PWM Control of Asymmetrical Converter Fed Switched Reluctance Motor Drive

P.Srinivas and P.V.N.Prasad

Abstract— **The Switched Reluctance Motor (SRM) drive has evolved as an alternative to conventional motors in variable speed drives because of advantages like simple and rugged structure, absence of rotor winding, adaptability to harsh environments and high speed operation. This paper presents the speed control of Asymmetrical converter fed 4 phase 8/6 Switched Reluctance Motor drive using PWM controller. Asymmetrical converter is popularly used because of its fault tolerant capability and independent excitation of all phases. Simulation and hardware setup of the controller have been implemented. The controller is tested for two different speeds at three different load torques. Steady state analysis of the drive has been carried out. The information pertaining to practical observations and waveforms are also incorporated. Finally, the experimental results are compared with the simulation results.**

Index Terms—**Switched Reluctance Motor, PWM Control, Asymmetrical Converter, DSP Controller, Power Analyzer.**

I. Introduction

SWITHED RELUCTANCE MOTOR has salient poles on stator and rotor with concentrated windings on the stator and no windings on the rotor. Thus, it is mechanically robust and naturally suited for high speed operation. The SRM achieves high torque levels at low peak currents by using small air gaps. The rotor losses are smaller compared to the stator, unlike motors like DC motor and Induction motor [1 - 4].

The phase winding of SRM is excited through the positive increasing region of the phase inductance region, which is performed through a converter. The popularly used converter is Asymmetrical converter, as it has fault tolerant capability, independent excitation of all phases and possibility of soft and hard switching [6]. At lower speeds, the motor back-EMF is small compared to the supply voltage and the current flowing through the stator winding can be regulated by PWM Control. In PWM Control strategy, the current is regulated below the reference value by applying voltage pulses of fixed frequency and variable duty ratio [1 - 5]. Xiaoyan Wang et al. have analyzed the performance of SRM drive with PWM Controller. In this paper also the performance comparison of PWM Current Control with the Hysteresis Current Control, both through simulation and by experimental results are executed. Both simulation and experimental results have indicated that the PWM Current Controller has the following advantages: a) constant switching frequency b) low audible noise c) small current ripple and d) smooth torque production. It has been shown that the experimental results are in agreement with the simulation results [7, 8].

Baiming Shao et al. have explained the fundamentals of the PWM Control for SRM [9]. This paper presents the DSP based speed control of Asymmetrical converter fed SRM drive using PWM Control.

II. PWM Control

In PWM Current Control both the switches are turned on simultaneously at high frequency. During the conduction angle, the average voltage is applied to the phase winding. The voltage is DV_{DC}, where D is the duty ratio and V_{DC} is the input voltage to the converter. The Fig. 1 shows the block diagram of PWM Current Control. The actual speed is compared with reference speed and error is given to a PI controller which outputs current reference. The inputs to the PWM control are reference current, actual current, turn-on angle (θ_{on}) and turn-off angle (θ_{off}). The output of the controller gives signals to the Asymmetrical converter. The Asymmetrical converter shown in Fig. 2 feeds the drive. When both the switches in a phase are turned ON, the state is defined as 'magnetizing' state. When one switch is turned ON and other is turned OFF, the state is defined as 'freewheeling' state. When both the switches are turned OFF, the state is defined as 'demagnetizing' state.

