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DSP based Speed Control of 4 phase 8 / 6 Switched Reluctance Motor Drive using DC Split Converter

This paper presents the speed control of 4 phase 8/6 Switched Reluctance Motor drive using Digital Signal Processor. The motor is fed from a DC split converter. The Hall sensors provided in the motor provide signals corresponding to the position of the rotor and the speed is controlled by varying the duty ratio of the PWM controller. The system has been tested and implemented in the laboratory from no-load to full-load for both open- loop and closed- loop operations. The actual current and voltage waveforms are captured by Power Analyzer.

Keywords: Switched Reluctance Motor, Digital Signal Processor, DC split Converter

1. INTRODUCTION

The industrial applications of Switched Reluctance Motor (SRM) are becoming increasingly popular because of its advantages like high speed, robustness, high reliability, low cost and high rotor temperature handling capability. The phase winding of the SRM is excited during the positive increasing region of the phase inductance to get the motoring action. This is done through a converter. The popularly used asymmetrical converter has the advantages of both hard chopping and soft chopping [1, 2]. The disadvantage of the asymmetrical converter is that it requires two switches in a phase. Two switches per phase can be eliminated by DC split converter [3]. But the disadvantage is that the soft chopping is not possible with this type of converter.

The control strategies of SRM are mainly the Hysteresis Current Control, PWM Control and the Single Pulse Voltage Control. Hysteresis Current Control and PWM Control are used for low and medium speed operations. The Single Pulse Voltage Control controls the speed and torque by regulating the turn-on and turn-off angles. This is suitable for high speed operation, but not to low speed operation because of high current peaks [4-6]. The speed control of asymmetrical converter fed 4 phase SRM using DSP is investigated experimentally in [7].

This paper presents the speed control of 4 phase 8/6 SRM using DSP TMS320F2407A. The converter is fed through a DC split converter. The speed is regulated through a PWM controller [8, 9] in which, the average phase voltage during the conduction period is controlled by varying the duty ratio of the switches.

2. MODELING OF SRM

The instantaneous voltage across single phase of the SRM winding is given by

$$v = Ri + \frac{d\psi(\theta,i)}{dt} \tag{1}$$

where $\psi(\theta,i)$ is the flux-linkages which is a function of rotor position θ and current i

Thus equation (1) can be expanded as

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$$v = Ri + \frac{\partial\psi(\theta,i)}{\partial t}\frac{di}{dt} + \frac{\partial\psi(\theta,i)}{\partial\theta}\frac{d\theta}{dt} \tag{2}$$

Multiplying both sides of equation (1) with *i*, gives an expression for instantaneous power in SRM motor as

$$vi = Ri^2 + i\frac{d\psi(\theta,i)}{dt} \tag{3}$$

$$i\frac{d\psi(\theta,i)}{dt} = \frac{dW_m}{dt} + \frac{dW_f}{dt} \tag{4}$$

where W_m , W_f are mechanical energy and magnetic field energy respectively.

The mechanical power can be written as product of torque and speed and is given by

$$\frac{dW_m}{dt} = T\omega = T\frac{d\theta}{dt} \tag{5}$$

Where T is the torque in Nm and ω is the speed in rad/sec
Substitution of equation (5) into equation (4) gives

$$i\frac{d\psi(\theta,i)}{dt} = T\frac{d\theta}{dt} + \frac{dW_f}{dt} \tag{6}$$

Rearranging the equation (6) for torque gives

$$T(\theta,\psi) = i(\theta,\psi)\frac{d\psi(\theta,i)}{d\theta} - \frac{dW_f(\theta,\psi)}{d\theta} \tag{7}$$

For constant flux the equation (7) simplifies to

$$T = -\frac{\partial W_f}{\partial\theta} \tag{8}$$

It is often desirable to express torque in terms of current rather than flux, it is common to express torque in terms of co-energy, *Wc*

$$T = \frac{\partial W_c}{\partial\theta}$$

3. DC SPLIT CONVERTER

The phase winding is excited through DC split converter. The DC link voltage is split with capacitors. A disadvantage is that soft chopping is not possible and balance must be carefully maintained between the phases, but the circuit successfully achieves the minimum of one transistor per phase without adding extraneous passive components or sacrificing control flexibility or efficiency.

