A Novel Chopper Converter Topology For Improving The Performance Of Stepping Motors

[1]Walid Emar, [2]Moh'd Al-Eweisi, & [3]Musbah J. Aqel

[1]Al-Isra private University,
College of Engineering,
Amman 11622, Jordan.

[2]Al-Ahliyya Amman University,
College of Engineering,
Amman 11121, Jordan.

[3]Applied Science University,
College of Engineering,
Amman11391, Jordan.

Abstract: *This paper presents a new topology of drive circuitry for variable reluctance stepping motors (VRSM) for improving the performance of such motor 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.*

This paper also covers the basic principles of stepping motors and stepping motor control systems. It focuses on a four winding variable reluctance motor (VRSM), from the elementary circuitry needed to control its speed, to the methods used for improving its time constant and stepping rate [1-5].

Keywords: Stepper motor, Variable reluctance motor, time constant, Chopper converter, Chopper control.

Received:

1. Introduction

Stepping motors can be viewed as electric motors without commutators. There are three main types of stepper motors: permanent magnet stepper motor, hybrid stepper motor and variable reluctance stepper motor.

Typically, all windings in these motors are part of the stator, and the rotor is either a permanent magnet or, in the case of variable reluctance motors, a toothed block of some magnetically soft material. All of the commutation must be handled externally by the motor controller, and typically, the motors and controllers are designed so that the motor may be held in any fixed position as well as being rotated one way or the other. Most steppers can be stepped at audio frequencies, allowing them to spin quite quickly, and with an appropriate controller, steppers may be started and stopped "on a dime" at controlled orientations [5, 7].

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.

In this paper two different topologies of chopper PWM control will be demonstrated. Different types of chopper PWM converters may be used. The result is a progressive decrease of the fall and rise time of the phase current of the motor, increase of the stepping rate of the motor and consequently providing higher torque and better dynamic response. At the end, a brief comparison is done to show the priority of each control method and drive circuitry [1].

2. Four Phase Variable Reluctance Stepper Motor

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

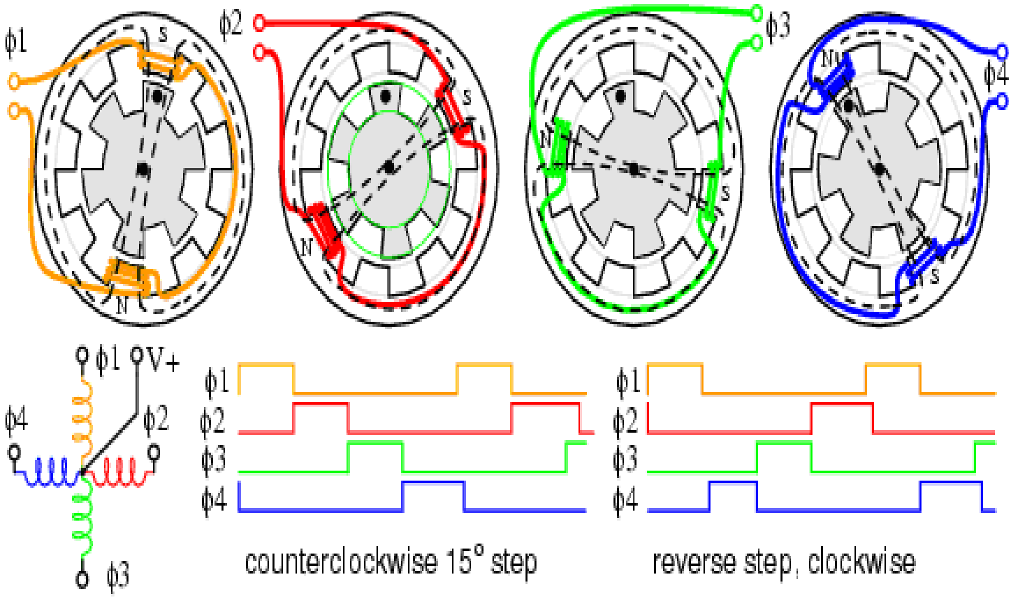


Figure 1. Stepping sequence for a 4-Ö variable reluctance stepper

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: $è_s$ is stator angle; N_S is number of stator poles.

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

Where: $è_R$ is rotor angle; N_{-R} is number of rotor poles.

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

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

$$N_S = m \times N_P \qquad (4)$$

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

Figure 1 shows that moving from Ö$_1$ to Ö$_2$, 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-Ö variable reluctance stepper motor.