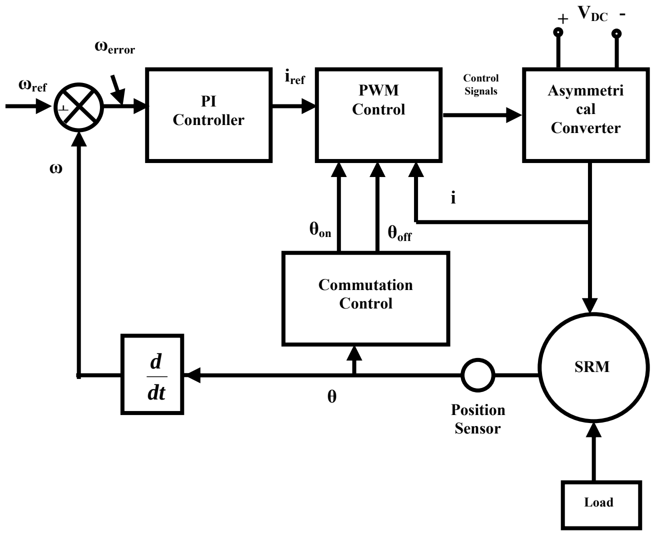

Fig. 1. Block diagram of PWM Current Control

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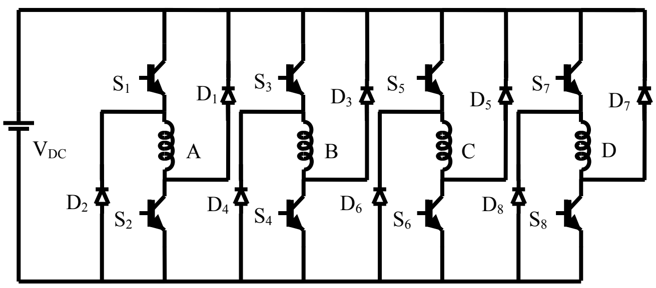

Fig. 2. Asymmetrical Converter

III. Simulation of PWM Controlled SRM Drive

The performance of the PWM controlled SRM drive is analyzed through simulation. The simulation is performed at 2000 rpm & 4000 rpm for three different load torques i.e at no load, 0.5 Nm and 0.75 Nm. The specifications of SRM are given in Appendix A. In this simulation, the MATLAB inbuilt 8/6 SRM model is used. The actual hardware specifications are used in the attributes of the model. Fig. 3 shows the simulation diagram of SRM drive with PWM control. The diagram consists of SRM model, Position sensor, Asymmetrical converter PWM controller and Pulse generator. The switching frequency of the IGBTs is maintained at 15 kHz for all loads.

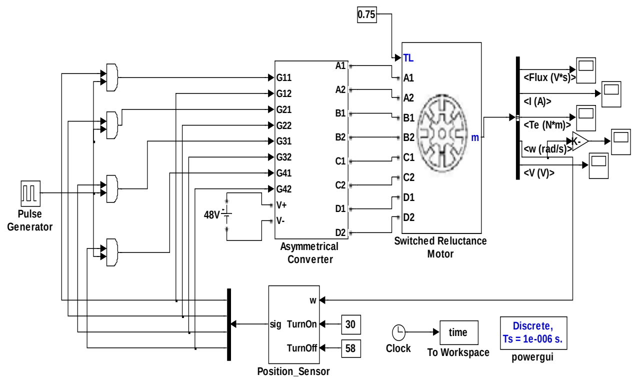

Fig. 3. Simulation diagram of SRM drive with PWM control

The simulation waveforms of the PWM controlled SRM drive at a speed of 4000 rpm for a load torque of 0.75 Nm are shown in Fig. 4. Here, N is the speed of the motor and T_L is the load torque. PWM gate signals applied to IGBTs S_1 to S_4 and S_5 to S_8 are shown in Fig. 4 (a) and Fig. 4 (b) respectively. As seen the top switch is turned on continuously and the bottom switch is turned-on and turned-off at the switching frequency. The sensor signals are shown in Fig. 4 (c). The motor current in four phases is shown in Fig. 4 (d). The peak current and average current in each phase are 21.65 A and 6.89 A respectively. Motor voltages in four phases are shown in Fig. 4 (e). The speed response is shown in Fig. 4 (f).

