Fuzzy controlled modified reduced switch converter for switched reluctance motor under dynamic loading

Ritika Asati[1], Deepak S. Bankar[1], Aishwarya Apte[2], Amit L. Nehete[3], Yogesh Mandake[1]
[1]Department of Electrical Engineering, Bharati Vidyapeeth (Deemed to be) University, College of Engineering, Pune, India
[2]Department of Electrical Engineering, AISSMS's College of Engineering, Pune, India
[3]School of Electrical Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, India

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ABSTRACT

In this paper, modified reduced switch converter topology is used to drive 8/6 pole, 7500 W switched reluctance motor (SRM) with an electric vehicle (EV) load. Fuzzy logic control (FLC) is developed for the modified converter topology and its performance is compared with the proportional integral (PI) controller. Analytical equations, switching pulses and different mode of operation are presented for modified reduced switch converter using double phase magnetization scheme. The converter topology adopts a modified switching sequence i.e., magnetization then freewheeling before demagnetization. It offers lesser torque ripples, reduced phase current and need only four switches for a 4-phase SRM drive. Modified reduced switch converter is simulated in MATLAB-simulation to investigate and compare the steady state waveforms and transient speed response of the PI and FLC. Torque ripple in modified converter is 50% less than the classical converter. Peak overshoot and settling time performance of FLC is superior as compared to PI, when applied to modified converter with EV loading.

Corresponding Author:

Ritika Asati
Department of Electrical Engineering, Bharati Vidyapeeth (Deemed to be) University
College of Engineering
Pune, India
Email: ritikaasati86@gmail.com

1. INTRODUCTION

Electric vehicles (EVs) are becoming progressively more common around the world as a result of their numerous advantages and growing environmental concern. Various factors prompted researchers to search for innovative ideas in the area of electric vehicles [1]. Numerous EV motors are available in the market; however, these motors require permanent magnets for its construction, which are rare earth materials with high mining and refining cost [2]. Switched reluctance motor (SRM) is continuously in research and gaining importance owing to the permanent magnet free structure, absence of rotor winding, ability to work at high temperature and good fault tolerance capability. SRM meets all of the EV requirements, offer a high torque output, and are inexpensive [3]. SRM drive comprises of DC power supply, power electronic converter, current, position sensor and controller. SRM runs on the variable reluctance concept, so the rotor position has to be continuously monitored. To energize a specific phase, controller unit supply triggering pulses to power converter switches [4]. Dynamic load used in this paper is an electric vehicle of 1,200 kg from the MATLAB Simulink library. Selecting a suitable power converter is the most crucial task; it should use the minimum switching devices per phase to provide acceptable performance while being small, simple and inexpensive. Due to doubly silent structure of SRM, it suffers from the high torque ripple, noise, and vibration [5].

Various control approaches with classical asymmetric half bridge converter (AHBC) have been explored in the literature [6]–[11] to reduce the torque ripple problem in SRM. A new direct torque control (DTC) is used to prevent negative torque generation during phase commutation and to increase torque per ampere ratio with less torque ripple [6]. Model predictive flux control (MPFC) combines the positive aspects of DTC and model predictive control (MPC) [7]. This technique is challenged by cost function design and torque hysteresis for voltage vector selection. A novel direct instantaneous torque control (DITC) using pulse width modulation (PWM) is proposed in [8] to overcome the limitation of conventional hysteresis based DITC. Direct predictive torque control (DPTC) is adopted and reduced copper losses are observed compared to PWM-DITC. DPTC occupy significant memory in look up tables [9]. Improved indirect instantaneous torque control (IITC) method is discussed by adopting modified torque sharing function (TSF) [10]. Here, current profiles must be pre-calculated, a new fuzzy logic controller (FLC) is used and compared with the sliding mode controller in [11].

All these control techniques employ classical AHBC due to its attractive characteristics. For SRM supplied by AHBC, number of switching devices required is double the number of phases. This increases the size and cost of the drive system; increased switching losses complicates the control algorithms [12]. A modular converter is used with DITC to provide multilevel voltage, improved power factor and less torque ripple [13]. But it uses more switches than the classical AHBC. DITC is used in novel modular multi-level power converter. It has 3-level switch module and an additional boost capacitor [14].

