Bi-level Control and Chopper Control Methods for Improving the Dynamic Performance of Stepper Motor

Walid Emar Walidemar@yahoo.com
Faculty of Engineering/Electrical Dept./Power electronics and Control
Isra University
Amman, 11622, Jordan

Ziad Sobih Zeyadsobeh@hotmail.com
Faculty of Engineering/Electrical Dept
Northeastern University
Boston, MA02115, USA

Musbah Aqel Musbahaqel@yahoo.com
Faculty of Engineering/Electrical Dept
Applied Science University
Amman, Jordan

Mahmoud S. Awad Dr_Awad_M@yahoo.com
Faculty of Engineering/Electrical Dept
Al-Balqa Applied University
Amman, Jordan

Abstract

This paper compares between chopper control method and bi-level control method. Both methods are used for improving the dynamic performance of variable reluctance stepper motor (VRSM) by modifying its time constant and thus, increasing its stepping rate. Therefore, the initial torque developed by the motor is high; the switching from one coil to the next is faster than normal and consequently, the rotor moves as quickly as it should be. The circuitry discussed in this paper is connected directly to the motor windings and the motor power supply, and this circuitry is controlled by a digital system that determines when the switches are turned on or off. Each class of drive circuit is illustrated with practical examples, but these examples are not intended as an exhaustive catalog of the commercially available control circuits, nor is the information given here intended to substitute for the information found on the manufacturer's component data sheets for the parts mentioned.

Keywords: Stepper motor, variable reluctance motor, time constant, new topology of chopper converter, chopper control.

1. INTRODUCTION

The dynamic response of stepper motor may be improved by using special drive and control circuits yielding better time constant, faster stepping rate and therefore higher torque and well working rotor [5].

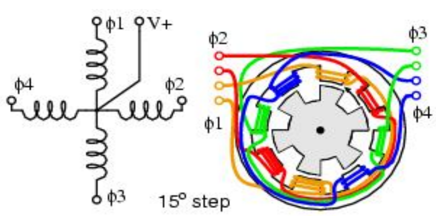
For most industrial applications stepping motors are controlled by using microprocessor techniques. With the microprocessor any of the types of control can be used such as linear constant current control, bi-level control or chopper PWM control. It can make the motor to run through the desired number of steps and can control the acceleration and deceleration of the motor when required[2-5].

In this paper a bi-level and chopper PWM control will be demonstrated. At the end, a brief comparison is done to show the priority of each control method and drive circuitry.

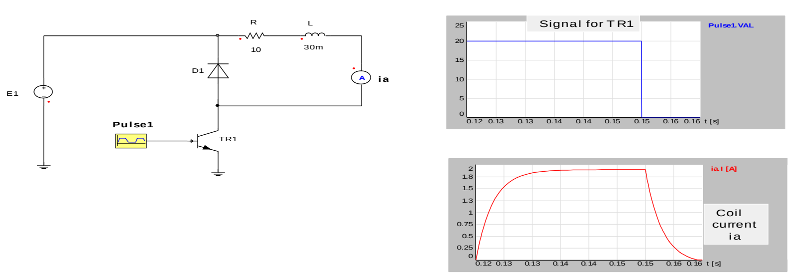
2. FUNDAMENTAL PRINCIPLE OF CHOPPER CONTROL OF STEPPER MOTOR

The typical stepper motor with four windings with the drive waveforms are shown in the schematic diagram in Figure 1a, with one terminal common to all windings; it is most likely a variable reluctance stepping motor.

In use, the common wire typically goes to the positive supply and the windings are energized in sequence [12].



(a)



(b)

Figure 1: (a) Four phase (4-Φ) variable reluctance stepper motor. (b) Fundamental connection of a chopper down converter and phase current waveforms: $(E_1 = 5-V, L = 30mH, R = 10\Omega)$.

Figure 1b shows the equivalent circuit of one phase of the motor and a fundamental chopper down (step down) converter and the waveforms of the motor phase currents.