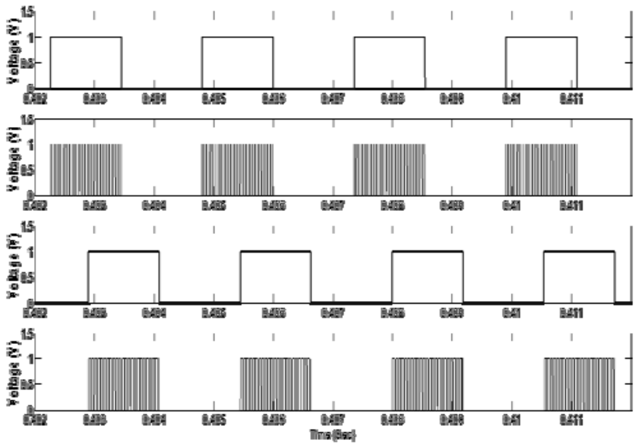

Fig. 4 (a). PWM gate signals to IGBTs (S_1 to S_4) at N = 4000 rpm, T_L= 0.75 Nm

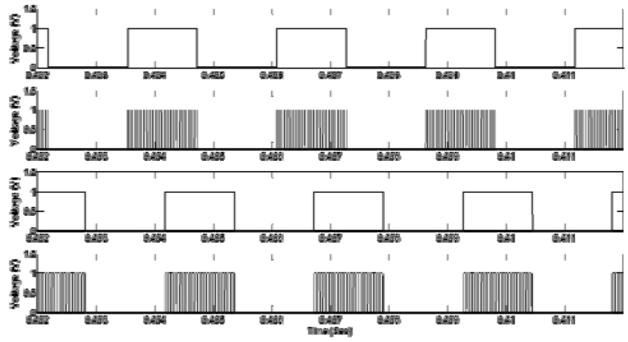

Fig. 4 (b). PWM gate signals to IGBTs (S_5 to S_8) at N = 4000 rpm, T_L= 0.75 Nm

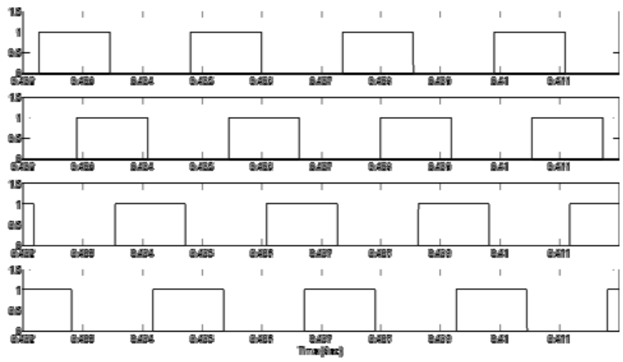

Fig. 4 (c). Sensor signals at N = 4000 rpm, T_L= 0.75 Nm

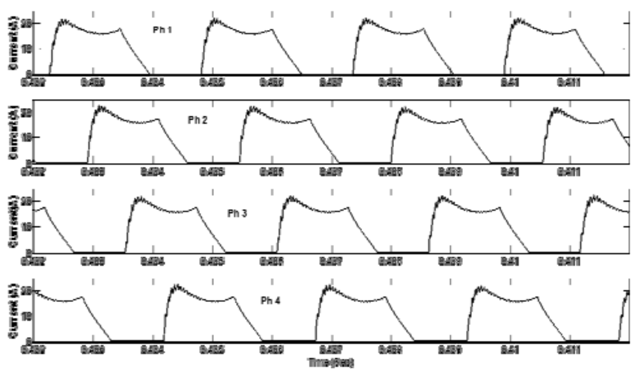

Fig. 4 (d). Current waveforms of four phases at N = 4000 rpm, T_L= 0.75 Nm

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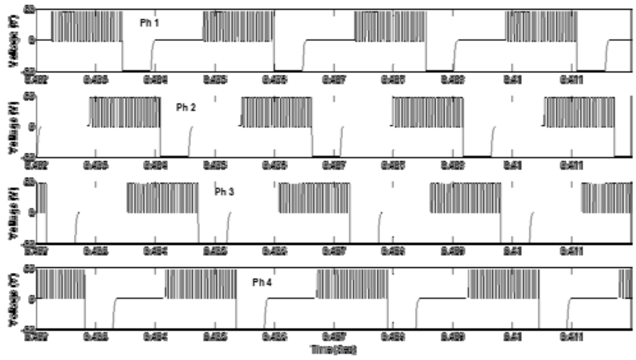