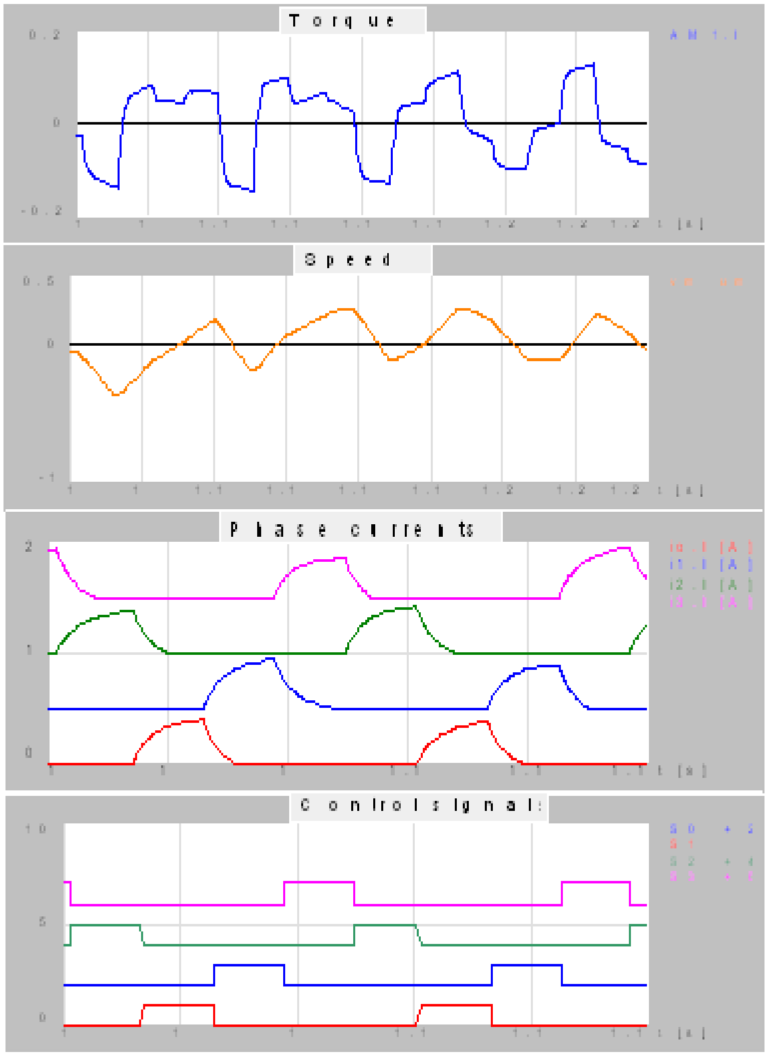


Figure 2. Schematic diagram showing torque, speed and phase current waveforms of a four phase variable reluctance stepper motor.

3. Effect of The Motr Time Constant and Stepping Rate

Usually, the current pulse in a winding of the stator is considered to rise almost immediately to its rated value at the beginning of the pulse and to drop immediately to zero at the end of the energizing pulse interval T. In practice, this does not happen because of the inductance of the windings as shown in figure 2. If a winding has an inductance of L henrys and a resistance of R ohms, its time constant ô is equal to L/R seconds. Furthermore, the torque developed by a stepper motor depends upon the current flowing into the motor.

If this current pulse is compared with the ideal current pulse shown in figure 3, two important facts may be observed [5]:

1. The initial torque developed by the stepping motor is smaller than normal. As a result, the rotor does not move as quickly as it would be expected.
2. The effective duration of the energizing pulse is long which means that the current cannot be switched from one coil to the next as quickly as it would have been thought.
3. If the pulse rate of the current in the windings is too fast, the rotor will be unable to accurately follow the pulses because of slowly changing phase currents and consequently a very low pullover torque, and so that steps will be lost.

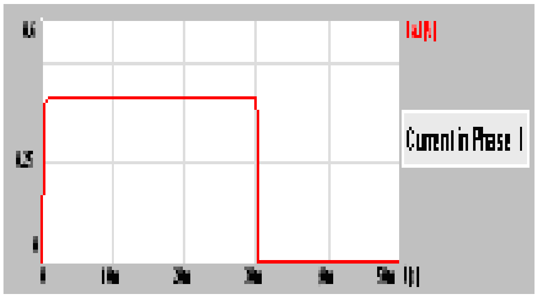


Figure 3. Ideal Waveform of phase current

These facts completely defeat the whole purpose of the motor, which is to produce a sufficient pullover torque for bringing the motor to the required speed as quick as possible and to correlate its instantaneous position (steps) with the number of net positive and negative pulses. In order to maintain synchronism, the rotor must settle down before advancing to the next position. With slowly increasing and decreasing phase currents shown in figure 2, it will be very difficult [1-5].

4. Modification Methods of Steeper Motor Time Constant

As it has mentioned earlier, the basic problem for the drive of a VRSM lies in the inductance of the stator winding. The time constant (ô=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. Usually, the torque speed performance can be improved by using one of the currently known control and drive methods [1-4]:

1. By increasing stator coil resistance by connecting an additional resistor in series with the coil.
2. By using bi-level control.

The principle of operation of the above mentioned methods is explained in [1-3]. Both methods still have some drawbacks. A greatly improved method is to use chopper drivers. Their principle of operation is similar to the bi-level method, except that the current is kept constant during the flat portion of the pulse by quick repeated on-off switching of higher variable voltage supply rather than by using a low fixed dc voltage.

5. Chopper Drivers and Chopped Current Supply

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 new topologies of chopper converters which significantly improve the behavior of stepper motors.

5.1. Four Phase Parallel Series Connected Chopper Down Converter

The system is described with the help of Fig. 4a. The circuit in this figure consists of four switches and two diodes.
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 [2-4, 7, 10].

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). Pulse width modulation (PWM) technique is used to generate the signals for the main switches TR1, TR2.

The basic principle of PWM technique and its application in this switching regulator may be explained as follows: In pulse width modulation the frequency is kept constant and the duty ratio, $k = \frac{t_{on}}{T_p}$, is varied to regulate the output voltage for the purpose of motor speed control. Symbol T_p is used here to indicate the operating period of the main transistor during which the transistor may be on. It is usually selected many times smaller than the conduction period (energizing pulse) of the stator coil. It may be as small as 5 to 20 times of the coil energizing pulse to keep the current through the coil as constant as possible. The differential gap may be about ± 5% of the rated value of the average current value.

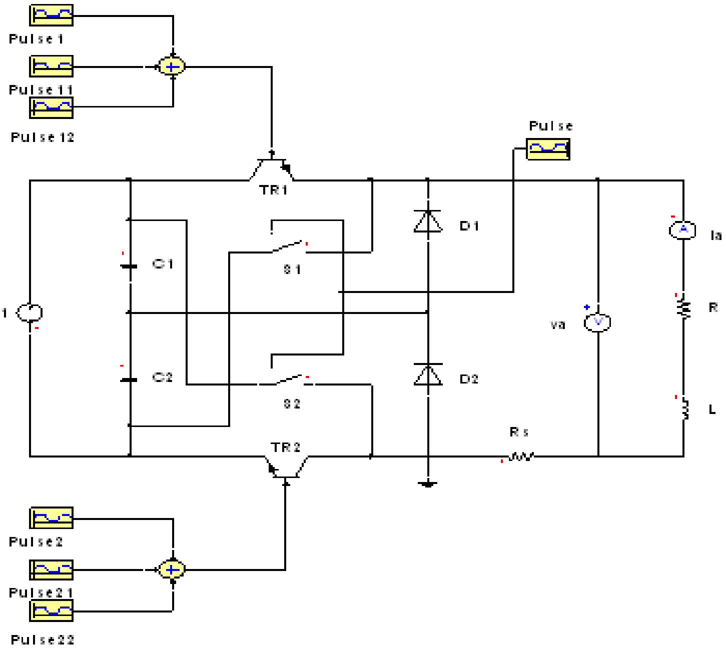


Figure 4a: schematic diagram of a parallel series connected four phase chopper down converter.