The basic principle of operation for a four winding variable reluctance stepper motor is illustrated in Figure 1.

The stator has 8 poles and the rotor has 6 teeth. When one of the stator coils is energized, the rotor teeth will align with the energized stator poles. This means, that the rotor will move to a position of minimum reluctance. Sequentially switching the stator phases produces a rotating magnetic field which the rotor follows. However, due to the lesser number of rotor poles, the rotor moves less than the stator angle for each step [1, 3, 6].

For a variable reluctance stepper motor, the step angle is given by:

$$\theta_s = 360^\circ / N_S \qquad (1)$$

Where: θ_s is stator angle; N_S is number of stator poles.

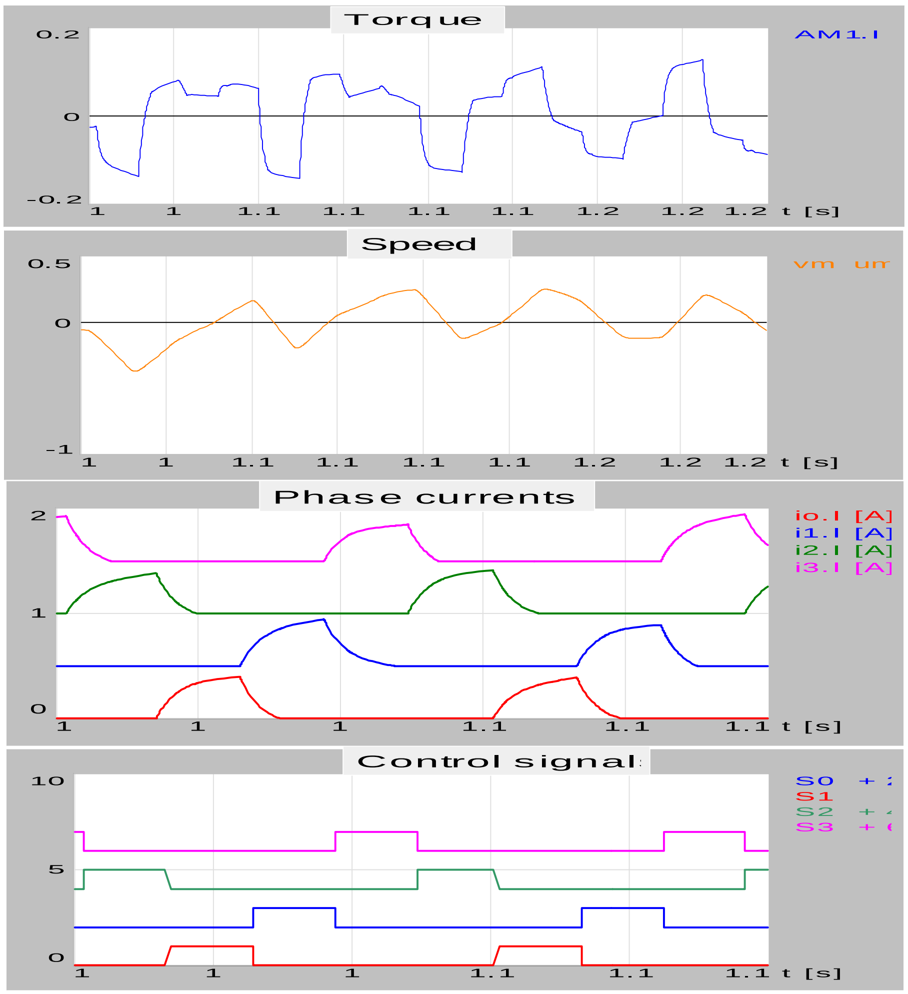


Figure 2: Schematic diagram showing torque, speed and phase current waveforms of a four phase variable reluctance stepper motor.

$$\theta_R = 360^\circ / N_R \qquad (2)$$

Where: θ_R is rotor angle; N_R is number of rotor poles.

$$\theta_{ST} = \theta_R - \theta_S = \frac{N_S - N_R}{N_S . N_R} \times 360^\circ \tag{3}$$

Where: θ_{ST} is step angle. The number of stator poles is the product of number of phases and number of poles per phase. Thus

$$N_S = m \times N_P \tag{4}$$

Where: *m* is number of poles; N_p is number of stator poles per phase.