Fig. 4 (e) Voltage waveforms of four phases at N = 4000 rpm, T_L= 0.75 Nm

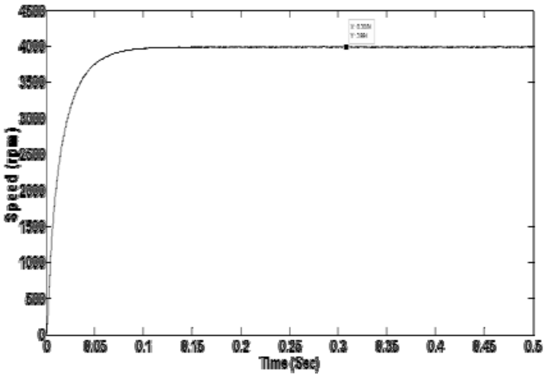

Fig. 4 (f) Speed response at N = 4000 rpm, T_L= 0.75 Nm

IV. Block Diagram of Hardware Setup

The block diagram of hardware setup is shown in Fig. 5. The whole setup consists of following important units viz. IGBT Intelligent Power Module (IPM), TMS320F2407A DSP Controller, Switched Reluctance Motor with Eddy current loading and Hall Sensors. IPM contains Bridge rectifier, Asymmetrical converter, Opto-coupler, Current sensors and Signal conditioner.

The IPM consists of a single phase Bridge rectifier, IGBT Asymmetrical converter, Opto-coupler, Current sensors, Signal conditioner and protective devices. The IPM is rated for 25 A, 1200 V. The Rectifier & Filter block outputs the filtered DC voltage to the converter. The converter excites the SRM phases in the required sequence to rotate the motor. The Hall Effect Current sensors sense the output currents of the converter and gives signals to the signal conditioner block.

The heart of the closed loop control scheme is the DSP controller. The inputs to the DSP are provided through 26 pin connector. The analog inputs to the DSP are conditioned phase current signals and the digital inputs are Hall sensor position signals of the SRM.

The DSP controller processes these inputs and gives the corresponding outputs to the Asymmetrical converter through an opto-coupler. The outputs of the DSP are eight PWM signals. These signals are fed to various IGBTs through high speed opto-isolators. The main function of the opto-isolator is to isolate the PWM signals from the main power circuit of the IGBT converter. The actual switching of the IGBTs is therefore controlled by the DSP controller by means of the PWM signals. The necessary software for operating the DSP controller is stored in PC. A 100 MHz, 4 Channel, 1 GS/s Sampling rate Digital Storage Oscilloscope with standard accessories and software is used for capturing the eight PWM waveforms. A Power Analyzer is used to measure, capture and analyze the voltage and current waveforms of the motor.