With respect to the above mentioned the pulse width modulation for the scheme shown in figure 4 can be achieved as follows: At the beginning of each energizing pulse of the coil both main switches TR1, TR2 should be simultaneously on for a time required for the circuit current i_a to reach slightly above 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 $0.5(A)/1000(A/s) = 0.5ms$.

Thereafter, the main switches are operating out of phase by the time $T_p/2$. During this period each switch is on for certain time t_{on} to yield the required mean value of the coil current and off for the rest of this operating period, $t_{off} = T_p - t_{on}$. Both transistors have the same operating period T_p.

When it is required to end the energizing pulse of the coil, both main transistors are simultaneously turned off and at the same time both helping switches S_{1-}, S_2 are turned on for a time enough for the coil current to decrease from its rated value to zero value. During the off period the trapped energy is dissipated very fast and the coil current is switched off very rapidly through the load, capacitors C_1, C_2 and switches S_1, S_2. The polarity of the voltage across the capacitor is now

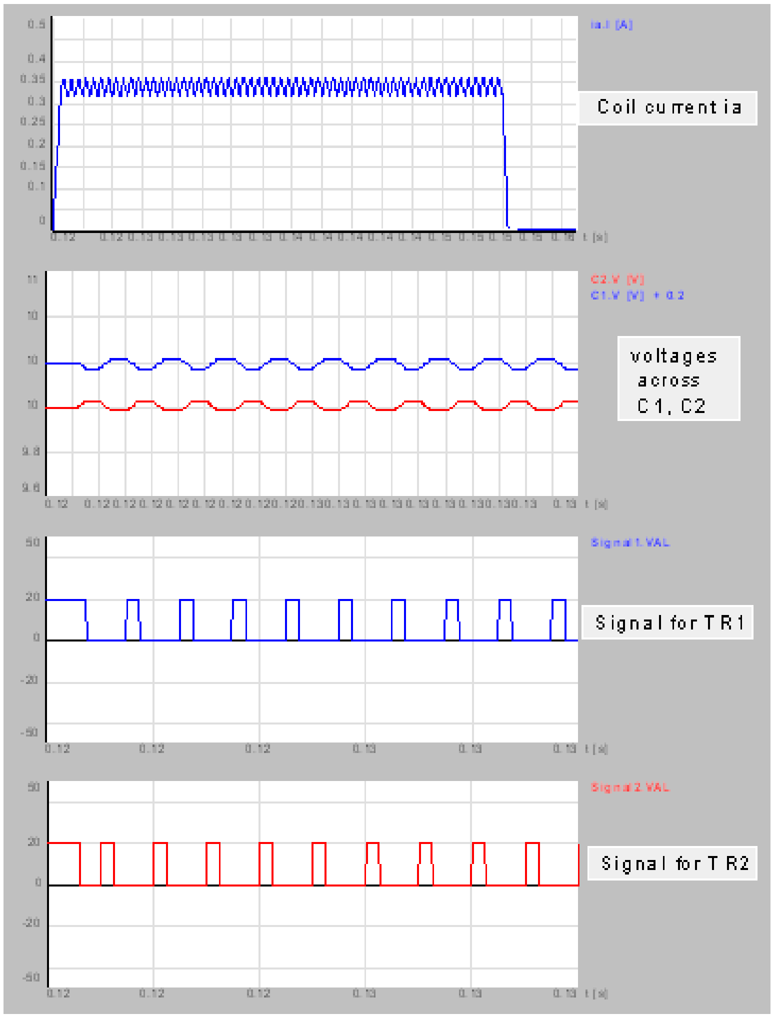


Figure 4b. Current, voltage waveforms and switching diagram for $k = \frac{t_{on}}{T_p} \le \frac{1}{2}$.

connected in the reverse direction across the load. This causes the current in the coil to fall down very rapidly. As soon asthe coil current reaches zero value or slightly above zero value, then both switches S_1, S_2 must be turned off before a big negative or positive over-voltage appears across the load. Figure 7b illustrates the current and voltage waveforms for $k \le \frac{1}{2}$. The control signals for TR1 and TR2 could be overlapped for "*k*" greater than ½.

For better understanding of the circuit behavior during the off period, let's do a simple analysis for the converter during this period. When both transistors S_1 and S_2 are simultaneously on during the off period, the following equation may be written for the circuit under the condition of ideally smoothed voltage across capacitor $C = C_1 + C_2$:

$$L\frac{di_a}{dt} + Ri_a + \left(\frac{1}{C}\int i_a\,dt + E_1\right) = 0 \qquad (5)$$

$$L\frac{di_a}{dt} + Ri_a + \frac{1}{C}\int i_a\,dt = -E_1 \qquad (6)$$

After re-arranging equation (6) and using Laplace transform, the equation governing the coil current becomes:

$$I_a(s) = \frac{-CE_1}{\left(LCs^2 + RCs + 1\right)s} \qquad (7)$$

Using the standard form of the second order equation yields:

$$I_a(s) = -CE_1 \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \qquad (8)$$

$\omega_n = \frac{1}{\sqrt{LC}}$ is called the un-damped natural frequency and $\xi = \frac{R}{2}\sqrt{\frac{C}{L}}$ is the damping ratio of such system. Hence the inverse Laplace transform of equation 8 is obtained as:

$$i_a(t) = -CE_1\left(1 - Ae^{-\xi\omega_n t}\right) \qquad (9)$$

Parameter A is defined as follows:

$$A = \cos\left(\omega_n\sqrt{1-\xi^2}\right)t + \\ + \frac{\xi}{\sqrt{1-\xi^2}}\sin\left(\omega_n\sqrt{1-\xi^2}\right)t \qquad (10)$$

When î is appreciably greater than zero and smaller than unity, the decaying current through the coil decreases very rapidly to zero value but it exhibits certain current oscillations around this value accompanied with unacceptable overvoltages across the phase as it is shown in figure 5a, 6. If î is equal to or greater than unity, then the coil current decrease very slowly to zero value as it is shown in figure 5b.

