A Digital PWM Control for Switched Reluctance Motor Drives

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***Abstract*—Switched reluctance motor (SRM) drives are highly non-linear. Therefore, their control over a wide speed range has unique difficulties. Conventional linear controllers are not ideal for SRMs. In this paper, a novel digital PWM control for SRM drives is presented. By treating the system digitally, the controller switches between two different duty ratios to get the desired speed. The proposed control technique is very easy to implement and has a wide speed range. Simulation and experimental results are presented to verify the proposed digital control approach.**

***Keywords*—Control, digital control, modeling, motor drives, power electronic converters, pulse-width modulation, switched reluctance machine.**

I. Introduction

Switched reluctance machines (SRMs) are attractive because of their manufacturing simplicity and high reliability. They do not have any windings or permanent magnets on the rotor which makes them very robust and easy to maintenance. On the other hand, SRMs are highly non-linear since they work in saturation. This causes problems such as high torque ripple and system noise [1], [2]. In addition, mutual inductance also needs to be considered for the high performance systems such as electric vehicles or aerospace applications. This effect could become critical when more than one phase is conducting [3]. This also makes them difficult for modeling and control [4]. Significant research on different control techniques has been done in order to improve the performance of the controller and present a good solution for the industrial applications with a reasonable cost [5]-[20]. Because of the complexity of the control, motor drivers could use digital systems by applying high-speed digital signal processors (DSP) or microcontrollers to the system in order to get better results.

However, it is not a truly digital system as long as the SRM drive is treated as an analog system with continues input. In this paper, a novel truly digital control technique based on the voltage PWM theory is presented. Unlike the regular PWM controller, the duty ratio will only assume two specific values, which are called high and low states. One of them could increase the speed of the machine, while the other one decreases it. By switching between these two states, the desired speed could be achieved easily. There are several advantages by applying this controller. First of all, for the PWM control, instead of putting current sensors on all phases, only one is needed on the DC link for the over-current protection. In addition, only simple logic chips are needed to implement this controller. Comparing with DSPs or microcontrollers, these chips are less sensitive to the noise and much cheaper. Furthermore, if a DSP or microcontroller has to be used in some applications, only two IF-THEN statements are needed in the program.

This paper is organized as the following. Fundamentals of the PWM control for SRM drives are introduced in Section II. The proposed digital PWM control technique is presented in Section III. Section IV includes the simulation and experimental results and Section V presents the conclusion.

II. Principles of PWM Control for SRM

Conventional control techniques for SRM drives include angular position control (APC), chopped current control (CCC), and pulse-width modulation (PWM). APC mode is only used when SRM is operating at a high speed or above its base speed, when conduction angle is the only control parameter. CCC and PWM are used for the low and medium speeds. In CCC mode, conduction angle is usually fixed and current on each phase of the SRM is limited in a small band. This technique has an inherent over-current protection feature. But, it is more complex than the PWM control. PWM control, on the other hand, is easier to implement. Although it cannot control the current directly, it has the advantage that only needs one current sensor in the DC link for the over-current protection.

Fig. 1a shows the conventional drive circuit for one SRM phase. There are three different conduction modes, which are called phase excitation, phase deflux (hard chopping), and phase deflux (soft chopping). In phase excitation mode, both

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S1 and S2 are turned on and current is injected to the phase winding. In the phase deflux mode, two switches could either be both turned off or keep one closed. These two modes are called hard chopping and soft chopping, respectively. In hard chopping mode, there is a negative voltage applied to the winding and energy stored in the phase inductance will go back to the DC link. Furthermore, the system is noisier since there are two switches working and phase current will drop rapidly.