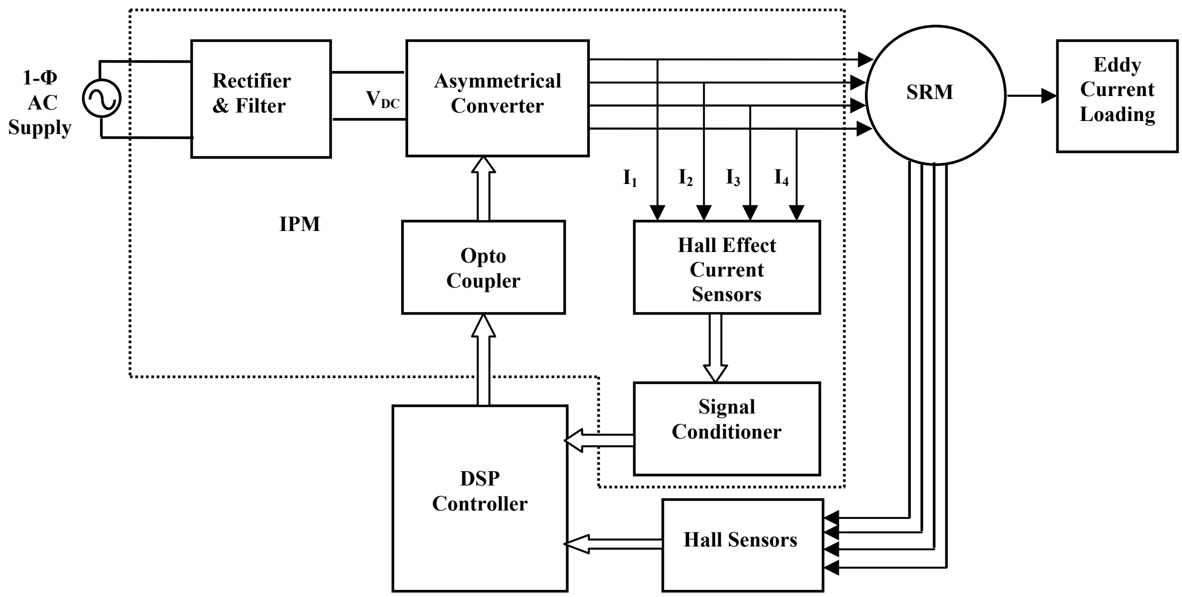

Fig. 5. Block Schematic Diagram of Control Scheme (with Asymmetrical Converter)

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V. Software Implementation

An assembly language program is used to operate the SRM in closed loop mode. The program generates PWM signals which are applied to the IGBTs of the Asymmetrical converter for current commutation. The motor is protected against over/under voltage, over current and rise in temperature. The reference speed is given as an input via an external potentiometer which is interfaced to the inbuilt Analog to Digital Converter (ADC) of the DSP. The program at start features the following tasks:

1) Initialization of all registers of DSP and resetting watchdog
2) Configuring the MUX control register, ADC, timer control registers in the Event Manager
3) Initialization of all the variables
4) Enabling of timer interrupts and watchdog
5) Hall sensor encoder is set at 0000
6) Low duty cycle of PWMs for soft start action of motor

The direction of rotation and the reference speed can be set. Depending on the set value, the appropriate lookup table is invoked. After the soft start action, the duty cycle of PWM signals are varied by the program to achieve the required speed. In closed loop control mode, the ADC of the DSP is configured to capture reference and feedback signals. The actual speed, calculated using position signals is compared with the reference speed and error signal is given to the PI algorithm. The PI controller gives the required duty ratio. Thus, the duty cycle of the switches are varied to maintain the speed of the motor equal to the reference speed [10, 11].

VI. Hardware Implementation of PWM Controlled SRM Drive

In order to verify the simulation results, experiments have been performed at same speeds and load torques on the SRM whose specifications are given in Appendix A. The PWM signals applied to IGBTs, Hall sensor output signal are captured by Digital Storage Oscilloscope. The waveforms of the phase currents, phase voltages and various associated numerical values are measured, captured and analyzed by Power Analyzer. The practical waveforms are shown for 4000 rpm at 0.75 Nm load torque. The load is applied by means of Eddy current loading.

The practical waveforms of the PWM controlled SRM drive at 4000 rpm & T_L = 0.75 Nm are shown in Fig. 6. PWM gate signals applied to IGBTs S_1 to S_4, and S_5 to S_8 are shown in Fig. 6 (a) and Fig. 6 (b) respectively. As seen the top switch is kept on continuously and the bottom switch is turned on and off at the switching frequency. The expanded view of PWM signals applied to IGBT S_2 is shown in Fig. 6 (c). The switching frequency is 14.71 kHz. The sensor signals are shown in Fig. 6 (d). The motor current in four phases is shown in Fig. 6 (e). The peak current and average current in each phase are 22.72 A and 7.14 A respectively. A motor voltage in four phases is shown in Fig. 6 (f). The expanded view of current and voltage of one phase is shown in Fig. 6 (g). The Numerical values are shown in Fig. 6 (h).