The four phase DC split converter is shown in Figure. 1(a). When T_1 is turned on, current flows through T_1 and phase A. When C_2 charges, C_1 gets discharged. This is called mode 1 and shown in Figure. 1(b). When T_1 is turned off, the current in phase A flows through C_2 and D_2. The capacitor C_2 is charged again and voltage across C_2 (V_{c2}) increases further. This is called mode 2 and is shown in Figure. 1(c). A similar procedure occurs when phases B, C and D are excited. During the normal operation, the conducting phase shift between the upper leg and the lower leg and the capacitors are charged and discharged in turn. The operational waveforms of the converter are shown in Fig. 2.

5. BLOCK DIAGRAM OF THE DRIVE/ EXPERIMENTAL SETUP

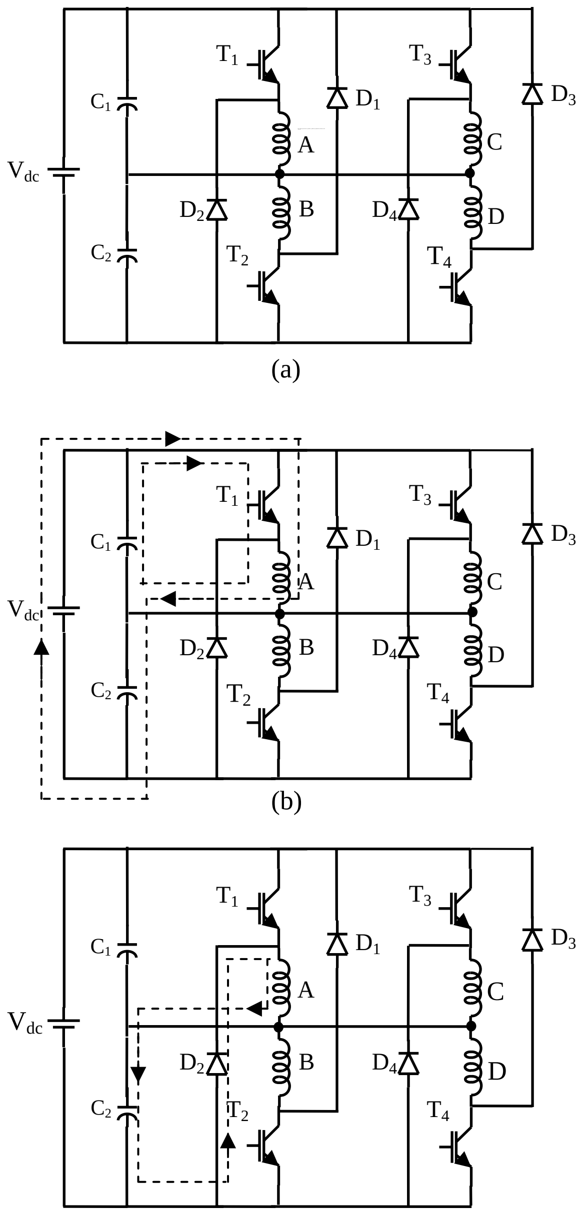
The whole setup consists of following important units viz TMS320F2407A DSP Controller, IGBT Intelligent Power Module (IPM), SRM, Signal Conditioner and Mechanical loading arrangement. The interconnections of these units are shown in the block schematic diagram of Figure. 3. The IPM consists of a single phase bridge rectifier with capacitors at the output. This rectifier provides the rectified DC voltage to the IGBT based DC spilt converter. The IPM is rated for 25A, 1200V. Hall Effect transducers are used to sense the dc link current, dc link voltage and the output currents of the converter. The heart of the closed loop control scheme is the DSP controller. The inputs to the DSP are provided through 26 pin connector. The various analog inputs to the DSP are dc link current I_{DC}, dc link voltage V_{DC}, the four phase currents of the DC split converter I_1, I_2, I_3 and I_4. These are given through signal conditioner block. The rotor position is sensed by Hall sensors and signals are given to the DSP.

