Speed Control of Switched Reluctance Motor Based on Fuzzy Logic Controller

Gamal M. Hashem                     Hany M. Hasanien

gamalhashem@eng.asu.edu.eg
hanyhasanien@ieee.org

Department of Electrical Power and Machines, Ain Sham University, Cairo, Egypt

Abstract—This paper presents a Fuzzy Logic Controller for Switched Reluctance Motors (SRM). The fuzzy logic controller is utilized to control the SRM speed. The dynamic response of the SRM controlled by the proposed controller is studied during the starting period and under different loading conditions. The effectiveness of the proposed fuzzy logic controller is then compared with that of the conventional PI controller. The dynamic simulation is performed on C program. Selected experimental results are reported to verify and to validate the effectiveness of the proposed system.

Index Terms — Fuzzy logic controller, Switched reluctance motor, PWM Inverter.

I. INTRODUCTION

The Switched Reluctance Motor is a doubly salient machine in which torque is produced by the tendency of the rotor to move to a position where the inductance of the excited windings is maximized (the aligned position) [1]-[2]. The SRMs are considered to be attractive solutions for variable speed applications with high power density. The SRM possesses many inherent advantages such as simplicity, robustness, low manufacturing cost, high starting torque, high speed, and high efficiency [3]-[4]. On the other hand, the stator windings are concentrated and no windings, no brushes on the rotor, as shown in Fig. 1. In addition to this, only simple converter circuit with reduced number of switches due to unidirectional current requirements are needed [5]-[6]. These advantages make this type of motors, a competitive choice to both the dc series motor and the squirrel cage induction motor [7]. The SRM can be used for general purpose industrial drives. The motor ability to operate in the four quadrants and its suitability for hazardous areas open a wide range of applications for switched reluctance motor drives including mining, explosion proof machinery, traction and domestic applications. Recently, a good deal of the research work focus on SRM control and torque smoothness in order to make it a competitor to both fully controlled dc and ac drives [8].

The paper proposes an improved controller based on fuzzy logic technique. The controller effects on the motor dynamic response are evaluated.

II. DYNAMIC MODEL OF SRM

The mathematical model of the SRM consists of three basic sets of equations:-
1- The motor phase equations.
2- The mechanical equation.
3- The angular speed equation.

The motor phase equations which describe the electrical behavior of the SRM are defined as follows:

\[ \frac{d\psi_k (\theta_k, i)}{dt} = \pm V - R i_k \]  (1)

Where, \( \psi_k \) is the phase \( k \) flux linkage as a function of the current and the rotor position, \( V \) is the supply voltage, \( R \) is the winding resistance per phase, and \( i \) is the phase current.

The mechanical equation which describes the mechanical motion of the motor is defined as follows:

\[ \frac{d\omega}{dt} = \frac{1}{J} \left( \sum_{k=1}^{q} T_k (\theta_k, i_k) - T_l \right) \]  (2)

Where:
\( \omega \) is the rotor speed, \( J \) is the moment of inertia of both the rotor and load, \( T_l \) is the load torque, \( q \) is the number of phases, \( T_k (\theta_k, i_k) \) is the torque produced by the \( K^{th} \) phase and \( \theta_k \) is the rotor position as seen by the \( K^{th} \) phase.

The angular speed equation is defined as follows:
These equations are representing the dynamic model of the SRM. They are solved simultaneously using Numerical integration technique with the aid of the motor look up tables [5].

III. SRM SPEED CONTROL WITH THE PROPOSED CONTROLLER

The block diagram of the system under study is shown in Fig. 2. It consists of an SRM with its controlled and power supply. The motor data is given in the appendix -a. The drive is tested under the following condition: First, the motor is started against its full load torque until the motor reaches rated steady state speed. Second, the motor is subjected to a severe load disturbance where the load is suddenly decreased to 50% from its initial value, followed by a removal of the disturbance after the motor reaches its steady state speed.

IV. THE FUZZY LOGIC CONTROLLER

The fuzzy logic controller (FLC) is proposed for SRM controller in this study. The aim of it is to control the motor speed and to enhance the speed regulation. The final output of the fuzzy logic controller is used to regulate the switching-on angle of the inverter to regulate the motor shaft speed. The inputs of the controller are the motor speed error \( e(t) \) and the change in the error \( \Delta e(t) \).