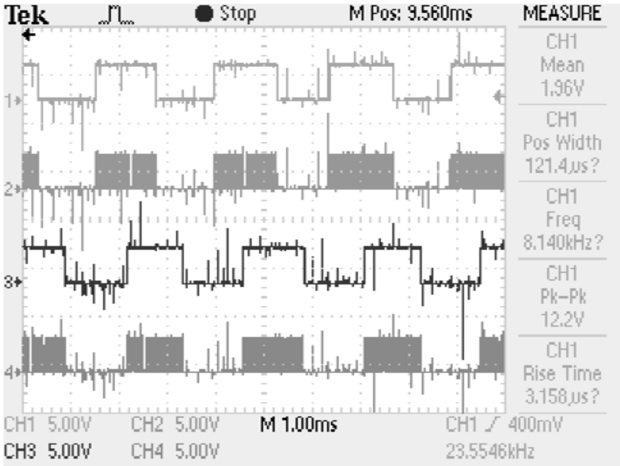

Fig. 6 (a) PWM gate signals to IGBTs (S_1 to S_4) at N = 4000 rpm & T_L= 0.75 Nm

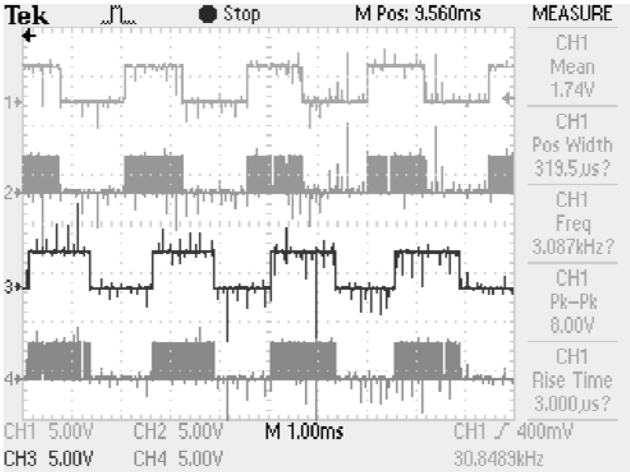

Fig. 6 (b). PWM gate signals to IGBTs (S_5 to S_8) at N = 4000 rpm & T_L= 0.75 Nm

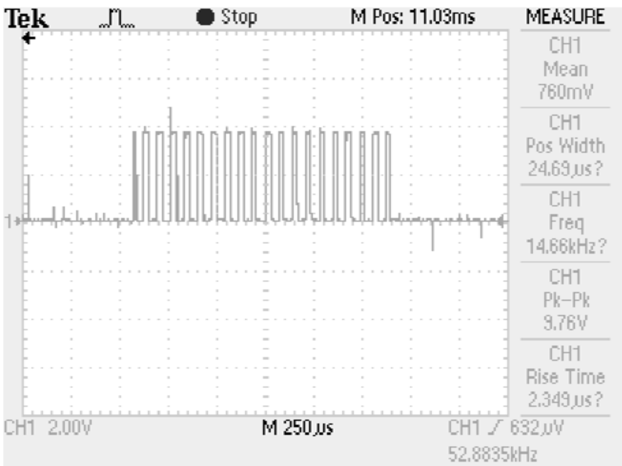

Fig. 6 (c). PWM gate signals to IGBTs S_2 at N = 4000 rpm & T_L= 0.75 Nm

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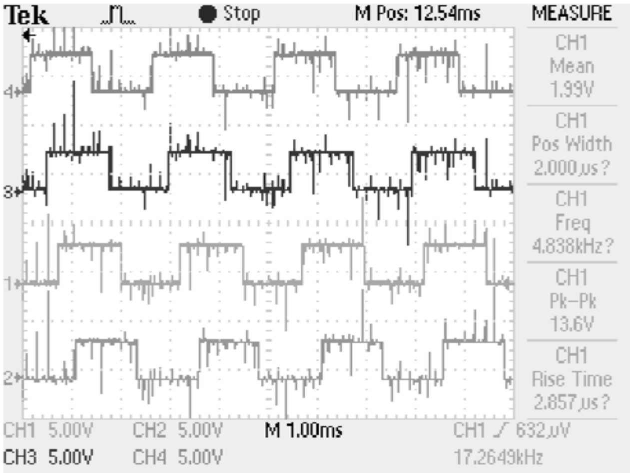