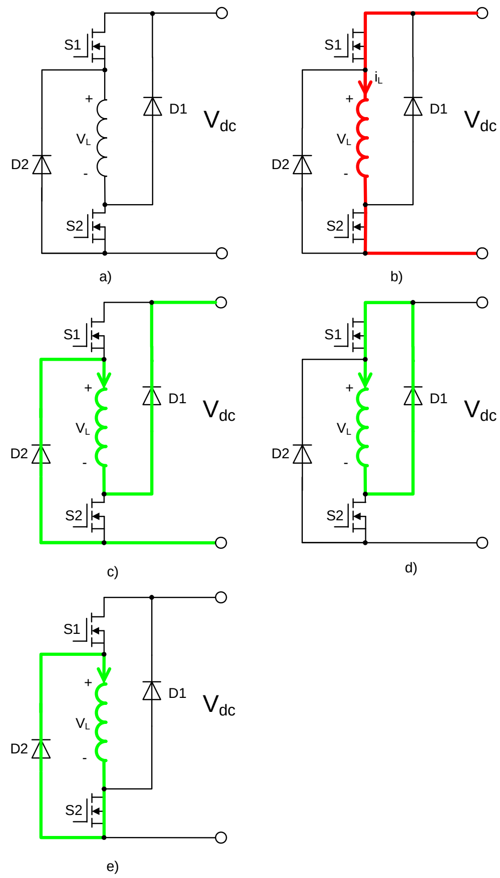


Fig. 1. Operating principle of conventional SRM drive circuit with PWM control: a) one phase drive circuit, b) phase excitation, c) phase deflux, hard chopping, d) phase deflux using upper switch, soft chopping, e) phase deflux using lower switch, soft chopping.

In soft chopping mode, zero voltage is applied to the phase winding. Energy flows inside the phase and current drops slowly during the deflux. [21] shows that the DC link voltage ripple is smaller in soft chopping mode compared with the hard chopping and it also decreases the current ripple. Thus, soft chopping is preferred during the conducting of the phase. It should also be noted that, when a certain phase stops conducting, the current on this phase should go to zero as quickly as possible in order to avoid the negative torque and both switches should be turned off at that time. Fig. 2 shows the current and phase voltage waveforms using the soft chopping method.

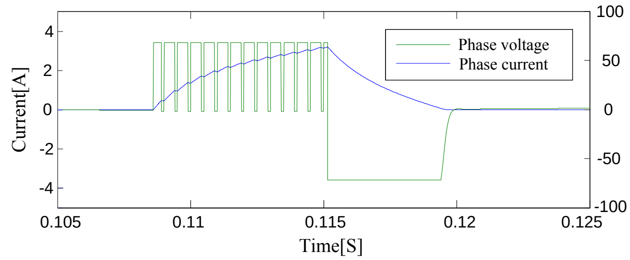


Fig. 2. Current and phase voltage waveforms in soft chopping mode.

Assuming phase current is continuous during each conduction period, in each PWM duty cycle, phase voltage is defined as:

$$V = \frac{DT_{pwm}V_{dc} + (1-D)T_{pwm}(0)}{T_{pwm}} = DV_{dc} \tag{1}$$

where V_{dc} is the DC link voltage, D is the PWM duty ratio, and T_{pwm} is the PWM period. The average phase voltage of each conduction period is:

$$V_{ave} = \frac{\sum_{i=1}^{n} D_i T_{pwmi} V_{dc}}{\sum_{i=1}^{n} T_{pwmi}} \tag{2}$$

where n is the PWM period number of each conduction time; D_i and T_{pwmi} present the duty ratio and period of each PWM cycle, respectively. For SRM, average phase terminal voltage could also be expressed as follows:

$$V_{ave} = iR + L\frac{di}{dt} + i\omega\frac{dL}{d\theta} \tag{3}$$

where i is the phase current, L is the phase inductance, R is the phase resistance, ω is the motor speed, and θ is the rotor position. The output toque is defined as:

$$T = \sum_{i=1}^{n} \frac{\partial W}{\partial \theta} \tag{4}$$

where n is the number of phases and W is the co-energy, which could be calculated from:

$$W = \frac{1}{2} i^2 L \tag{5}$$

From (4) and (5), the torque is given by:

$$T = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta} \tag{6}$$

With (2) and (6), (3) could be rewritten as:

$$\frac{\sum_{i=1}^{n} D_i T_{pwmi} V_{dc}}{\sum_{i=1}^{n} T_{pwmi}} i = i^2 R + \frac{d}{dt}\left(\frac{1}{2} L i^2\right) + T\omega \tag{7}$$

It is clear that, by changing the duty ratio, output torque and motor speed could be controlled.