The motor speed error \( e(t) \), is define as following:

\[
e = (\omega_{\text{ref}} - \omega) \tag{4}
\]

In the FLC, The reference speed \( \omega_{\text{ref}} \) is compared with the actual speed \( \omega \) to get the speed error \( e(t) \) as shown in Fig. 3. Also this error is compared with the previous error \( e(t-1) \) to get the change in error \( \Delta e(t) \). The inputs of FLC are \( e(t) \) and \( \Delta e(t) \). The output of the proposed controller is \( \Delta \theta_{\text{on}}(t) \) which is added to the previous state \( \theta_{\text{on}}(t-1) \) to get the \( \theta_{\text{on}}(t) \).

V. PERFORMANCE EVALUATION

The SRM is tested with the same load torque variations stated before in section III Where in this section the descriptions of the system under study.
A. Dynamic response during Starting (Zone one)

For a good motor performance during starting, the design requirements will be as follow:
The maximum overshooting is very small and it tends to zero, the rise time is less than or equal to 0.01 sec, the settling time is less than or equal to 0.04 sec, the steady state value is less than or equal to 0.15 [9]. Therefore, according to these requirements the damping ratio $\zeta$ equals 0.6, the undamped natural frequency $\omega_n$ is 180 rad/sec, the damped frequency $\omega_d$ is 144 rad/sec.
The new switching on angle can be expressed using the following formula:
\[ \theta_{on\ new} = \theta_{on\ ref} - \theta_{on\ actual} \] (5)

Fig. 5, shows the dynamic response of the motor during starting when provided with the FLC as compared with the PI controller of gains $k_p = 0.005$ and $k_i = 5$, where these values represent the optimal values of the PI controller parameters. As shown in this figure, it can be realized that the dynamic response of the SRM when provided with the FLC is improved compared with the motor is provided by PI controller. The response is fast with minimum overshoots.

B. Dynamic response during a step down load torque Disturbance (Zone two)

For a good motor performance during this zone, the design requirements are minimum overshooting (less than or equal to 0.2), the rise time is less than or equal to 0.01 sec, the settling time is less than or equal to 0.04 sec, the steady state value is less than or equal to 0.15 [9]. Therefore, according to these requirements $\zeta$ equals 0.5, $\omega_n$ is 200 rad/sec, and $\omega_d$ is 173 rad/sec.

Fig. 6, shows the dynamic response of the motor during the second zone. The motor is driven by the FLC as compared with the PI controller of gains $k_p = 0.005$ and $k_i = 5$. As shown in this figure, it can be realized that the dynamic response of the SRM in this case, has the maximum overshoot lower than that experienced when a PI controller is used. Also, it will be of better damped response after the first overshoot. Accordingly, the motor reaches its steady state speed faster. In addition, the steady state error is smaller.

C. Dynamic response during a step up load torque Disturbance (Zone three)

For a good motor performance during this zone, the design requirements are the same as that of zone two. Therefore, according to these requirements $\zeta$ equals 0.48, $\omega_n$ is 208 rad/sec, and $\omega_d$ is 182 rad/sec.

Fig. 7, shows the dynamic response of the motor during the third zone, when provided with the FLC as compared with the case in which a PI controller of gains $k_p = 0.005$ and $k_i = 5$ is used. From this figure, it can be realized that the dynamic response of the SRM when provided with the FLC has the first overshoot slightly lower than that experienced by the PI controller. The FLC improves the system damping after the first overshoot in comparison with that of the PI controller. It also yields a much faster response that allows the motor to reach the steady state after 20 ms, while in the PI controller, it reaches the steady state after 60 ms.

VI. FPGA HARDWARE ARCHITECTURE

In this study, FPGA hardware is implemented to drive the switched reluctance motor. The driver is built on FPGA Spartan-3E Starter from Xilinx. The Spartan-3E Starter Kit board highlights the unique features of the Spartan-3E FPGA family and provides a convenient development board for
embedded processing applications [10]. Spartan-3E specific features are illustrated in details in Appendix-b.

VII. HARDWARE IMPLEMENTATION

Fig. 8 presents the structure of the switched reluctance motor drive system. The modules of the system are: a four phase switched reluctance motor, FPGA Spartan-3E Starter Kit, a driving circuit, dc generator and resistive loads. The rated current is 1.5 A per phase, the rated torque is 3 N.m, the dc supply voltage is 24 V, and the rated speed is 100 rpm. The motor is equipped with an optical encoder to measure position and speed of rotor shaft. The encoder is optical type with 2048 lines. The driving circuit is asymmetric half bridge circuit, which consists of two IGBTs and two freewheeling diodes for each phase. The input to the driving circuit is a pulse train voltage signal with magnitude of 0 or 5 V. The output of the driving circuit is switch, with a 24 V nominal dc voltage. A dc generator is coupled to the shaft of the SRM to simulate the load torque disturbance. The dc generator is loaded by different resistive loads. VHDL is used for programming the FPGA kit.

