2 FIVE PHASE 10/8 SRM

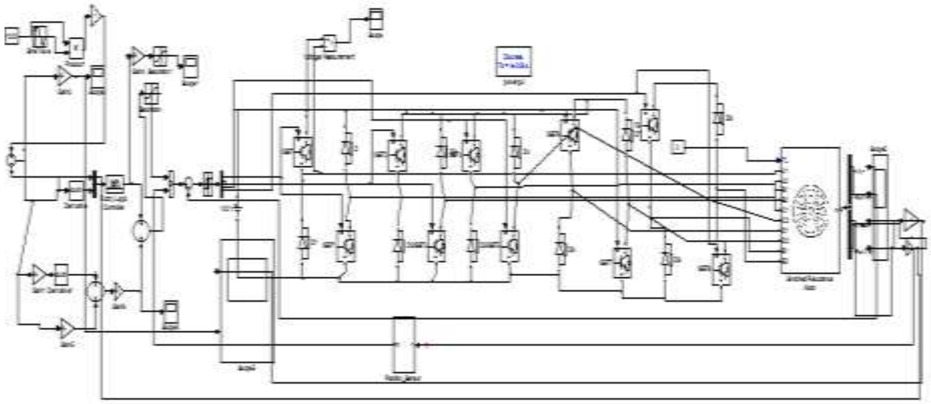

Fig – 16: MATLAB/SIMULINK model of five phase 10/8 ATSKFC SRM

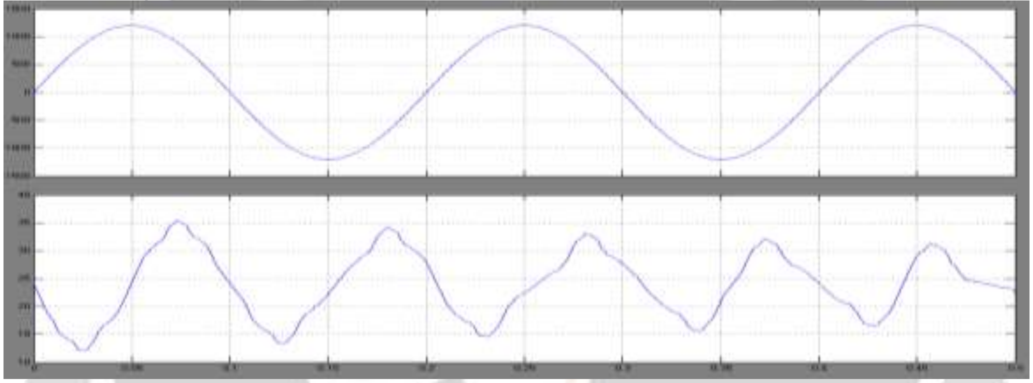

Fig – 17: Simulation results of the five phase 10/8 ATSKFC SRM under speed at 1200 sin(t) r/min

6. CONCLUSIONS

In this concept using control circuit is used to any number phases of SRM is applicable. Our work is done in 5-phase SRM and 4-phase also. The main concepts of 5-phase 10/8 SRM by using fuzzy logic controller were proposed. Then, the phase transposition problem, occurred in 10/8 SRM, and its solution were introduced. The comparable simulation results between two PI and fuzzy control methods were presented. An adaptive TSK-fuzzy controller for the SRM drive system, Compared with the other two schemes, the ATSKFC provides better speed tracking capability under single quadrant, four-quadrant, and full-load operations. The stability of the proposed ATSKFC is guaranteed because the Lyapunov stability theory is utilized to derive the adaptation laws. The successful development of an improved compensating control strategy to ensure control performance in both transient and steady state. The successful application of the ATSKFC for SRM drive system to track various speed references with robust control performance. The control performance of the proposed ATSKFC has been confirmed by simulation results. The above results comparison of 4-phase and 5-phase 10/8SRM the speed torque characteristics of the same control strategy by using MATLAB/SIMULINK software.

7. REFERENCES

[1] L. Xu and E. Ruckstadter, "Direct modeling of switched reluctance machine by coupled field-circuit method," IEEE Trans. Energy Conv., vol. 10, pp. 446-454, Sept. 1995.
[2] N. J. Nagel and R. D. Lorenz, "Modeling of a saturated switched reluctance motor using an operating point analysis and the unsaturated torque equation," IEEE Trans. Ind. Applicat., vol. 36, pp. 714-722, May/June

2000.
[3] P Jinupun and P. C. K. Luk, " Direct torque control for sensorless switched reluctance motor drives," in Proc. 7th Int. Conf. Power Electron. Variable speed drives, pp. 329-334, 1993.
[4] A. D. Cheok and Y. Fukuda, " A new torque and flux control method for switched reluctance motor drives," IEEE Trans. Power Elect., vol. 17, pp. 543-557, 2002.
[5] Chan. S and Bolton. HR, “Development of sub-kW single phase switched reluctance drives,” Conf. Rec. of ICEM, 2, pp. 527- 531, 1992.
[6] D. G. Taylor, "Adaptive control design for a class of doubly-salient motors," in Proc. 30th IEEE Conf. Dec. Cont., vol. 3, pp. 2903 2908,1991.
[7] C.Dinakaran, “Modeling and Simulation of Speed Control of Induction Motor by Space Vector Modulation Technique using Voltage Source Inverter,” Journal of Electrical Engineering, Vol. 15, Edition 3, September 2015, PP. 280-287.
[8] N. J. Nagel and R. D. Lorenz, "Complex rotating vector method for smooth torque control of a saturated switched reluctance motor," in Proc. 34th Annu. Meeting IEEE Ind. Applicat. Vol. 4, pp. 2591-2598, 1999.
[9] N. Matsui, N. Akao and T.Wakino, "High –precision torque control of reluctance motor," IEEE Trans. Ind. Aplicat., vol..27, pp. 902-907, Sep./Oct. 1991.
[10] A. M. Stankovic, G. Tadmor, Z. J. Coric and I. Agirman, "On torque ripple reduction in current-fed switched reluctance motors," IEEE Trans. Ind. Electron., vol. 46, pp. 177-183, Feb. 1999.
[11] B. Y. Ma, T. H. Liu and W. S. Feng, “Modeling and torque pulsation reduction for a switched reluctance motor drive system,” in Proc. IEEE IECON. 22nd Int. Electron. Cont. Instrum.., vol.1, pp. 72-77, 1996.
[12] C.Dinakaran, K.Bhavani and K.Eswaramma, “Design and Performance Evaluation of Direct Torque and Indirect Flux Control of BLDC Motor,” Global Research Analysis – International, Vol. 2, Issue 8, August 2013, PP. 48-52.
[13] M. Ilic'-Spong, R. Marino, S. M. Peresada and D. G. Taylor, "feedback linearizing control of switched reluctance motors," IEEE Trans. Automat. Contr., vol. AC-32, pp. 371-379, May 1987.
[14] R. S. Wallace and D. G. Taylor, "A balanced commutator for switched reluctance motor to reduce torque ripple," IEEE Trans. Power Electron., vol. 7, pp. 617-626, July 1992.