Figure 1 shows that moving from Φ_1 to Φ_2, etc., the stator magnetic field rotates clockwise. By reversing the sequence of pulses, the direction of rotation is reversed above right. The direction, step rate, and number of steps are controlled by a stepper motor controller feeding a driver or amplifier. This could be combined into a single circuit board [1, 2, 10].

Figure 2 shows the resultant torque, speed and current waveforms of a 4-Φ variable reluctance stepper motor.

3. IMPROVEMENT METHODS OF DYNAMIC RESPONSE OF STEPPER MOTOR

It has been mentioned earlier that the basic problem for the drive of a VRSM lies in the inductance of the stator winding. The time constant ($\tau = L/R$) of the motor winding prevents the current to follow the winding voltage pulse**.** The current rises slowly and does not reach the full rated value, particularly at high speed. As a result the torque decreases with increase of pulse rate. Hence, the torque speed performance can be improved by using one of the following drive methods:

- Bi-level control method.
- Chopper control method

3.1 Bi-level control method

A good approach to improve the dynamic response of stepper motor is to use two power supplies instead of one. This is called bi-level control as shown in Figure 3. Bi-level drive enables us to obtain fast rise and fall times of current without using external resistors[5].

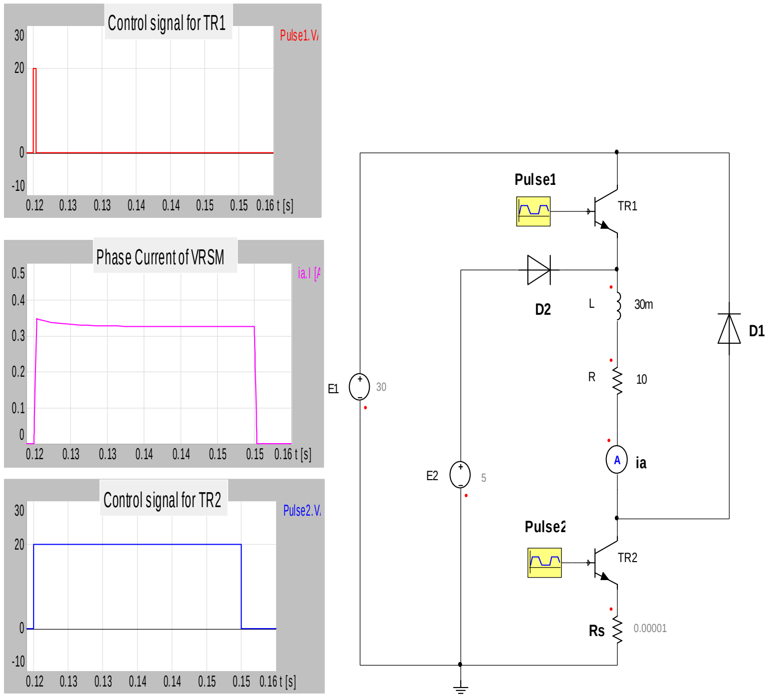


Figure 3: Bi-level control scheme of VRSM drive with current waveforms.

The principle of a bi-level control can be explained as follows: In this system there are two power supplies E_1, E_2. The upper supply E_1 is about *5* to *10* times higher than E_2 which is the rated value of the motor supply. The current sensing resistor R_s is not considered in this case ($R_s \to 0$).
At the starting of each step E_1 is connected to the motor coil. The coil current rises much faster than the rated supply and as soon as the coil current reaches the rated value; the supply is changed from E_1 to E_2. This continues with TR1 off and TR2 on upto the end of one step. When it is required to end the pulse TR2 is turned off and the current decays through the load, both freewheeling diodes D1, D2 and both supply voltages E1, E2. In this way losses in the circuit are reduced and the overall efficiency is increased.