Such system with energy storage elements will exhibit oscillatory responses around zero whenever it is subjected to dc inputs. It is desirable that the transient oscillation be sufficiently small, fast and be sufficiently damped. Thus, for a desirable decay of the coil current, the damping ratio î must be between 0.6 and 0.8. Small values of this ratio yield excessive overshot of the coil current around zero and with large values of î, the current decreases very sluggishly.

A rapid response is necessary for positive and negative changes in the demand of current level. In order to maximize torque, the current in a phase should be switched on during the constant low inductance region so that the current can build up before the period of increasing inductance starts. Furthermore, the current should be switched off before the end of the increasing inductance period to allow the current to decay fully before the inception of decreasing inductance so that no negative torque is produced. Thus each stator phase must be energized by unidirectional current pulse while the rotor is appropriately positioned in relation to the stator.

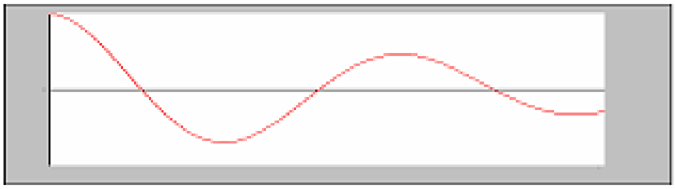
5.2. Four Phaseanti-Parallel Series Connected Chopper Down Converter

The major problem associated with VRSM operating with parallel series four phase chopper down converter explained previously is that the current is turned off with maximum phase inductance, and therefore; arrangements have to be provided to limit the current to a safe level. In addition to the over-voltage and current oscillation that could appear across the phase coil of the motor, the energy stored in the magnetic field when the VRSM is driven in the motoring regime should be dissipated or pumped back at the end of the energizing pulse to the supply source.

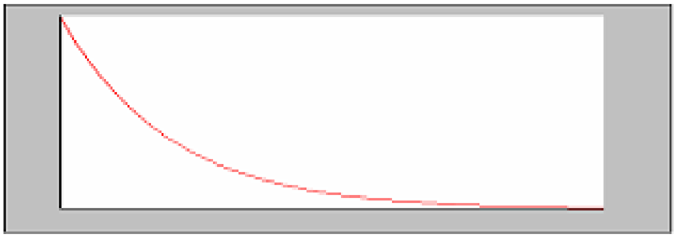
The third important thing is that current in one phase should be reduced to zero before the next phase is turned on. Furthermore, achieving a shorter fall time requires a very accurate design of the circuit parameters (î, ù$_n$) as it is previously mentioned.

These problems may be solved by using another topology of four phase chopper down converter. The scheme of such converter is shown in figure 7a. The circuit consists of anti-parallel series connected chopper down converter with switches TR1, TR2 connected in series with each other and in anti-parallel way with the so-called freewheeling switches TR3, TR4 which produces a new topology known as four phase anti-parallel series chopper down converter. Switches

TR1 and TR2 are turned on and off using PWM technique in the same manner as in section 5.1. Switch TR3 resp. TR4 is just used to conduct the current when TR1 resp. TR2 is off during the energizing pulse of the coil. When TR1 is opened (turned off), the inductive kick in the coil inductor L drives its upper terminal negative until the freewheel switch TR3 latches in and becomes on since a suitable signal is applied at its gate all the time during the energizing pulse of the coil.



(a) $\xi \rightarrow 0$



(b) $1 \leq \xi \leq 2$

Figure 5: Decay of coil current for different values of damping ratio î.

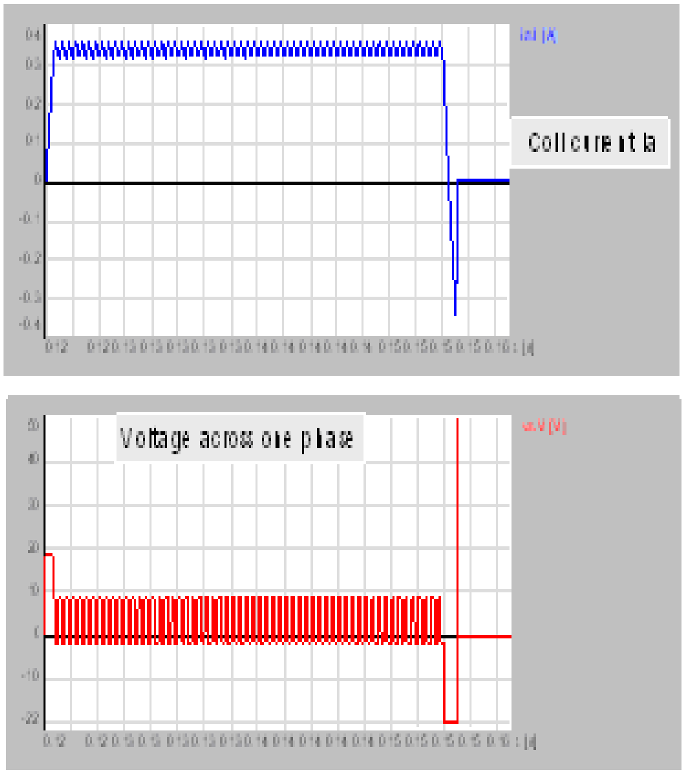


Figure 6. Phase voltage and current waveforms for $\xi \rightarrow 0$.