III. Digital PWM Control for SRM

From [17], the conventional PWM control system using PI controller could be modeled as Fig. 3.

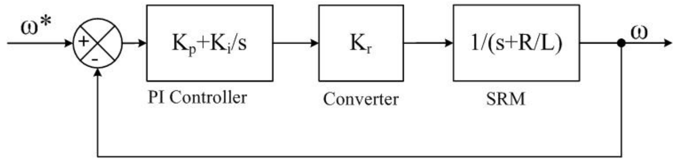


Fig. 3. Conventional SRM PWM control mode.

The transfer function for speed is given as:

$$\frac{\omega}{\omega^*}=\frac{K_pK_rS+K_iK_r}{S^2+\frac{R}{L}S+K_pK_rS+K_iK_r} \tag{8}$$

Fig. 4 is the inductance profile of the SRM that will be used for this paper. It shows that the machine starts saturated as current goes up. Thus, the transfer function will change because the inductance value is changed. The system becomes unstable if K_p and K_i have the same value all the time. Research work has been done to use a variable parameter PI controller to address this issue [7]-[9]. However, they are very complex to implement.

Fig. 5 is the block diagram of the proposed digital control system for a 4-phase 8/6 SRM. As mentioned before, speed feedback is the only close loop in this system. Without the current control, the controller follows a very simple logic: (1) if the motor speed is smaller than the commanded speed, high state will be chosen, which results in increasing the speed; and (2) if motor speed is larger than the commanded speed, low state will be chosen, which results in decreasing the speed.

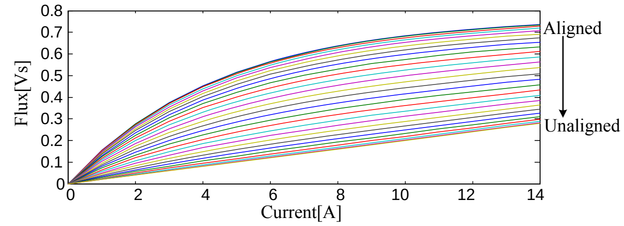


Fig. 4. Inductance profile at different positions.

One should note that high and low states indicate two different duty ratios, which are D_H and D_L in the PWM mode. Since the output of the new controller is only switching between the two values, it could be modeled as a regular PI controller with very big K_p and K_i. Therefore, (8) could be rewritten as:

$$\frac{\omega}{\omega^*}=\frac{K_pK_rS+K_iK_r}{S^2+\frac{R}{L}S+K_pK_rS+K_iK_r}=1-\frac{S^2+\frac{R}{L}S}{S^2+\frac{R}{L}S+K_pK_rS+K_iK_r}\approx 1 \tag{9}$$

It indicates that the new controller is not affected by the working region of the machine. The system could work properly in both linear and nonlinear conditions since its transfer function is not related to the inductance value.