The requirements of small converter size and reduced torque ripple inspired researcher to look for the converter with reduced switches and advanced control approach. Proposed, modified reduced switch converter topology is one of the best solutions to these requirements by using single switch per phase with reduced torque ripple and improved performance. Proposed converter follows double phase magnetization technique. The commutation sequence followed by this topology is different than the AHBC. In this paper, the simulation results of a modified reduced switch converter fed 4-phase SRM employing PI and FLC are compared. FLC outperforms in terms of steady-state and transient response than the PI controllers.

This paper is organized in different sections; the mathematical torque and torque ripple equation with its explanation for SRM is provided in section 2. In section 3 presents features, operational modes and equations of modified reduced switch converter topology. Section 4 evaluate the performance of modified converter by incorporating conventional PI and advanced FLC method. In section 5 presents a set of simulation waveforms and compare findings of both control strategies for steady state and transient state with three different reference input signals. At the last, section 6 summarizes the simulation results and conclude the paper.

2. MATHEMATICAL TORQUE AND TORQUE RIPPLE OF SRM

Torque is generated in SRM by natural alignment of rotor poles with the excited stator pole pair. Mutual coupling between different phases is assumed to be negligible. The torque in SRM is a non-linear function of inductance and phase winding current. Mathematically it is represented as [15]:

$$T_{inst} = 0.5 * i^2 * \frac{dL(\theta,i)}{d\theta} \tag{1}$$

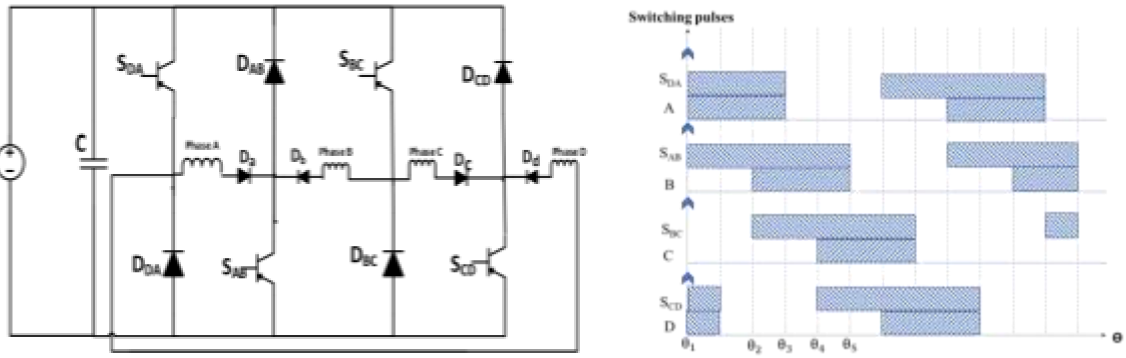
Here, in (1), i is the phase winding current, θ is the position of rotor and $\frac{dL(\theta,i)}{d\theta}$ represents the change in winding inductance with respect to rotor position θ. It is observed that electromagnetic instantaneous torque is independent from the direction of current. The torque is produced due to the variation of inductance and it is pulsed because current shifts from one phase to another phase in the stator winding. Torque ripple is caused by pulsed torque generation, which is the most serious issue with SRM drives. Torque ripple is defined by (2) and is expressed in percentage [16], [17].

$$\text{Torque ripple} = \frac{T_{max}-T_{min}}{T_{avg}} \times 100\% \tag{2}$$

For performance improvement and torque ripple reduction, this article considered a modified reduced switch converter design with fuzzy logic control. The added benefit of reduce converter is half the number of switches than the conventional AHBC topology [18].

3. MODIFIED REDUCED SWITCH CONVERTER TOPOLOGY

The modified reduced switch converter topology shown in Figure 1, is similar to AHBC but has a minor structural modification due to the fewer switches used. This converter employs four switches and eight diodes while, commonly used classical AHBC requires eight switches and eight diodes for a 4 phase SRM drive. Figure 1(a) shows, the circuit structure and Figure 1(b) displays, the switching pulses of the modified reduced converter topology in double phase magnetization strategy.