It conducts initially at the same instantaneous current that had been flowing in TR1 just prior to its opening. Thus, as soon as TR1 becomes off, the energy stored in inductor L maintains current flow to the load coil circulating through switch TR2, capacitor C_2 and switch TR3. Switches TR2 and TR4 operate with respect to each other in the same manner as switch TR1 and TR3. Hence, switches TR3, TR4 work as protection diodes for switches TR1, TR2 from the energy stored in the coil inductor.

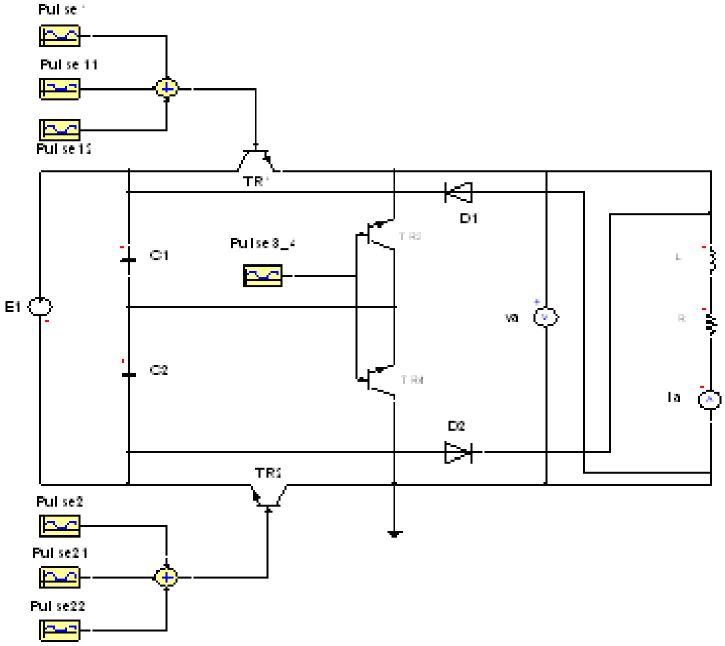


Figure 7a. Four phase anti-parallel series connected chopper down converter.

For the calculation of operating period T_p of main transistors operating in the regime of $0<k<1/2$, the input voltage to the coil is assumed to be $E_1/2$ during t_{on} and zero during t_{off} as shown in figure 7b.

Under the condition of the same value of the capacitance of both capacitors, $C_1=C_2$ and in a quasi-stationary state during the energizing pulse of the coil, the voltage across the coil inductor L, is in general,

$$\frac{E_1}{2} = L\frac{di_a}{dt} + V_R \qquad (11)$$

Where V_R is the voltage across the coil resistor R. With reference to figure 10c the coil current rises linearly from I_1 to I_2 in time t_{on} during which TR1 resp. TR2 is on. Hence,

$$\frac{E_1}{2} - V_R = L\frac{I_2 - I_1}{t_{on}} = L\frac{\Delta i_a}{t_{on}} \qquad (12)$$

Again the coil current falls linearly from I_2 to I_1 in time t_{off} during which diodes D_1 and D_2 are on, and therefore,

$$V_R = L\,\frac{\Delta i_a}{t_{off}} \qquad (13)$$

Where Äi$_a$ is the peak-to-peak ripple current of the coil. From the above equations the switching period T_p can be calculated as

$$\begin{aligned} T_p &= t_{on} + t_{off} \\ &= \Delta i_a \,.\, L\,\frac{E_1/2}{V_R\left(E_1/2 - V_R\right)} \end{aligned} \qquad (14)$$

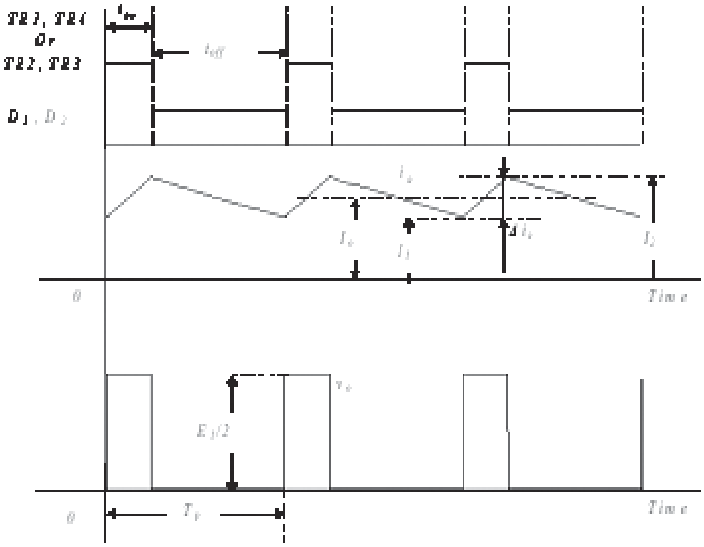


Figure 7b. Switching diagram for the four phase converter with the coil current waveform within a portion of the energizing pulse of the coil in the regime of $0<k<1/2$.

Where $f=1/T_a$ is the switching frequency of the main transistors TR1, TR2. By using analogous methods, similar expressions may be obtained for T_p in the regime of $0<k<1/2$

Let's see how the circuit behaves using numerical values. Thus, the winding is assumed to have a resistance of 10 Ω ,an inductance of 30mH, and a rated current of 0.5A. The power supply is $E_1=20V$ Thus, if power supply E_1 were applied permanently, the resulting current in the winding would be nearly $20V/10\Omega = 2A$. This is much greater than the rated current of 0.32A.

The time constant of this electronic circuit is $\tau = 20mH/10\Omega = 2ms$. The current initially rises up to the value of 2A at 2ms. Thus, the current in the winding rises at a rate of $2A/2ms=1000\ A/s$. But the time required to reach the rated value of the circuit current (0.32A) is, therefore,$0.32A/1000=0.32ms$.This means that during the time that TR1 and TR2 are on, the higher voltage E_1 is applied to the load causing the coil current to increase very fast to its rated value as shown in figure 10b.