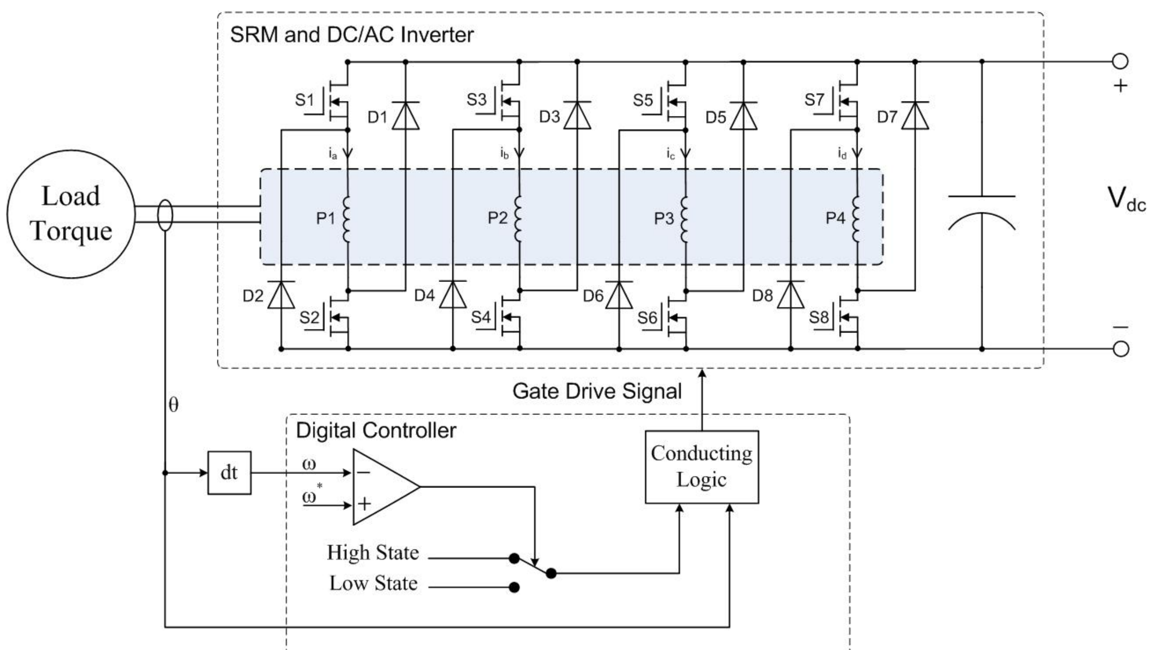
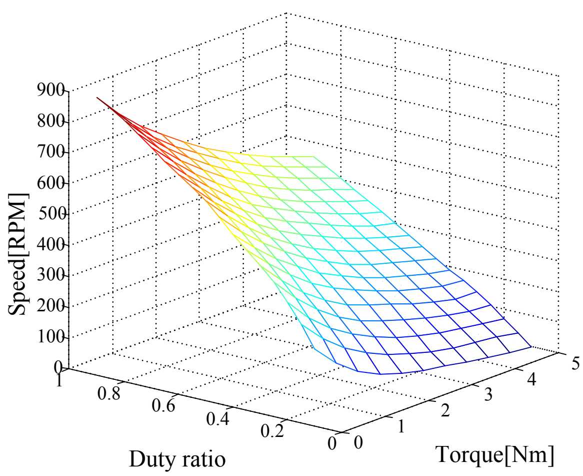


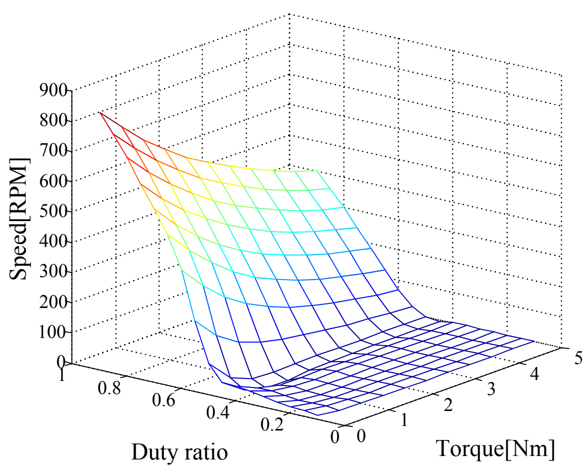
Fig. 5. Block diagram of the proposed digital PWM control.

IV. Simulation and Experimental Results

In order to verify this new control technology, a non-linear 4-phase 8/6 SRM model is build based on [4] for simulation verification. Experiment results are also presented in this section. Since it is difficult to get a simple relationship between the speed and duty ratio from (6), specific measurements are done in order to get proper duty ratios for high and low states. The results are shown in Fig. 6a. As a comparison, Fig. 6b shows the relationship between speed, duty ratio, and torque in the hard chopping mode. It indicates that the motor speed is lower in the hard chopping mode than the soft chopping for the same duty ratio and load since it feeds more power back to the DC link during the chopping in this mode.



a)



b)

Fig. 6. Speed versus duty ratio and torque: a) soft chopping and b) hard chopping.