(a) (b)

Figure 1. 4 phase SRM using modified reduced switch converter (a) circuit configuration and (b) switching pulses using double phase magnetization

3.1. Distinct features

Modified reduce switch converter structure as shown in Figure 1(a) uses only four switches for 4 phase SRM drive. Switches are shared by adjacent phase windings. Four diodes, out of eight are shared by adjacent phase windings; remaining four diodes are connected in series with each phase of 4 phase winding of SRM. Phase winding is not independent but connected to a neighboring node. The conducting sequence of this converter is: magnetization, freewheeling and demagnetization. This modified converter has three voltage states ($+V_{dc}$, $-V_{dc}$, and 0). This converter concept was initially analyzed and discussed in [19] with constant load for a 6 phase SRM drive. This research paper applied the similar converter topology for commonly used 4 phase SRM with dynamic load and fuzzy logic controller.

3.2. Operation and working stages

The functioning of modified converter can be comprehended by referring to various stages illustrated in Figure 2. As per double phase magnetization, two phases are under commutation at the same time. Out of 4 phases; only A and B phase are taken into consideration here. Each switch is separately turned on according to the rotor position. In this converter freewheeling state lie between the magnetization and demagnetization state.

Stage 1: triggering pulses are supplied to switch S_{AB} at θ_1 and will continue to operate until θ_5 as indicated in Figure 1(b). Switch S_{DA} is already in conduction. Only phase A winding will be magnetized due to turning on of S_{AB} and S_{DA} at the same time. The current path for this magnetized A-phase is depicted in Figure 2(a).

Stage 2: now triggering pulses are applied to switch S_{BC} at θ_2; this in turn will magnetize the phase B as well. As per step-1, phase A is already magnetized which remain on from θ_1 to θ_3. Both phase A and B will conduct simultaneously from θ_2 to θ_3. Figure 2(b) illustrate the conduction path of phases (double phase magnetization).

Stage 3: as illustrated in Figure 2(c); A-phase comes in freewheeling from θ_3 to θ_5 while B-phase magnetized. Operation of the modified converter is different in stage-3 as AHBC follows demagnetization for A-phase.

Stage 4: in this, A-phase enters into the demagnetizing mode after stage-3. Phase winding current begins to decrease and reaches zero at θ_5. Phase-B freewheels simultaneously, as shown in Figure 2(d). The other phases of the motor follow the same commutation order from stage-1 to 4. The magnetization, freewheeling, and demagnetization cycle is followed by all phases of SRM using modified reduced switch converter.

3.3. Analytical equation

In modified reduced switch converter topology; consider switching state Q_A, for the magnetization, as 1; for demagnetization, it is -1; and for the freewheeling, as 0. According to this voltage equation for A- phase winding is represented by (3) [19]:

$$V_{phase\,(Modified\,reduced\,switch)} = \begin{cases} V_{dc} = 2V_m + V_A & Q_A = 1 \\ V_A + 2V_d + V_m & Q_A = 0 \\ V_{dc} = -(3V_d + V_A) & Q_A = -1 \end{cases} \quad (3)$$

In (3), V_{dc} is the dc input voltage to the converter unit and V_A is the voltage of the A-phase winding. V_d and V_m are used here to represent the diode and switch voltage respectively. Consider in reduced switch converter, each switch conduction period is θ'_m while conduction period for the phase winding is θ'_p then it's value is specified by (4) [19].

$$\theta'_p = \theta_3 - \theta_1; \theta'_m = \theta_p + \theta_s \text{ and } \theta_s = \frac{360^0}{m*N_r} \quad (4)$$

Here, θ_1 and θ_3 are the angles of switching pulse application from Figure 1(b). θ_p is the conduction period of phase winding in AHBC and θ_s is the stepping angle of SRM. N_r and m represents the rotor poles and number of phases respectively [19], [20].