3.2 Chopper control method

Chopper control may be achieved by using different types of chopper converters. Not all of these converters help to improve the performance of stepper motors. This paper introduces a new topology of chopper converters which significantly improves the dynamic performance of stepper motors.

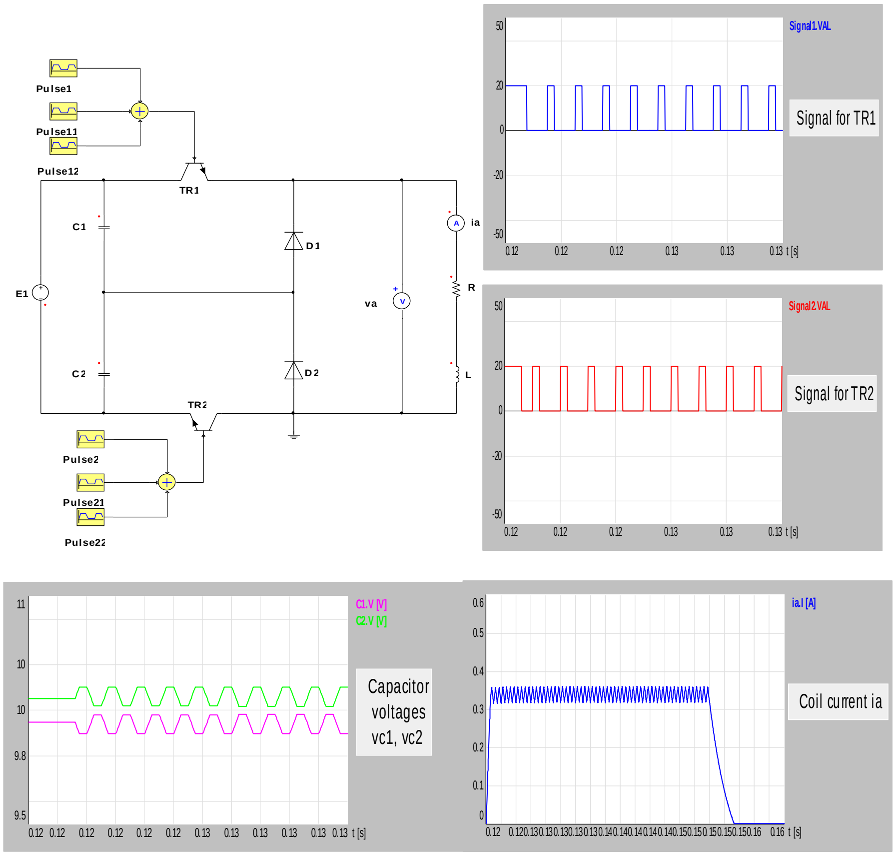


Figure 4: schematic diagram of a series connected double phase chopper down converter with Current and voltage waveforms.

The system is described with the help of Figure 4. The circuit in this figure consists of a chopper-down converter with two channels connected in series. In this scheme higher supply voltage E_1 is used. It may be as high as 2 to 4 times of the rated value of the motor voltage. This connection is also used to increase the voltage-handling capability of the power devices. It also gives with a variable output voltage the possibility of varying the motor speed by varying its terminal voltage.

Principle of operation of such connection may be explained as follows: The motor is switched on by the sequencer signal with this high voltage supply and the two capacitors (C_1, C_2). At the beginning both switches are on for a time required for the circuit current i_a to reach its rated value. Thus, if the supply voltage had a value of 30-V and if the switches were on all the time, the resulting current in the circuit would be $30V/10\Omega=3A$. This is much greater than the required rated current (*0.5A*). The rate of rise of coil current increases and reaches its rated current much faster. The time constant of the circuit is again $L/R=30/10=3ms$. Thus, the current in the coil rises at a rate of $30/3ms=1000A/s$. The time to reach *0.5A* is then $0.5(A)/1000(A/s)=0.5ms$.