Fig. 7 shows the simulation results when D_H and D_L are chosen as 0.8 and 0.4, respectively. Reference speed is 500 RPM and PWM frequency is 2 kHz. Phase turn-on and turn-off angles are 42° and 132°, respectively; conduction angle is 90°. Thus, only one phase is conducting at any given time and mutual inductance effects could be ignored. Note that the small current indicates the system is in the low state since average terminal voltage is smaller and current is bigger in the high state. In Fig. 7, it could be find out that the control system is switching between D_H and D_L in the steady state. Fig. 8 is the detailed view of the gate signal and phase current. It also demonstrates that only two duty ratios are applied to the system. Figs. 9 and 10 show the controller performance under transient state. Fig. 9 shows the simulation results when the load torque changes from 0 Nm to 0.4 Nm. In Fig. 10, reference speed changes from 400 RPM to 600 RPM. However, Fig. 6a shows that the speed cannot be maintained at 400 RPM if D_L is 0.4. Thus, 0.2 is used as a new value of D_L.

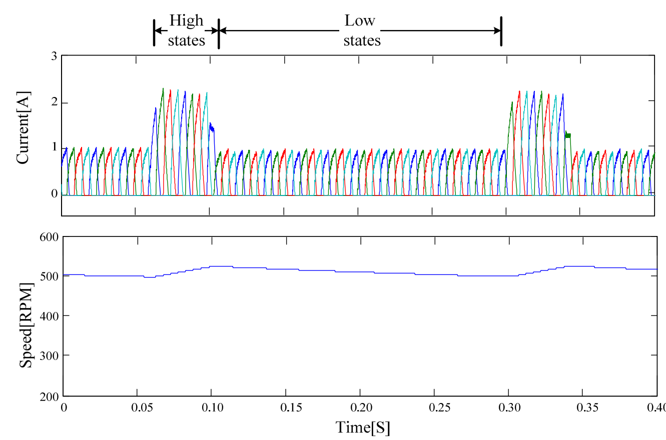


Fig. 7. Simulation results when D_H is 0.8 and D_L is 0.4 without load.

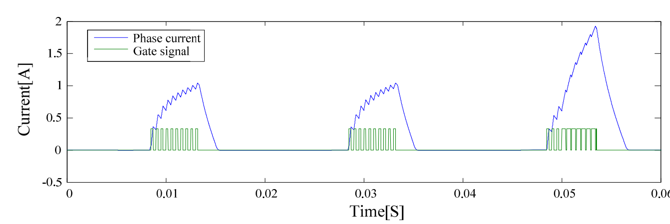


Fig. 8. Current and gate signal waveforms.

In order to verify the simulation results, a 1 kW, 8/6 SRM test bed has been built, which is shown in Fig. 11. A 32-bit, 150 MHz digital signal processor TMS320F2812 from Texas Instruments is used. A 12-bit incremental encoder is also used to provide the high resolution position information. Ideally, the minimum movement that could be captured by this setup is 0.527°.