As soon as the current reaches slightly above this rated value, then the applied PWM technique with main switches, TR1 and TR2 operating out of phase by the time $T_p/2$ ensures that the coil current will stay within the given limits around its rated value as shown in figure 7c for $0<k<1/2$.

When it is required to end the energizing pulse of the coil of one phase, all four switches TR1, TR2, TR3 and TR4 are simultaneously off and because of the energy stored in the coil inductor which changes its polarity to drive the current through diodes D1, D2. By this way, the energy stored in the inductor L is reversed back to the input supply. This causes the coil current to decrease to its zero value with a time constant of 2ms, and therefore, the current will decrease at a rate of $(20V/20\ V)x1000=1000\ A/s$ .This forces the current to remain zero until the next energizing pulse is initiated. The voltage and current waveforms are shown in figure 7c.

5. Practical Implementation And Modeling Of Stepper Motor With Four Phase Anti-Paraller Series Converter

The stepper motor mathematical model may be simulated in MATLAB for analysis and for studying its response in different environments. The following motor parameters (Table I) were taken from the motor specification and are constant throughout the simulation.

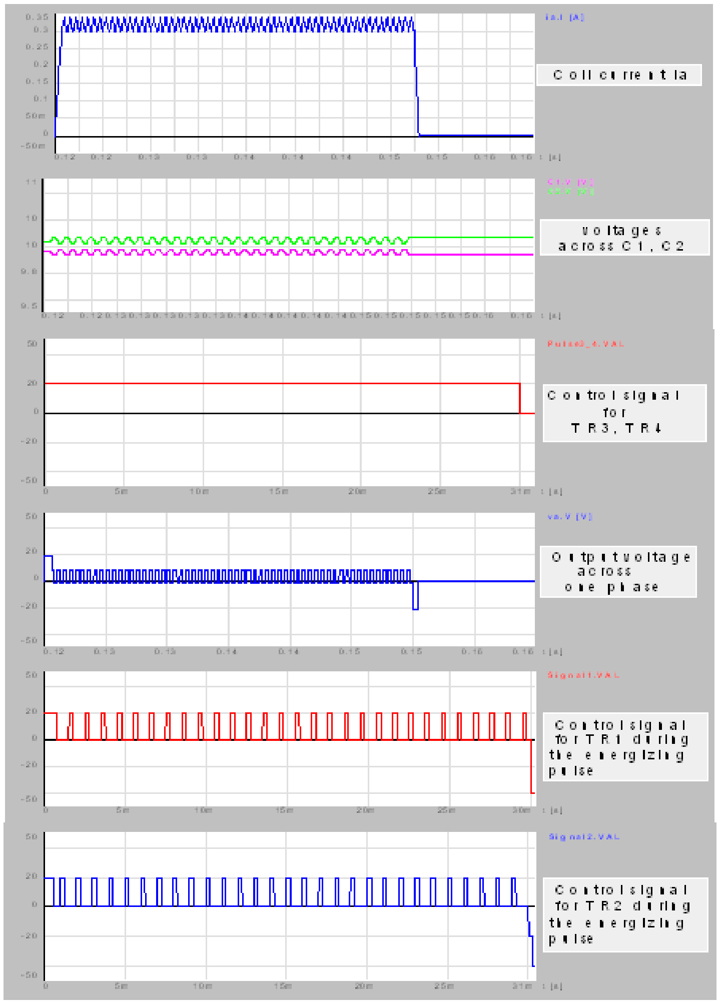


Figure 7c. voltage, current waveforms and switching diagrams for anti-parallel series connection within the region of $0<k<1/2$.

Figure 8 shows the control circuit of the main switches with galvanic isolation from the power supply. It consists of a DC-DC converter with a 5-V power supply and an opto-coupler (OK1) used for triggering the power devices (MOSFET and IGBT transistors). The main switch (TR1 or TR2) turns on directly after logic “0” is applied at the input. The electric circuit consisting of R2 and C1 serves as a protective element for the power transistor.

This paper deals only with the variable reluctance stepper motor which is most suitable for most industrial applications and purposes. The current flowing into the individual phases of the motor is turned on depending on the rotor position. For example, let’s consider an electric vehicle driven by a variable stepper motor with a maximum speed of 120Km/h which is 33.3 m/s. The total diameter of the wheel of such vehicle is 60 cm with a surrounding periphery of $0.6\times\pi=1.885m$. The maximum rotational frequency of the wheel may be calculated as follows: $f_m=\frac{33.3}{1.885}=17.68\,Hz$. So, for each complete cycle of rotation of the rotor there will be 8 pulses if a 8-pole motor is used. The maximum switching frequency should then be $17.68\times 8=141.4\,Hz$ which is corresponding to a period of 7 ms. Thus, when the motor phase is connected to the voltage supply, the current flowing into the stator inductor starts to increase exponentially according to the following equation:

a surrounding periphery of $0.6\times\pi=1.885m$. The maximum rotational frequency of the wheel may be calculated as follows:

TABLE I: Motor Parameters

Motor Parameters	Value	Units
Rotor Load Inertia	$2.02*10^{-6}$	N-m-S^2/rad
Viscous Friction	$1*10^{-3}$	N-m-S^2/rad
Self Inductance of Windin	30	mH
Resistance in Phase Winding	10	Ω
Number of Rotor Teeth	100	
Motor Torque Constant	0.05	V-S/rad

$f_m = \frac{33.3}{1.885} = 17.68\,Hz.$ So, for each complete cycle of rotation of the rotor there will be 8 pulses if a 8-pole motor is used. The maximum switching frequency should then be $17.68 \times 8 = 141.4\,Hz$ which is corresponding to a period of 7 ms. Thus, when the motor phase is connected to the voltage supply, the current flowing into the stator inductor starts to increase exponentially according to the following equation:

$$i_a(t) = \frac{E_1}{R}\left(1 - e^{-t/\tau}\right), \tau = \frac{L}{R} \qquad (15)$$

However, for $t \to 0$ the following expression is valid:

$$\Delta i_a / \Delta t = E_1 / L \qquad (16)$$

Since the value of the motor inductance varies with the rotor rotation, it is necessary to take into consideration the average value for the inductance which is calculated as:

$$L = \frac{E_1\,\Delta t}{\Delta i_a}$$

It is evident from the above analysis that the optimal timing for switching on/off the main switches TR1 and TR2 must be obtained using microprocessor technology. Furthermore, it is necessary to periodically determine the position of the rotor with respect to the stator. The rotor position is determined indirectly from the waveforms of the stator voltage and current waveforms. However, this method may not be sufficiently reliable and applicable for certain industrial applications, so the rotor position may also be determined using a certain sensor technology which is more reliable, transparent and accurate.