6. SOFTWARE IMPLEMENTATION

An assembly language program was developed to operate the SRM in closed loop mode. The program generates PWM signals which are applied to the IGBTs of the converter. The motor is protected against over/under voltage, over current and rise in temperature by software. The reference speed is given as an input through 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: (a) Initialization of all registers of DSP and resetting watchdog (b) Configuring the MUX control register, ADC, timer control registers in the Event Manager (c) Initialization of all the variables (d) Enabling of timer interrupts and watchdog (e) Hall sensor encoder is set at 00 (f) Low duty cycle of PWMs for soft start action of motor. 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. After evaluating the error and amplifying it, the duty ratio of the PWM is varied to implement PWM control. The switching frequency of the converter is maintained at 20 kHz. The flow chart for open-loop and closed-loop operation is shown in Figure. 4.

7. RESULTS

The DSP controlled SRM drive was operated from no-load to full-load in open-loop and closed-loop modes. The open-loop and closed-loop performance of the drive is tested at three different speeds 500 rpm, 2000 rpm and 4000 rpm for different loading conditions. The variations of voltage, current, torque and efficiency on motor side are recorded at different loads using Power Analyzer. The open loop performance of the drive at three different speeds is tabulated in Table I, Table II and Table III. The closed-loop performance of the drive is also tested at the same speeds and is tabulated in Table IV, Table V and Table VI. Figure 5 shows the plot between speed and torque in open-loop and closed-loop operations. Specifications of the SRM are given in Appendix.