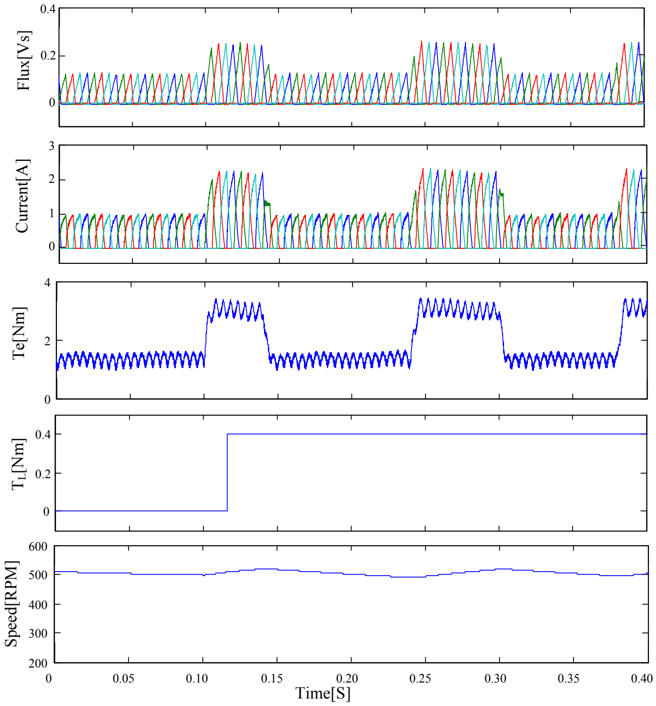


Fig. 9 Simulation results when D_H is 0.8, and D_L is 0.4, torque changes from 0 to 0.4 Nm.

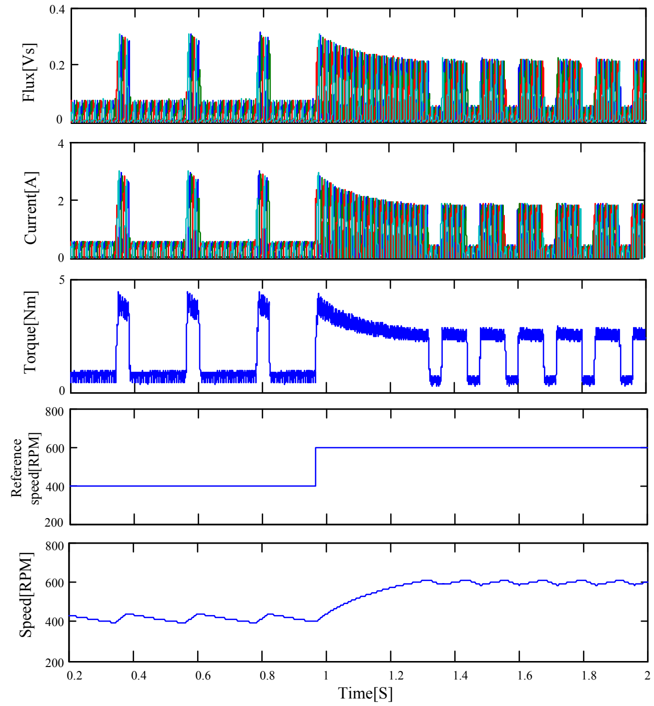


Fig. 10. Simulation results when speed command changes from 400 RPM to 600 RPM. D_H is 0.8, and D_L is 0.2.

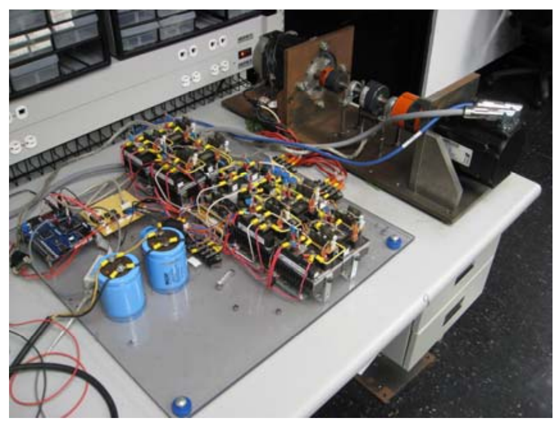


Fig. 11. Experimental setup.

Fig. 12 shows the experimental results, when D_H is 0.8 and D_L is 0.4 and reference speed is 500 RPM. Fig. 13 is the system response when the load changes. It should be noted that the driver has to apply more high states to the system in order to maintain the commanded speed after the load is added. As shown in Fig. 14, the control system could track the speed command properly when it changes from 400 RPM to 600 RPM. It also shows that the current value is smaller when the speed is higher. That is because the conduction time is shorter for the same conduction angle at a higher speed. This will in turn decrease the torque. When machine runs at a high speed, it needs a bigger conduction angle to provide enough torque. These experimental results verify that the system works well and support the analysis and simulation results presented in this paper.