Another technical problem to be solved is the control circuit of the current flow into the stator coils. If the control circuit is electrically isolated from the power supply, then it is necessary to solve whether the control circuit should be galvanically isolated from the power supply or not. This problem can easily be circumvented by using an analog comparator with hysteresis loop for the control of the current flow and the set-point (desired value) of the current (reference voltage) is then obtained using PWM circuit with RC filter as shown in Figure 9. The control circuit in this figure is separated from the power circuit through a dashed line. The value of the current is measured by resistor R3.

However, The desired value of the current is adjusted using a digital PWM Processor modulated signal, filtered by a filter consisting of resistors R7, R8 and capacitors C1,C2 and then applied to comparator input 2. When the voltage drop across the resistor R3 exceeds reference voltage at input 2, the main switch TR1 respective TR2 turns off and the coil current begins to flow through switch TR4 respective TR3, and will decay until it reaches the low hysteresis limit, which is set by resistors R2, R6. The controller is powered via the DC converter, through which the galvanic isolation from the control circuit is achieved. At the end of the energizing pulse all switches TR1, Tr2, Tr3 and TR4 are turned off and the current is forced to flow through diodes D1, D2 and will decay to zero value which represents the end of one energizing pulse for one phase. The same thing is done to other phases of the stator and then the process repeats periodically.

The driver provides stepper driver outputs with an update rate of 0.1 ms to position the stepper motor. The PWM frequency should be 20 kHz.
The model provides a value between –1 and 1 as the fractional part of a 16.16 number which is passed as an int32 out of the model. The user’s application software must scale this signed integer into a uint16 for the PWM drive output where 50% duty cycle corresponds the zero current. It is also recommended that these counts be limited between 5 and 95% duty cycle to protect the drive circuitry [13].

Before implementing the system in actual hardware, we can simulate the system model in MATLAB with required inputs to achieve desired level of control and results. In MATLAB first of all the open loop system can be simulated to test under no-load condition as well as load condition. Then the closed loop is simulated with PI control. The complete practical implementation of a variable reluctance stepper motor is similar to that explained in [5].

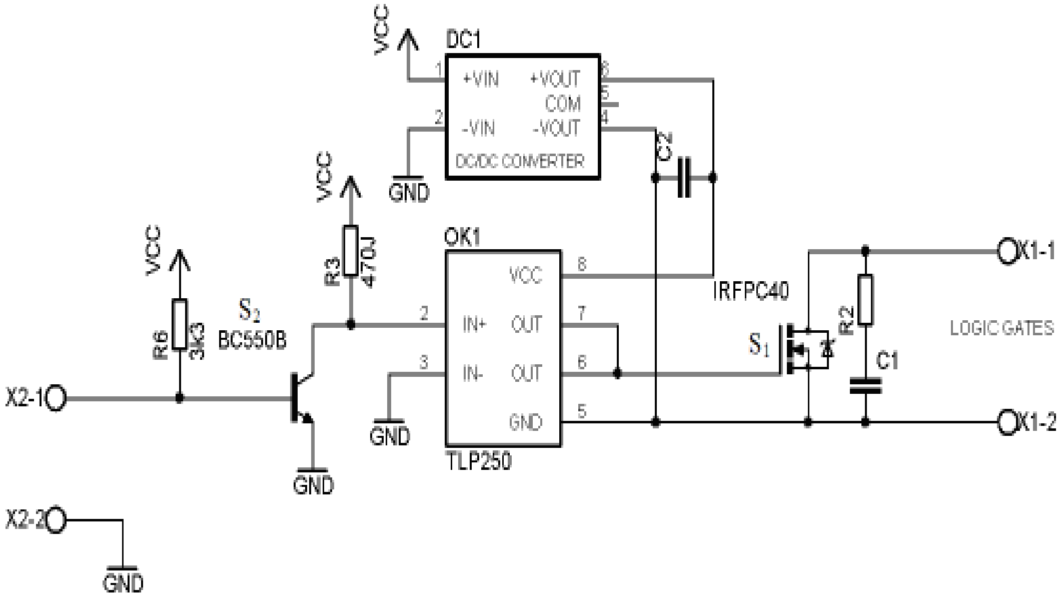


Figure 8. The main switch triggering circuit with galvanic isolation

7. PWM Control Curcuit of Variable Reluctance Stepper Motor

The basic PWM control circuit to implement a pulse width modulator for one phase (one coil) of the anti-parallel series four chopper down is shown in figure 10.

The PWM circuit may be composed of two square wave oscillators operating out of phase by the time $T_p/2$ (square wave generator1, and generator2) with two integrators (integrator1, integrator2), a flip-flop used with two pulse generators (pulse1 and pulse2) to generate the energizing pulse for one coil, and two AND gates. The output of the PI controller used to control the output voltage and current of the coil is fed to be compared with the triangular output of the two integrators and with the output of the short pulse generator used to make both transistors TR1, TR2 simultaneously on at the beginning of each energizing pulse.

The frequency of the square wave oscillators (switching frequency of the main transistor) is usually many times higher than the frequency of the circuit which is understood here as the reciprocal of the period during which the stator coil should be energized.