(c)
Figure 1: (a) DC Split Converter (b) Mode 1 (c) Mode 2

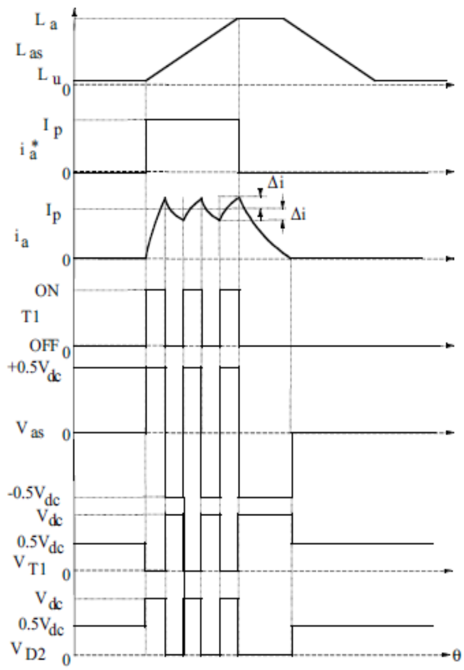


Figure 2: Operational waveforms of the converter

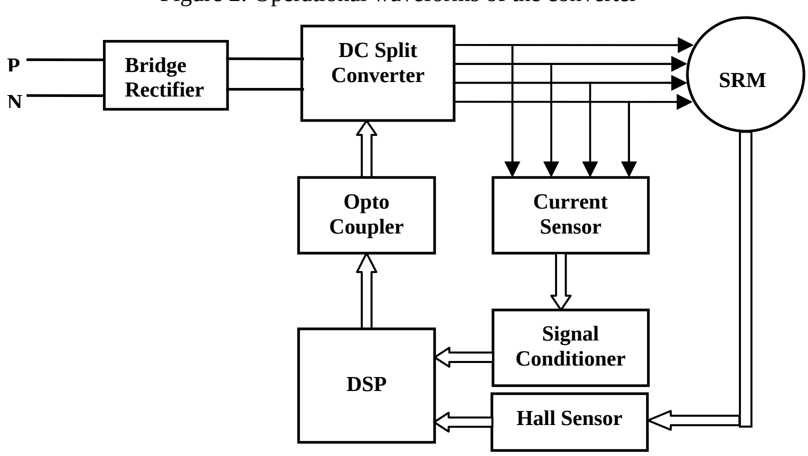


Figure 3: Block Diagram of Control Scheme

The voltage applied to the motor remains constant in open -loop condition, whereas it increases linearly in closed-loop condition in order to compensate the impedance drop and to maintain speed at constant value. In closed-loop operation there is no change in speed from no-load to full load, whereas, in open-loop operation the speed regulation is about 30%. Waveforms of the phase currents, voltage across the windings and numerical values captured by the Power analyzer when the drive is operating in closed loop running at rated load is shown in Figure 6 . When the drive is operating at rated load the speed is maintained at 4000 rpm. Enlarged view of the voltage and current in one phase in closed-loop when the motor is speed is maintained at 4002 rpm under load condition is shown in Figure. 7.

CONCLUSIONS

The DSP based speed control of 4 phase 8/6 SRM is analyzed. The performance of the drive is tested in open-loop and closed-loop conditions at different loads with DC split converter. The waveforms of the phase currents, phase voltages and various associated numerical values are captured by Power Analyzer. It is observed that the speed regulation in open-loop is 25% to 30% and it is almost zero in closed-loop condition at different loads.

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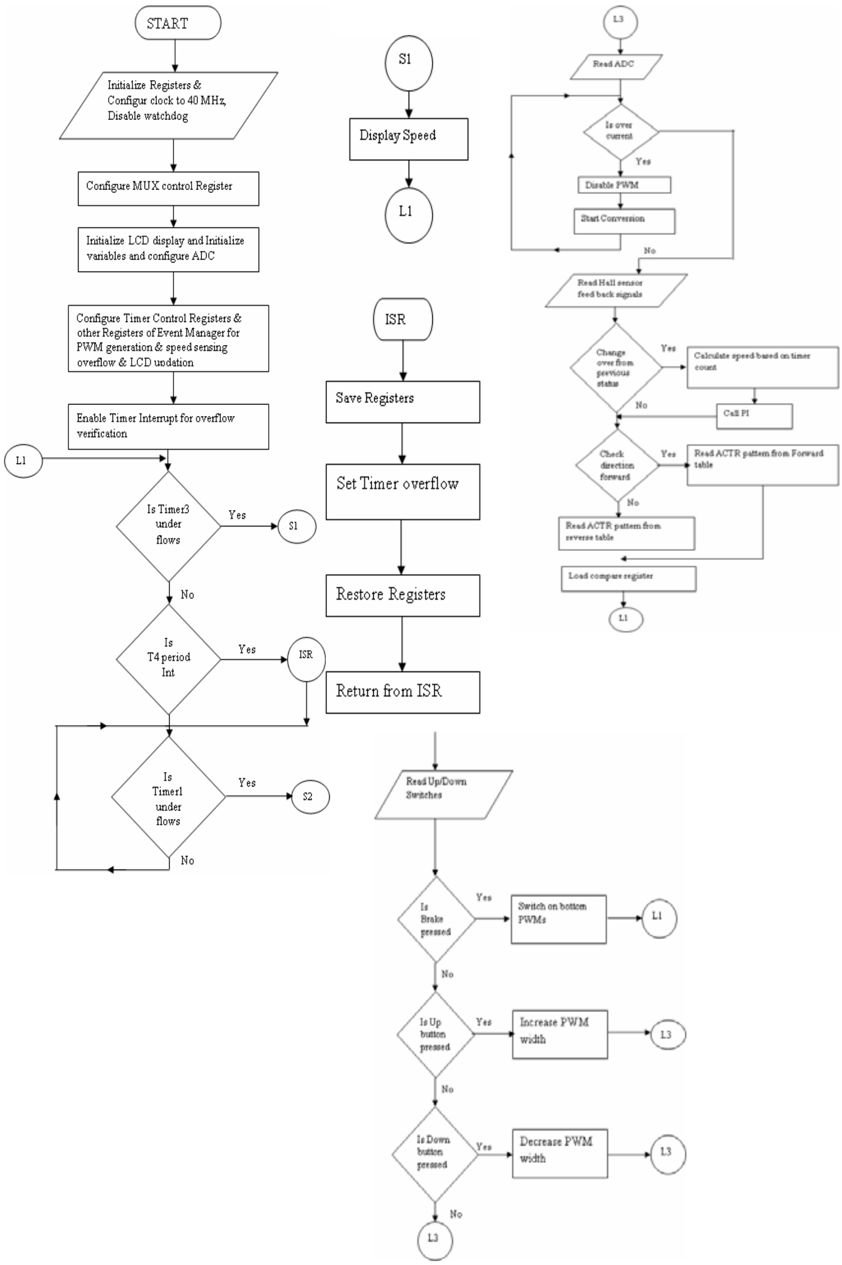