As soon as the current reaches slightly above the rated value, both switches are periodically turned off and on using pulse width modulation (PWM) technique. The switches connected in series are usually operating out of phase by the time *T/2*. During this period each switch is on for certain time t_{on} to yield the required mean value of the coil voltage and off for the rest of this operating period, t_{off}. Both transistors have the same operating period T_p which is many times smaller than the energizing pulse (period) of the coil. When it is required to end the energizing pulse of the coil, both transistors are simultaneously turned off and the circuit current i_a begins to decrease through diodes D_1, D_2 as shown in Figure 4.

4. STEPPER MOTOR FOR BOTH DIRECTIONS

The following mechanical model in Figure 5 obtained from Simplorer 6 shows a 4-phase step motor. Whose electrical part is modeled by 4 electrical circuits in parallel connection.

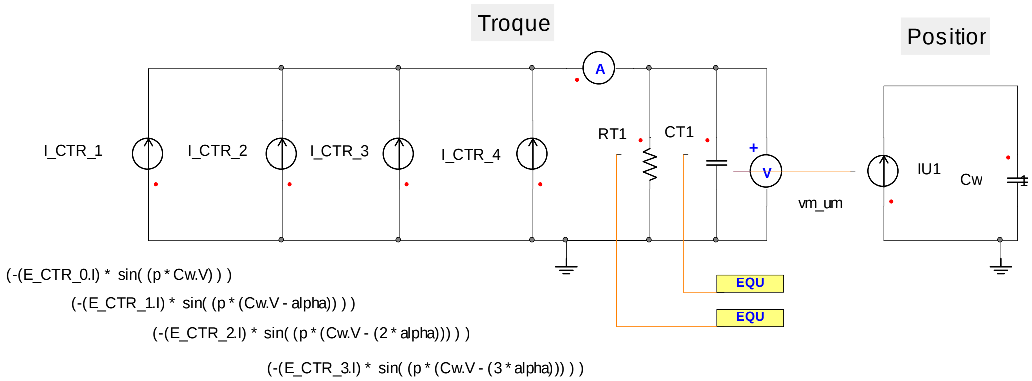


Figure 5: Mechanical part of four phase stepper motor.

There are different ways to model the mechanical part of the motor in Simplorer. Here it is used according to Simplorer 6 an electrical circuit to describe its mechanical behavior. It can be modeled as block diagram as well.

The control signal of the step motor is produced by 3 state machines. One for direction control, e.g. the required step length and moving direction. The others for generating pulse signals, which depends on the moving direction as shown in Figure 6.

By using static transistor model in Simperlor, the logic control signal can be connected directly to the transistor as a switch signal. A static transistor model is good enough to simulate the controlled behavior of the step motor in this case as shown in figure 7. Figure 7 also shows the waveform of the speed, torque and position of both-directional stepper motor.