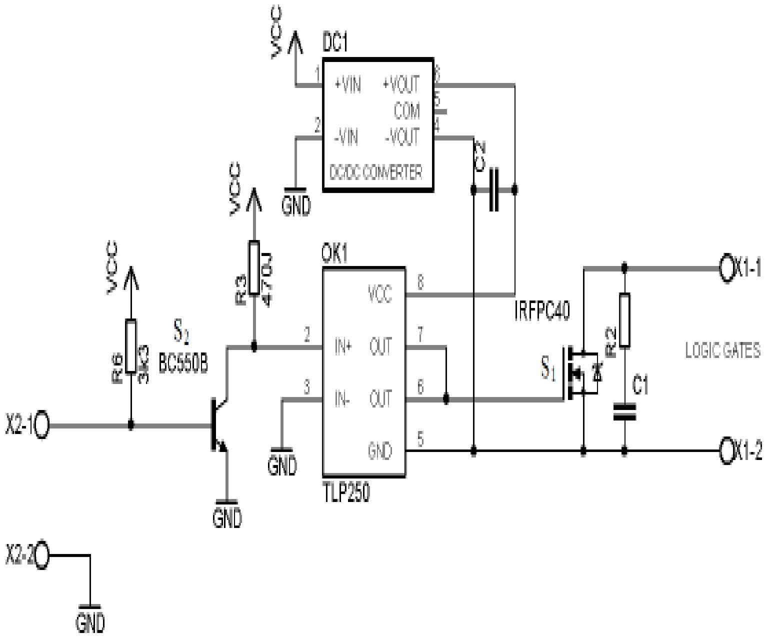


Figure 10. Four phase anti-parallel series connection of Chopper down converter with PWM modulation circuit scheme.

The input to the PWM comparator (Sum) is the error voltage, derived from a comparison of the regulator PI output with a reference voltage. This PI regulator generates the reference current which is then compared with the actual value of the coil current. The current limiter instead of current clamping has the advantage of feeding back the short-circuit current in case of fault and keeping the current fluctuation within a given range.

The main switches are driven by signals from the sequencer, square-wave generators, comparators with associated circuitry, voltage and current sensing elements (i_a, v_a). The level of the error voltage sets the pulse width or the duty cycle ($k = \frac{t_{on}}{T_p}$) of the two comparators (comparator1, comparator2) and consequently of both transistors TR1 and TR2. The outputs of these two comparators and that of the flip-flop are connected to the two inputs of the AND gates.

The turn-on and turn-off process of transistors TR3 and TR4 is controlled by the OR gate whose input is derived from the AND gates as shown in the figure. By this way, transistors TR3 and TR4 are prepared to be on during the entire period of the energizing pulse of the coil and off otherwise. The AND and OR gates output signals may be first amplified and then fed to the main transistors.

The system described above provides the underlying principle of PWM technique. But there may be a large number of it to meet special requirements. These control circuits have the facilities of soft start, current limiting and shut down in addition to pulse width control.

8. 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. Working in limit areas, where improved electronics with optimized drive sequences allow the use of less expensive motors, it is even possible to obtain a cost reduction.

The following notes explain the basics of stepper motor driving and help to select the most suitable drive technique.

The dynamic response of a stepper motor depends on the behavior of its rotor which is usually influenced by inertia, frictional forces and holding torque which are significantly dependent on the motor current.

A natural limit against any current increase by using additional resistors and 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.

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 also gives with a variable output voltage the possibility of varying the motor speed by varying its terminal voltage.

On the other hand, the additional resistance method increases the power dissipation thereby reducing the overall efficiency of the system.

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. Furthermore, the current is not limited or controlled and consequently, the torque of the motor is out of control.

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.

References

[1] D. W. Jones: “Control of stepping motors”, University of Jowa, Dept. of Computer Science, http://www.cs.uiowa.edu/~jones/step/.

[2] P. C. Sen: “Modern Power Electronics”. Published by S. Chand & Company LTD. New Delhi, 2004.

[3] W. Theodore: “Electrical machines, drives, and power systems”, sixth edition. Published by Pearson education international, New Jersey 07458, 2006.

[4] W. D. Harries and J. H. Lang: “A simple motion estimation for variable reluctance motors, IEEE Trans. Ind. Appl., pp 237-243, March 1990.

[5] P. P. Acarnley: “Stepping Motors: A Guide to Modern Theory and Practice”. IEE Control Engineering Series 19, Peter Peregrinus Ltd., 1982.

[6] T. Kenjo: “Stepping Motors and Their Microprocessor Controls”. Monographs in Electrical and Electronic Engineering, Oxford Univ. Press, 1986.

[7] 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.

[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] Y. H. William: “Handbook of small electric motors”. Mcqraw-Hill, c2001, LC number TK2537.

[11] D. Austin: “Generate stepper-motor speed profiles in real time”. Article in Embedded Systems Programming, January 2005.http://www.embedded.com//showArticle.jhtml?articleID=56800129

[12] D. W. Jones: “ Control of Stepper Motors”. Sections 5.2.10, 10.8, 10.9 and 10.10 of the Handbook of Small Electric Motors edited by W. H. Yeadon and A. W. Yeadon, McGraw-Hill, 2001. http:// www.cs.uiowa.edu/~jones/step/

[13] Woodward, module user’s guide, Stepper Motor Controller Module User’s Guide, http://www.woodward.com

Biography:

[1]**Walid Emar** received the Dipl.-Ing. (M.Sc.) degree in industrial electronics and the Dr.-Ing. (Ph.D.) degree in power electronics and control from the University of West Bohemia, Pilsen, Czech Republic. Currently, He is now teaching at Al-Isra Private University in Jordan as a full-time assistant professor. He is engaged in research and development of high power multilevel converters for industrial and traction applications, as well as dc/dc converters and regulators.

[2]**Moh'd A. Al-Eweissi** has a PH.D in electronics and space physics from Nagpur university, India in 1988. He is currently is working as assistant professor at Department . His research interest includes data acquisition system, Ionospheric irregularities, and Computer aided design.

[3]**Musbah J. Aqel** is currently working as a Professor in computer engineering in Applied Science University, Jordan. He has a PH.D in computer engineering from BHU. India. His research interest is in Image processing , Data acquisition systems, and expert systems.