VIII. EXPERIMENTAL RESULTS

The proposed control technique was tested in the laboratory when the motor was operated under full load torque at the starting process and under load torque disturbances.

Fig. 9 and Fig. 10 demonstrate the measurements of speed under full load torque and load torque disturbances. It can be observed that the speed response is very smooth and the ripple is reduced to a very small value using the fuzzy logic controller in comparison with the conventional PI controller. These good practical results agree with the simulation results. In addition, the measured speed has a fast and better damped response than that of the conventional PI controller.

IX. CONCLUSION

The paper presents a new fuzzy logic controller to ensure excellent reference tracking of switched reluctance motor drives. The fuzzy logic controller is enhanced the speed regulation of this type of drives over both starting and load disturbance periods. The SRM response when controlled by FLC is superior to that corresponding to the conventional PI controller. Experimental results have verified the validity and effectiveness of the proposed control scheme.

X. APPENDIX

a) The motor under study is three phases, SRM, the rated power is 4 kW at 3000 rpm. The phase resistance is 0.1 Ω, the motor inertia is 0.0012 kgm². DC supply voltage = 360 V.

b) Spartan-3E kit features.

- Spartan-3E specific features
  1. Parallel NOR Flash configuration
  2. MultiBoot FPGA configuration from Parallel NOR Flash PROM
3. SPI serial Flash configuration
   • Embedded development
     1. MicroBlaze™ 32-bit embedded RISC Processor
     2. PicoBlaze™ 8-bit embedded controller
     3. DDR memory interfaces

The Spartan-3E Starter Kit board is more advanced and complex compared to other Spartan development boards. The key features of the Spartan-3E Starter Kit board are: Xilinx XC3S500E Spartan-3E FPGA, up to 232 user-I/O pins, 320-pin FBGA package, and over 10,000 logic cells. It has 4 Mbit Platform Flash configurations PROM, 64 MByte (512 Mbit) of DDR SDRAM, x16 data interface, 100+ MHz, and 16 MByte (128 Mbit) of parallel NOR Flash (Intel StrataFlash). Also, it contains FPGA configuration storage, 2-line, 16-character LCD screen, VGA display port, and 10/100 Ethernet PHY (requires Ethernet MAC in FPGA). In addition, the processor is MicroBlaze™ 32-bit embedded RISC. Moreover, it has a four-output, SPI-based Digital-to-Analog Converter (DAC) and two-input, SPI-based Analog-to-Digital Converter (ADC) with programmable-gain pre-amplifier.

XI. REFERENCES


XII. BIOGRAPHY

Gamal M. Hashem was born in September 1960, in Cairo, Egypt. He received the B.Sc. and the M.Sc. degrees in Electrical Engineering from Ain Shams University, Cairo, Egypt, in 1983, and 1988, respectively. In 1994 he received the Ph.D. degree in Electrical Engineering according to the agreed channel system between Ain Shams University, Egypt, and Brunel University, U.K.

From 1994 to 2006, he was an Assistant Professor, and since September 2006 to recent, he is Associate Professor at Electrical Power and Machines Dept., Ain Shams University, Egypt. His research activities are in the area of Power Electronics Including PWM Techniques, Enhancement of Induction Motors Performance, PWM AC Choppers, and Multilevel PWM Inverter.

Dr. Gamal is listed in *Who’s Who in science and engineering*, in the 9th edition. He authored or coauthored numerous technical papers published in leading journals and conference proceedings.

Hany. M. Hasanien (M’09). He was born in Cairo, Egypt on 1976. He received his B.Sc., M.Sc. and Ph.D degrees in Electrical Engineering from Ain Shams University, Faculty of Engineering, Cairo, Egypt, in 1999, 2004, and 2007 respectively. Currently, he is an Assistant Professor at the Electrical Power and Machines Dept., Ain Shams University. His research interests include machine design, modern control techniques, electrical drives, artificial intelligence applications on electrical machines and renewable energy systems.

Dr. Hasanien is a member of the Institution of Electrical and Electronics Engineers (IEEE) and also of Power & Energy Society (PES). He has published in many International Conferences and Journals. He is a reviewer of many International Conferences and Journals papers. He has published a book (Co-authored with Dr. S. M. Muyeen and Prof. J. Tamura), “Switched Reluctance Machine”, Praise Worthy Prize, Italy, in Feb. 2010.