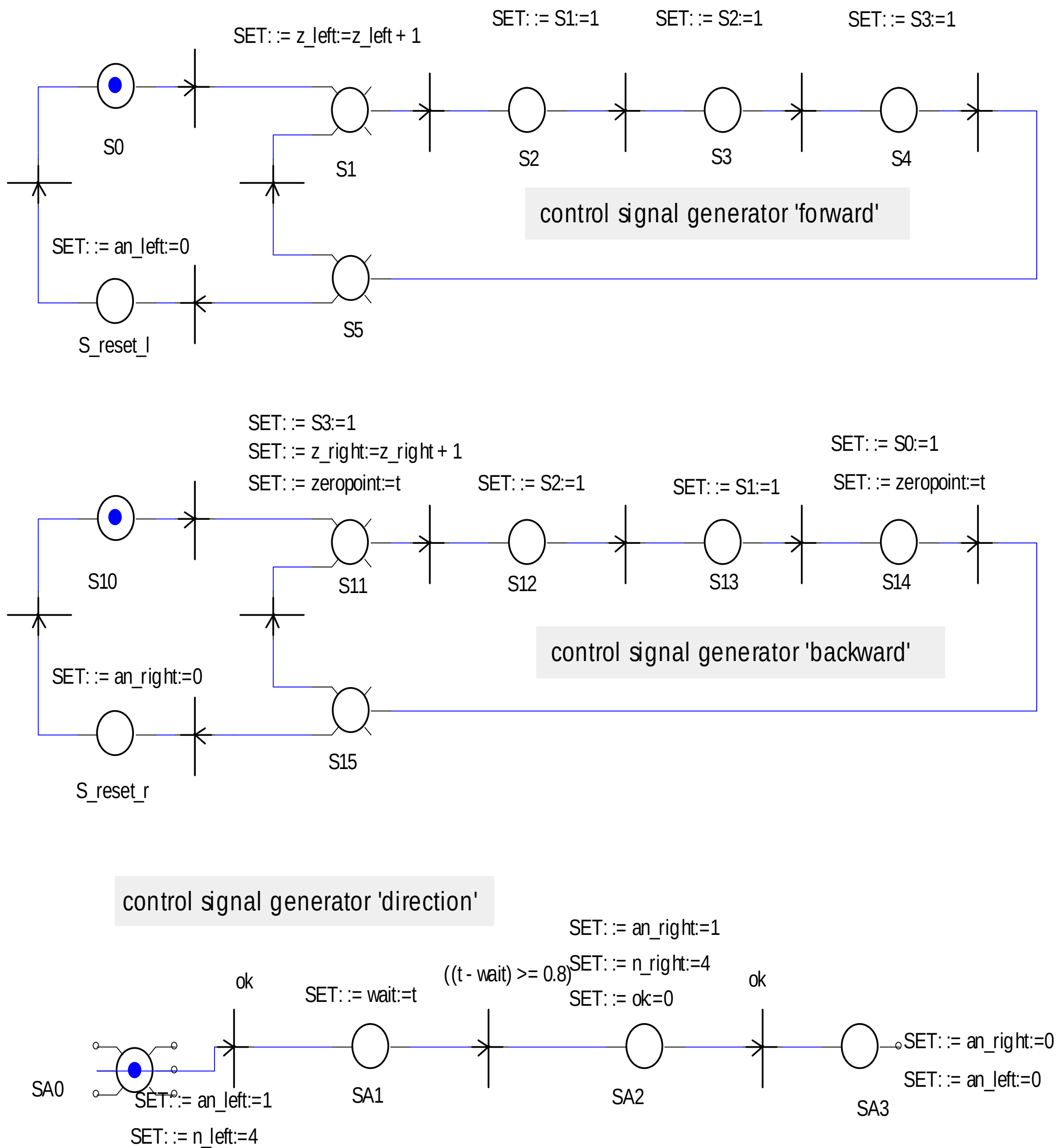


Figure 6: State graph.