Figure 4: Flow chart of the open-loop and closed-loop operation of the drive

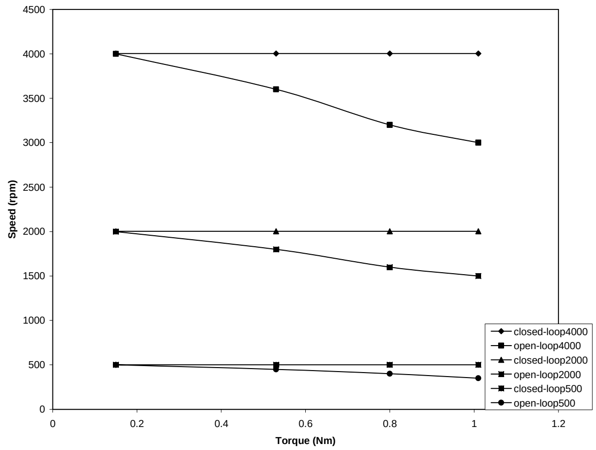


Figure 5: Variation of speed with torque in open-loop and closed loop conditions.

Appendix

SRM Specifications

Voltage: 48 V
Power: 1.1 HP
Torque: 1.2 Nm
Current: 10 A
Speed: 6000 rpm

Table. I : Performance of the drive under open-loop at 500 rpm

Sl.No.	V_{mean}(V)	V_{rms} (V)	I_{mean} (A)	I_{rms} (A)	T (Nm)	N (rpm)
1	22.78	26.32	1.32	1.70	0.15	500
2	22.60	25.41	4.97	6.21	0.53	450
3	23.12	25.55	7.51	9.32	0.80	400
4	23.04	24.82	8.51	10.52	1.01	350

Table. II : Performance of the drive under open-loop at 2000 rpm

Sl.No.	V_{mean}(V)	V_{rms} (V)	I_{mean} (A)	I_{rms} (A)	T (Nm)	N (rpm)
1	22.50	25.58	1.40	1.77	0.15	2000
2	24.53	27.00	5.42	6.64	0.53	1800
3	24.14	25.77	8.22	9.92	0.80	1600
4	24.28	25.72	9.56	11.52	1.01	1500

Table. III : Performance of the drive under open-loop at 4000 RPM

Sl.No.	V_{mean}(V)	V_{rms} (V)	I_{mean} (A)	I_{rms} (A)	T (Nm)	N (rpm)
1	23.35	26.36	1.48	1.85	0.15	4000
2	26.72	28.73	5.78	6.87	0.53	3600
3	26.93	28.31	8.64	10.04	0.80	3200
4	26.10	28.10	9.66	11.82	1.01	3000