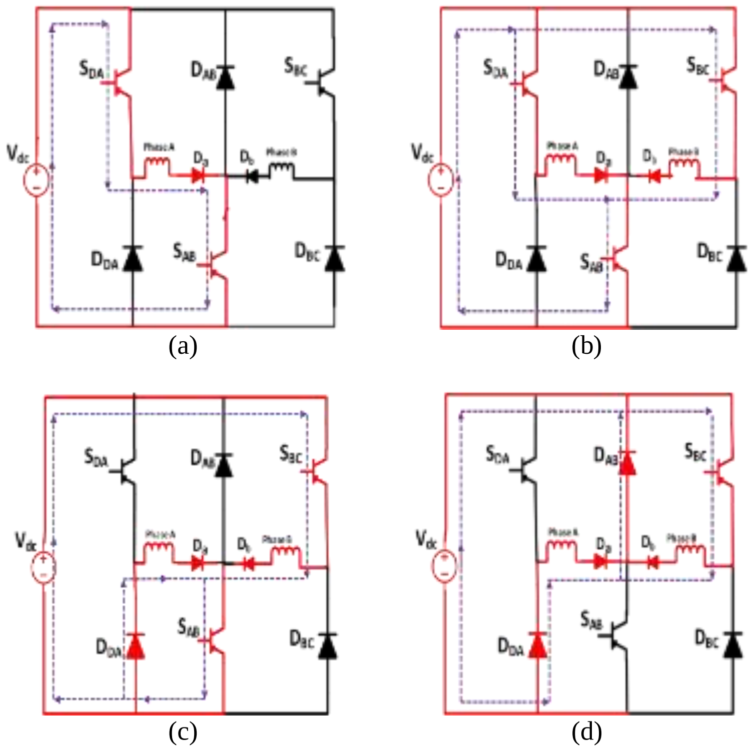


Figure 2. Commutation sequence from A to B phase in modified reduced switch converter; (a) only A-phase magnetized, (b) both A and B phases are magnetized (doubly magnetized), (c) phase-A in freewheeling and phase-B in magnetizing, and (d) phase-A in demagnetization and phase-B in freewheeling

4. CONTROL TECHNIQUES FOR MODIFIED REDUCED SWITCH CONVERTER

The control technique has an essential role in the converter unit to enhance dynamic response for adjusting different speed demands. To assess the effectiveness of the PI and FLC techniques, few SRM parameters are evaluated and compared. The intent is to attain steady and accurate control over the SRM in order to fully utilise the modified reduced switch converter.

4.1. PI control with modified reduced switch converter

PI control is the most straightforward and extensively used approach in variable speed SRM drive. PI controller with constant gain creates disturbance in some operating areas making it inappropriate for efficient control. This control is ineffective for nonlinear control systems. Selection of PI parameter is a crucial task that depends on the operating conditions [21], [22].

4.2. Fuzzy logic control with new reduced switch converter

Figure 3 shows the FLC process flow diagram. FLC is replacing the PI speed controller for faster dynamic response. It is well-suited for handling non-linear control like SRM and can efficiently approximate complex and non-linear functions. It has a rule-based design, which makes them relatively easier to implement and fine-tune compared to other complex control techniques [23]. FLC excels in SRM control by adapting to load variations, simplifying mathematical modeling, and low-computational power requirement. It provide robust performance even for noisy data, ensuring better and faster response [24]. The input of the fuzzy system passes through the most common and accurate, Mamdani type FIS to determine the output distribution.

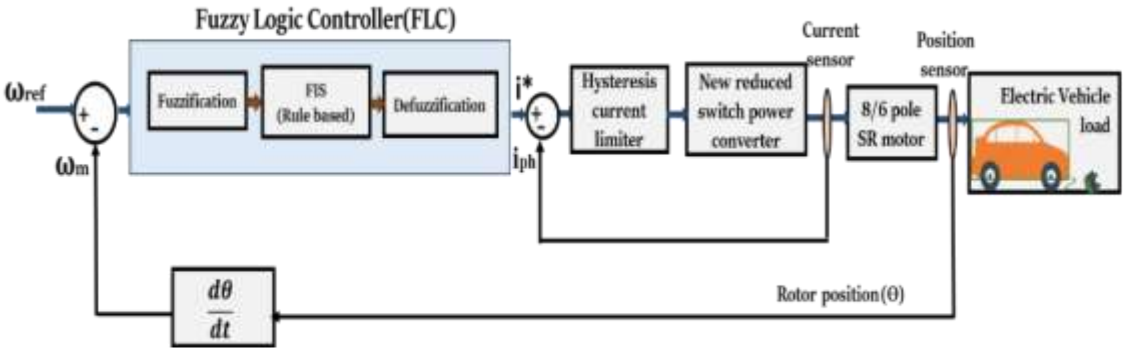


Figure 3. Schematic of fuzzy logic control with new reduced switch converter fed SRM drive