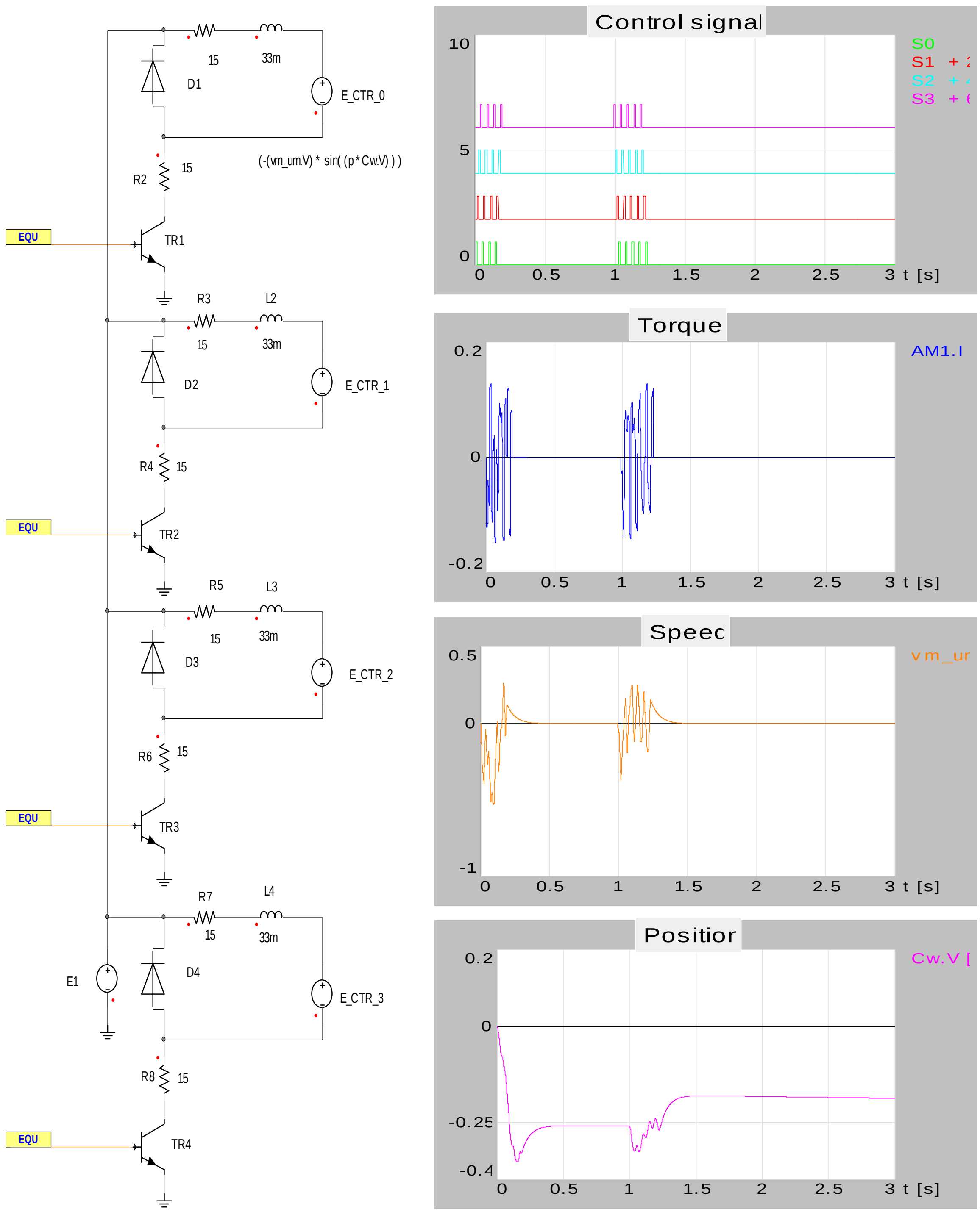


Figure 7: Electrical model and output waveforms.

5. CONCLUSION

The above described application examples of modern control and drive circuits show that performance and efficiency of variable reluctance stepper motors may be remarkably increased without any excessive expense increase like before.

A natural limit against any current increase by using very high power supply as in the bi-level control method is the danger of saturating the iron core and increasing the maximum temperature rise of the motor, due to the power loss in the stator windings. This shows one advantage of the modified chopper control method defined in this paper, which, compared to others, has the motor's power loss within a reasonable limit since the current in the windings is controlled.

The winding current is chopped and limited within a certain limit and this produces a direct proportional and positive effect on the torque. At their power loss limit stepper motors with anti-parallel series four phase chopper control may deliver more torque than stepper motor with other drive circuits.