Table. IV : Performance of the drive under closed-loop at 500 rpm

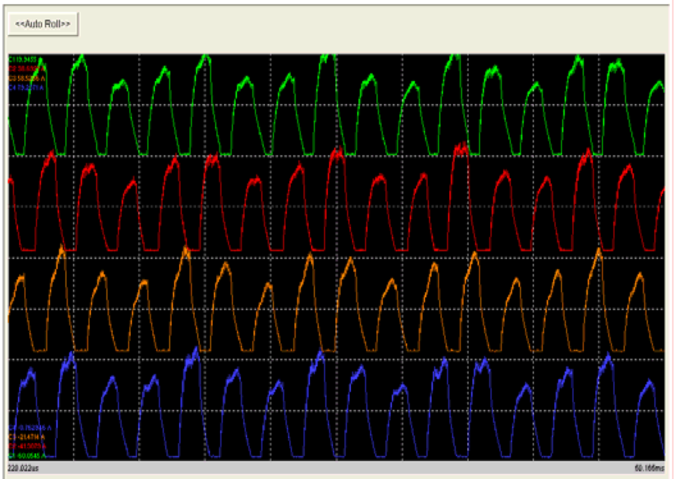
Sl.No.	V_{mean}(V)	V_{rms} (V)	I_{mean} (A)	I_{rms} (A)	T (Nm)	N (rpm)
1	23.22	26.90	1.42	1.78	0.15	502
2	21.85	25.34	5.13	6.38	0.53	502
3	20.91	23.34	8.03	9.99	0.80	502
4	20.79	23.36	8.69	10.70	1.01	502

Table. V : Performance of the drive under closed-loop at 2000 rpm

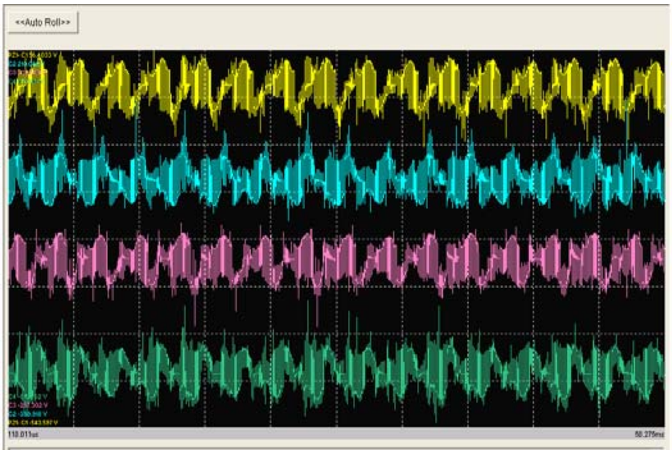
Sl.No.	V_{mean}(V)	V_{rms} (V)	I_{mean} (A)	I_{rms} (A)	T (Nm)	N (rpm)
1	21.79	25.46	1.51	1.93	0.15	2003
2	23.46	26.23	5.49	6.67	0.53	2003
3	22.81	24.69	8.62	9.10	0.80	2003
4	24.06	25.83	9.83	10.08	1.01	2003

Table. VI : Performance of the drive under closed-loop at 4000 rpm

Sl.No.	V_{mean}(V)	V_{rms} (V)	I_{mean} (A)	I_{rms} (A)	T (Nm)	N (rpm)
1	22.44	26.01	1.65	2.06	0.15	4002
2	26.29	28.19	6.14	7.08	0.53	4002
3	26.11	27.40	9,39	10.65	0.80	4002
4	25.50	26.55	9.76	11.09	1.01	4002



(a)



(b

Numeric Values[PZ4000-1]