For designing FLC in this work, FIS is described by 49 sets of rules to demonstrate every possible output of every possible input [25]. Also, there are seven membership functions represented as NB, NM, NS, ZE, PB, PM, PS; where P stands for positive, N-negative, B-big, M-medium, S-small, and ZE for zero. Fuzzification is an approach used to convert crisp input into fuzzy values. The speed error serves as crisp input to FLC. To manage the phase current and subsequently create the control pulses for the converter unit, a defuzzied crisp value of output is used [26], [27].

5. SIMULATION RESULTS AND DISCUSSION

A 7,500 W, SRM drive is simulated in MATLAB/Simulink to assess and compare the viability of the modified reduced switch converter with PI and FLC. Table 1 gives the technical parameters of the 4-phases, 8/6 pole SRM used in the simulation. To achieve the best performance, turn on and turn off angles are adjusted to 30^0 and 45^0, respectively. DC voltage of 250V is used for both the simulations.

Table 1. Specifications of four phase switched reluctance motor

Parameters	Value	Parameters	Value
Power rating	7,500 W	Stator/rotor pole	8/6 pole
No. of phases	Four	Stator resistance	0.5 (ohm)
Friction	0.02 (N-m. s)	Aligned inductance	145.9×10^{-3} (H)
Unaligned inductance	9.15×10^{-3} (H)	Saturated aligned inductance	0.15×10^{-3} (H)
Maximum current	35 (A)	Maximum flux linkage	0.9 (V.s)

5.1. Steady state analysis

Simulation waveforms of speed, current and torque during steady state are presented in Figure 4 for modified reduced switch converter with PI and FLC. Reference base speed of 1,000 RPM is set for steady state analysis in both the control techniques. The commutation sequence followed in new reduced converter is magnetization, freewheeling then demagnetization, which is different than the classical converter topologies that interchange freewheeling and demagnetization. According to steady state speed waveform in Figure 4, FLC settles in about 0.13 seconds whereas, the PI control requires 0.8 seconds and also exhibits peak overshoot in speed. Implementation of the modified reduced switch converter results in high starting torque of 55 N-m and an average torque of 7 N-m for both the control approaches. Furthermore, torque ripples are computed using (2) is also found 28% for modified reduced converter in both control techniques.

PI reaches steady speed, torque and current values in 0.8 seconds whereas FLC does it in just 0.13 seconds as indicated in Figure 4 and listed in Table 2. Also, speed waveform of PI controller shows overshoot which is not visible in FLC.