V. Conclusion

In this paper, fundamentals of the PWM control for SRM drives are explained and a new digital PWM control technique is presented. By utilizing only two high and low states, a low-cost wide speed range controller is implemented. Hard and soft chopping methods are also discussed in the paper. It has been shown that soft chopping method is better in this motor application. Different simulation and experimental results for the proposed digital control technique are presented. They demonstrate that the new control technique works well.

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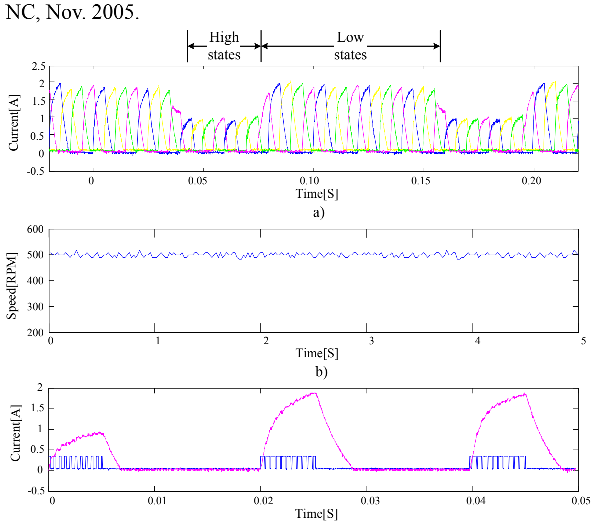

Fig. 12. Experimental results when D_H is 0.8, and D_L is 0.4: a) phase current, b) speed response c) phase current and gate signal.

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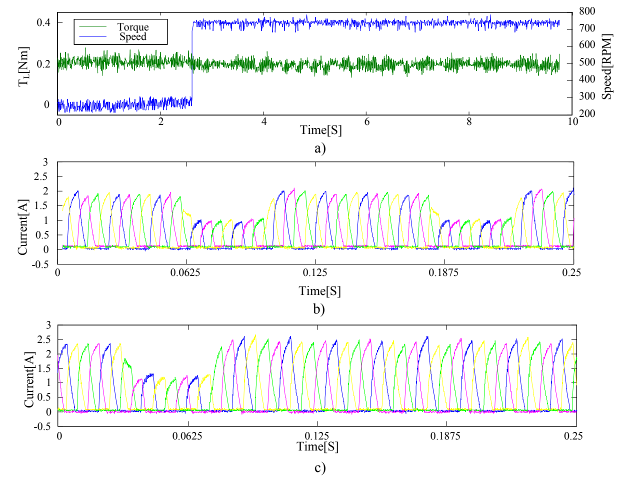

Fig. 13. Experimental results when D_H is 0.8, and D_L is 0.4: a) Speed and torque, b) phase current before torque is changed, c) phase current after adding the load.

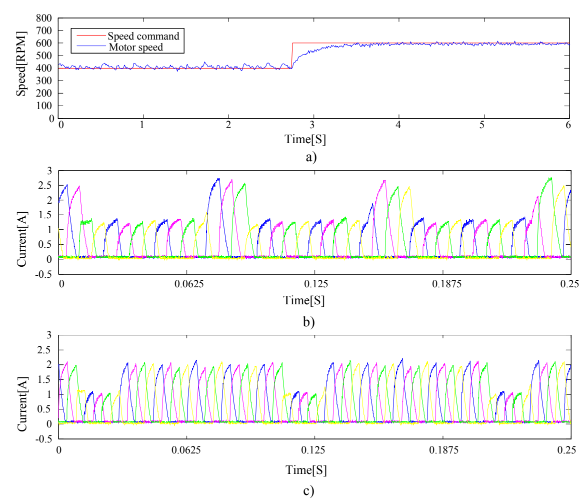

Fig. 14: Experimental result when D_H is 0.8, and D_L is 0.2. Reference speed changes from 400 RPM to 600 RPM: a) Speed response, b) phase current before reference speed is changed, c) phase current after reference speed is changed.