Color

Function	Element1	Element2	Element3	Element4	Sigma A	Sigma B
Urms [V]	26.559	26.0995	26.0947	26.4041	26.559	26.0971
Umean [V]	25.5012	24.5767	24.341	24.7731	25.5012	24.4589
Udc [V]	2.24752	-1.47378	2.03249	-1.61466	2.24752	0.279357
Uac [V]	26.4637	26.0579	26.0154	26.3547	26.4637	26.0366
Irms [A]	11.097	10.2709	9.64168	10.7113	11.097	9.9563
Imean [A]	9.75612	8.57062	7.99823	9.14386	9.75612	8.28443
Idc [A]	8.78044	7.71196	7.19623	8.2291	8.78044	7.45409
Iac [A]	6.7858	6.78362	6.41688	6.85661	6.7858	6.60025
P [W]	102.379	-99.6976	88.7711	-94.697	102.379	-10.9265
S [VA]	294.725	268.066	251.596	282.821	294.725	519.663
Q [var]	276.372	248.837	-235.416	266.497	276.372	13.4214
ƒÉ [ ]	0.347372	-0.371914	0.352831	-0.33483	0.347372	-0.0210261
ƒÓ [□‹]	69.6733	111.834	290.661	109.562	69.6733	91.2048
fU [ ]	7707.32	9360.86	7928.25	8679.03	---------	---------
fI [ ]	318.766	318.832	318.943	329.622	---------	---------
U+pk [ ]	56.8882	151.281	66.0946	105.025	---------	---------
U-pk [ ]	-121.899	-71.1939	-98.7384	-75.5276	---------	---------
I+pk [ ]	21.8842	20.7072	21.2891	21.6329	---------	---------
I-pk [ ]	-0.279344	-0.337644	-0.346485	-0.332099	---------	---------
CfU [ ]	4.58974	5.79631	3.78385	3.9776	---------	---------
CfI [ ]	1.97209	2.0161	2.20803	2.01964	---------	---------
FfU [ ]	1.1568	1.17954	1.19074	1.18385	---------	---------
FfI [ ]	1.26338	1.33107	1.33895	1.30112	---------	---------
Z [ƒ¶]	2.39335	2.54111	2.70644	2.46508	2.39335	5.24234
Rs [ƒ¶]	0.831383	-0.945075	0.954918	-0.825382	0.831383	-0.110226
Xs [ƒ¶]	2.24431	2.35883	-2.53238	2.32279	2.24431	0.135395
Rp [ƒ¶]	6.88988	-6.83251	7.67064	-7.36219	6.88988	-62.331
Xp [ƒ¶]	2.55229	2.73748	-2.89247	2.61608	2.55229	50.7443
Pc [W]	98.2203	-93.7113	82.6055	-88.6673	98.2203	-11.1058
ƒÅ [%]	-10.6726	-10.6726	-10.6726	-10.6726	-10.6726	---------
1/ƒÅ [%]	-0.0936982	-0.0936982	-0.0936982	-0.0936982	-0.0936982	---------

Figure 6: Performance of the drive in closed-loop at 4000 rpm under load condition (a) Current in four phases (b) Voltage across four phase windings (c) Numerical Values

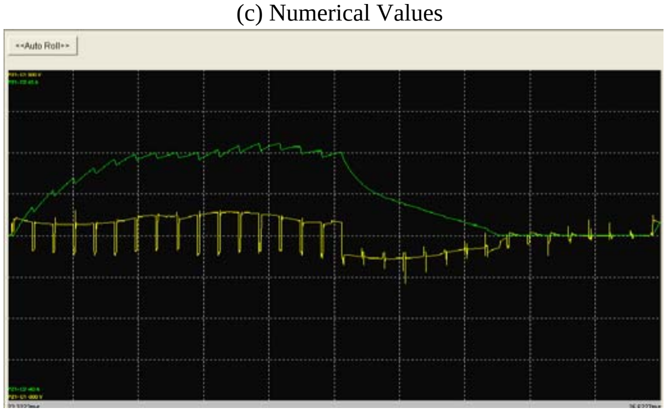


Figure 7: Enlarged view of the voltage and current in one phase in closed loop at 4000 rpm under load condition.