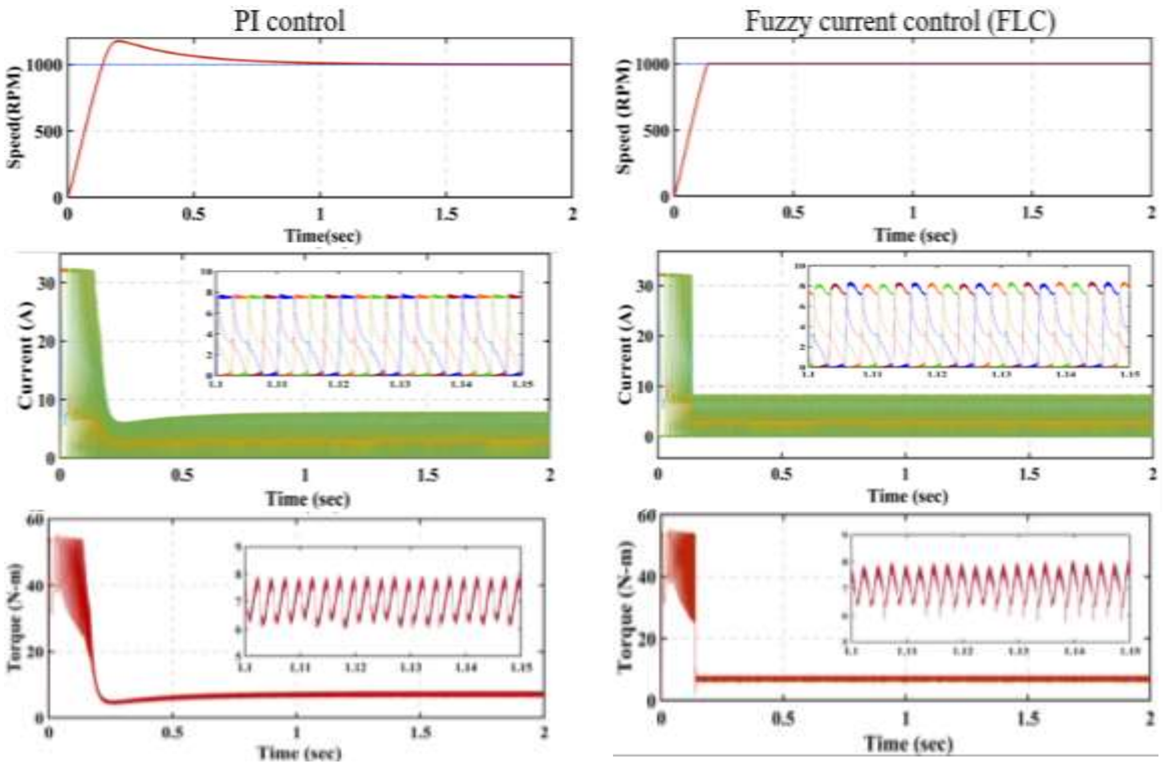


Figure 4. Steady state response of modified reduced switch converter with PI and FLC for 4 phase SRM

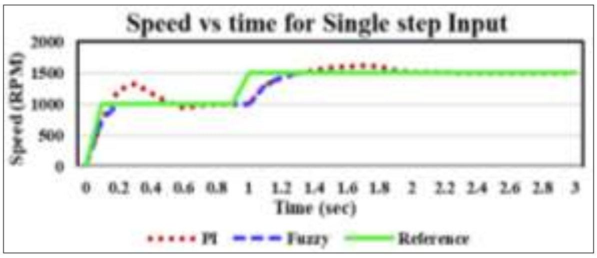
Table 2. Comparison of PI and FLC for modified reduced switch converter

Performance parameter	PI control	FLC
Peak (in RPM)	1175	1001
Peak time (in seconds)	0.2016	0.1396
Settling time (in seconds)	0.8063	0.1361
Overshoot	17.5632	0.0284

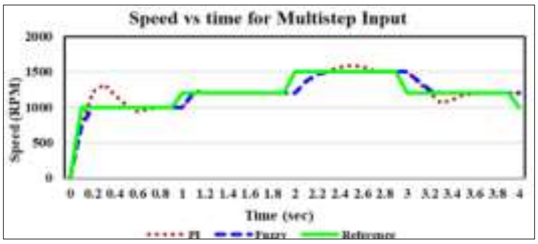
5.2. Transient speed analysis

Different speed references i.e., single step, multistep and trapezoidal are applied as input to analyze PI and FLC for modified reduced switch topology. Figure 5 depicts the simulation results of different transient reference speeds under dynamic EV load. The curves for a single step input are shown in Figure 5(a). Initial speed of 1,000 RPM is set as reference, which is then raised to 1,500 RPM after one second. In contrast to fuzzy control, which takes about 0.2 seconds to settle, PI control exhibits settling time of 0.8 sec and overshoot. The reference speed in Figure 5(b), is changed every 1 second. The starting reference speed is 1,000 RPM. It increases to 1,200 RPM after one second, then to 1,500 RPM after another one second. In a similar manner, after this speed drops to 1,200 RPM, then restores to the reference speed of 1,000 RPM. PI control is unable to stabilize the speed due to the constant variation in the reference speed. While, fuzzy control reacts quickly to these changes.