Fig. 6 (d) Hall Sensor signals N = 4000 rpm & T_L= 0.75 Nm

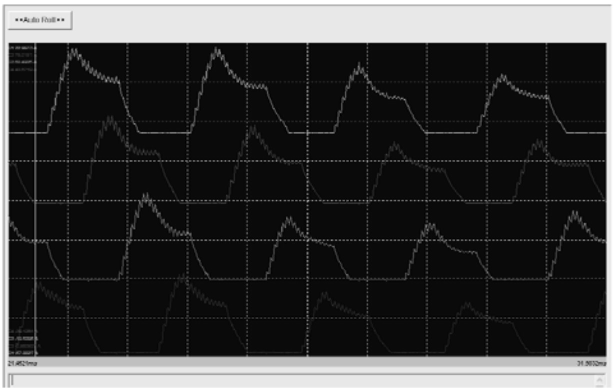


Fig. 6 (e) Currents of four phases at N = 4000 rpm & T_L= 0.75 Nm

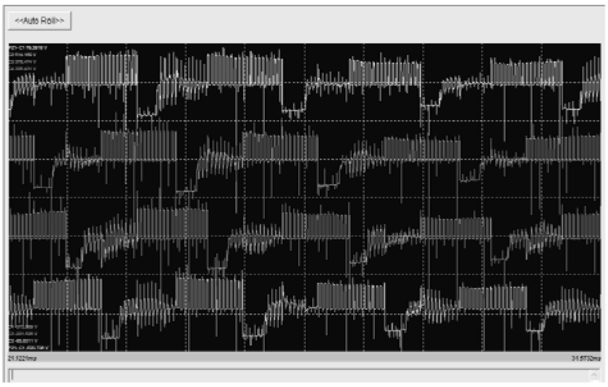


Fig. 6 (f). Voltages of four phases at N = 4000 rpm & T_L= 0.75 Nm

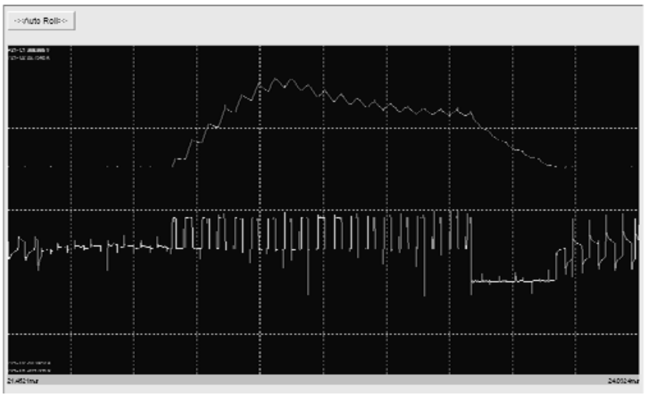
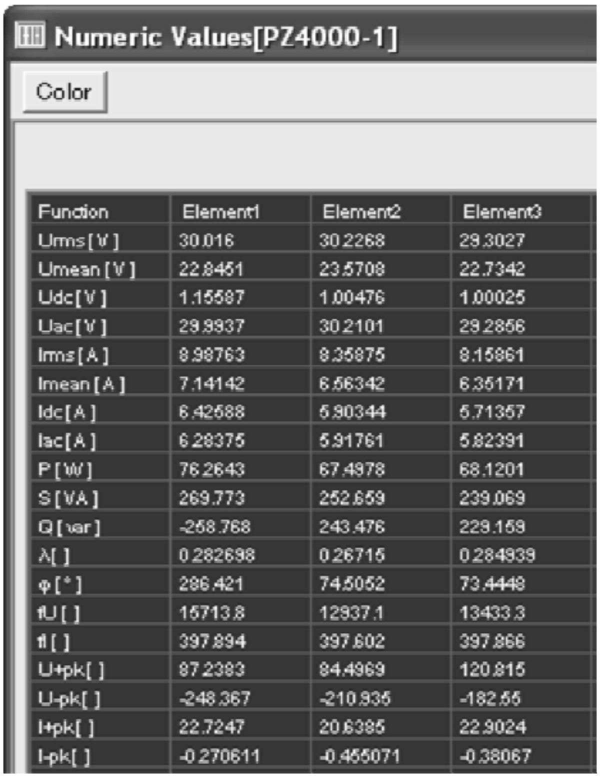