Furthermore, if a higher torque is not required, one may either reduce the motor size or the power loss by utilizing the chopper control method. It gives only as much voltage as needed and makes the motor to run at as high speed as required and independently from the winding resistance.

On the other hand, the bi-level control method requires higher power supply than other methods which increases the economical costs of the system and the power supply is more expensive because it has to deliver 5 times as much power ($5E_1$ instead of E_1). Furthermore, the current is not limited or controlled anyhow and therefore, the magnetic field is not controlled. Consequently, the torque of the motor is out of control since it is proportional to the current and the magnetic field of the motor's windings.

Dedicated integrated circuits have dramatically simplified stepper motor driving. To apply these ICs designers need little specific knowledge of motor driving techniques, but an under-standing of the basics will help in finding the best solution.

6. REFERENCES

1. E. Walid, TT. Issam, A. Rateb. "A novel topology of delta modulation technique for improving the power factor of AC-DC converters". International journal of engineering (IJE), CSC journals, Volume 4, Issue 1, January/February 2010.

2. M. F. Rahman, A. N. Poo and C. S. Chang. "Approaches to Design of Ministepping Step Motor Controllers and Their Accuracy Considerations". IEEE Trans. Industrial Electronics, vol. IE-32, No. 3, pp. 229-233, August 1985.

3. M. F. Rahman and A. N. Poo. "An Application Oriented Test Procedure for Designing Microstepping Step Motor Controllers". IEEE Trans. Industrial Electronics, vol. 35, No. 4, pp. 542-546, November 1988.

4. P. C. Sen. "Modern Power Electronics". Published by S. Chand & Company LTD. New Delhi, 2004.

5. W. Theodore. "Electrical machines, drives, and power systems", sixth edition. Published by Pearson education international, New Jersey 07458, 2006.

6. W. D. Harries and J. H. Lang. "A simple motion estimation for variable reluctance motors, IEEE Trans. Ind. Appl., pp 237-243, March 1990.

7. P. P. Acarnley. “Stepping Motors: A Guide to Modern Theory and Practice“. IEE Control Engineering Series 19, Peter Peregrin Ltd., 1982.

8. M. F. Rahman and A. N. Poo. “An Application Oriented Test Procedure for Designing Microstepping Step Motor Controllers”. IEEE Trans. Industrial Electronics, vol. 35, No. 4, pp. 542-546, November 1988.

9. D. Carrica, M. A. Funes and S. A. Gonzalea. “Novel Stepper Motor Controller Based on FPGA Hardware Implementation”. IEEE/ASME Trans. Mechatronics, vol. 8, No. 1, pp.120-124, March 2003.

10. P. D. Ziogas, L. Morán, G. Joos, and D. Vincenti. "A refined PWM scheme for voltage and current source converters". IEEE-IAS Annual Meeting, 1990, PP. 997-983.

11. R. Wu, S. B. Dewan, and G. R. Slemon. "Analysis of an AC-to-DC voltage source converter using PWM with phase and amplitude control". IEEE Transactions on industry Applications, vol. 27, No. 2, March/April 1991, pp. 355-364.

12. X. Ruan, L. Zhou, and Y. Yan. "Soft-switching PWM three-level converters". IEEE Transactions on Power Electronics, Vol. 6, No. 5, September 2001, pp. 612-622.

13. M. H. Rashid. “Power Electronics, Circuits, Devices and applications”. Third edition, 2004, Pearson Education, Prentice Hall, Upper Saddle River, NJ 07458.

14. Miftakhutdinov, R. “An Analytical Comparison of Alternative Control Techniques for Powering Next Generation Microprocessors”. TI Seminar, 2002.

15. G. Moschopoulos, P. Jain. "Single-phase single-stage power-factor-corrected converter topologies". IEEE Trans. on Industrial Electronics, vol. 52, no. 1, pp. 23- 35, Feb 2005.