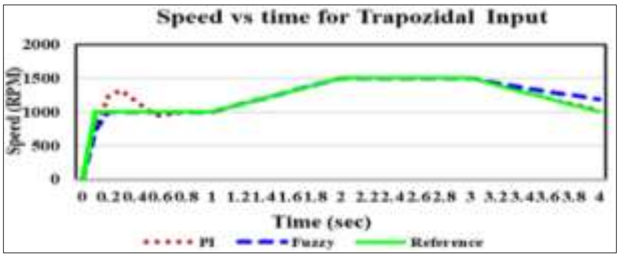
In Figure 5(c), trapezoidal traction input is assessed. Both control technique shows good performance except some initial peak overshoot observed in PI control scheme. The reference speed is initially set to 1,000 RPM, then it accelerates for one second before being reset to 1,500 RPM than deaccelerate to 1,000 RPM. As PI controller is getting enough time during acceleration interval, speed stabilizes and follows the reference speed curve.



(a)



(b)



(c)

Figure 5. Comparison of PI and fuzzy control speed curves with different reference speed curve; (a) single step input, (b) multistep input, and (c) trapezoidal input

6. CONCLUSION

This work proposes a modified reduced switch converter fed four-phase SRM drive with fuzzy controller to enhance the dynamic performance of EV's. First, a modified reduced switch converter topology that uses a different commutation sequence is investigated. It uses half as many switches as commonly used typical AHBC, while simultaneously improving torque profile by reducing torque ripple also switching losses are minimized. Later, performance of a modified reduced switch converter is compared for PI and fuzzy current controller. FLC gives better performance for both steady state and transient conditions by settling the speed, current and torque in just 0.1 seconds. Whereas, PI suffers peak overshoot and significant settling period. Simulation results shows that new reduced switch converter with fuzzy control give satisfied dynamic results for different speed inputs.

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BIOGRAPHIES OF AUTHORS

Ritika Asati received the B.E. (Electrical) in 2007 and M.E. (Power Electronics) in 2009 with gold medal from Rajiv Gandhi Technical University, Bhopal, India. She has teaching experience of 13 years. She is currently working towards the Ph.D. degree in Electrical Engineering from Bharati Vidyapeeth (Deemed to be) University, College of Engineering, Pune, India. Her research interest includes power electronics and switched reluctance motor drive system. She can be contacted at email: ritikaasati86@gmail.com.

Dr. Deepak S. Bankar received M.E. (Electrical Power System) from Government College of Engineering, Pune and Ph.D. (Electrical Engineering) from Bharati Vidyapeeth Deemed to be University, Pune. He is working as Professor and Head of Department of Electrical Engineering at BVDUCOE, Pune. He has guided more than 20 students for M.Tech. and 02 research candidates have completed Ph.D. His research areas are renewable energy systems and power quality. There are more than 32 research publications to his credit and 22 books. He can be contacted at email: dsbankar@bvucoep.edu.in.

Dr. Aishwarya Apte received her Ph.D. degree from Savitribai Phule Pune University, Pune, Maharashtra India. She is currently an Associate Professor with the AISSMS College of Engineering, Pune. Her research interests include electric machine drives, control of electric drives, drives for electric vehicles, embedded systems and nonlinear control systems. She can be contacted at email: aaapte@gmail.com.

Amit L. Nehete received the M.Tech. degree in Power Systems in 2013 and presently pursuing Ph.D. degree in Engineering from Bharti Vidyapeeth (Deemed to be University) College of Engineering, Pune, India. He is currently an Assistant Professor at the Department of Electrical and Electronics Engineering, MIT World Peace University, Pune, India. He is a research student member of IEEE and the life member of Indian Society for Technical Education (ISTE). He has authored several research publications and textbooks in his areas of interest; power systems, electric vehicles, and energy audit. He can be contacted at email: amit.nehete@mitwpu.edu.in.

Yogesh Mandake received master degree of M.Tech. (Electrical power system) and presently pursuing Ph.D. in Electrical Engineering from Bharati Vidyapeeth (Deemed to be University), Pune. Also, he is working as an Assistant Professor at BVDUCOE, Pune. His research areas are electric vehicles, electrical power systems, underground cables, electric machines. He can be contacted at email: yogesh.mandake@bvucoep.edu.in.