Fig. 6 (g). Current and voltage of one phase at N = 4000 rpm & T_L= 0.75 Nm



Numeric Values[PZ4000-1]

Color

Function	Element1	Element2	Element3
Urms[V]	30.016	30.2268	29.3027
Umean[V]	22.8451	23.5708	22.7342
Udc[V]	1.15587	1.00476	1.00025
Uac[V]	29.9937	30.2101	29.2856
Irms[A]	8.98763	8.35875	8.15861
Imean[A]	7.14142	6.56342	6.35171
Idc[A]	6.42688	5.90344	5.71357
Iac[A]	6.28375	5.91761	5.82391
P[W]	76.2643	67.4978	68.1201
S[VA]	269.773	252.659	239.069
Q[var]	-258.768	243.476	229.159
λ[]	0.282698	0.26715	0.284939
φ[°]	286.421	74.5052	73.4448
fU[]	15713.8	12937.1	13433.3
fI[]	397.894	397.602	397.866
U+pk[]	87.2383	84.4969	120.815
U-pk[]	-248.367	-210.935	-182.55
I+pk[]	22.7247	20.6385	22.9024
I-pk[]	-0.270611	-0.455071	-0.38067

Fig. 6 (h). Numerical values at N = 4000 rpm & T_L= 0.75 Nm

The peak current, average current, peak voltage and average voltage are obtained through simulation and experiments for 2000 rpm and 4000 rpm at three different load torques is tabulated in Table I. It is clear that the simulation results are in close agreement with experimental results at different speeds and load torques.

TABLE I

COMPARISON OF SIMULATION AND EXPERIMENTAL RESULTS WITH ASYMMETRICAL CONVERTER FED SRM DRIVE

Simulation						
Load (Nm)	**Speed (rpm)**	**%Duty Ratio**	**Peak Current (A)**	**Average Current (A)**	**Peak Voltage (V)**	**Average Voltage (V)**
0.75	4001	52.12	21.65	6.89	48	25.43
0.50	4002	41.23	18.08	5.69	48	24.20
No load	4002	27.57	4.83	1.32	48	10.00
0.75	2001	36.66	20.09	6.13	48	24.98
0.50	2001	26.98	17.98	5.88	48	24.18
No load	2001	24.89	4.96	1.38	48	10.00
Experiment						
Load (Nm)	**Speed (rpm)**	**%Duty Ratio**	**Peak Current (A)**	**Average Current (A)**	**Peak Voltage (V)**	**Average Voltage (V)**
0.75	4005	50.12	22.72	7.14	48	25.14
0.50	4005	40.75	17.83	5.57	48	24.60
No load	4006	26.56	4.95	1.44	48	9.80
0.75	2003	36.02	20.49	6.41	48	24.78
0.50	2003	26.12	17.07	5.45	48	24.03
No load	2004	24.12	5.19	1.53	48	9.80

VII. CONCLUSIONS

The performance of PWM controlled Asymmetrical converter fed SRM drive is analyzed through simulation and by hardware experimentation. The gating signals with required duty ratios are fed to the IGBTs through DSP controller to maintain speed at the reference value. The switching frequency is maintained at 15 kHz. The switching frequency obtained in experiment is 14.71 kHz. The controller is tested at 2000 rpm and 4000 rpm for three different load torques. It is observed that the peak current, average current, peak voltage and average voltage obtained through simulation and experiments are in close agreement. The duty ratios are almost same in simulation and experiment.

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Appendix-A

Specifications of SRM for Simulation and Hardware Implementation

Power : 1 HP
Voltage : 48 V DC
Current : 10 A
Speed : 6000 rpm
Aligned Inductance : 4.85 mH
Unaligned Inductance : 0.345 mH
Resistance : 0.3 Ω

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