Microstepping Of Stepper Motor And Sources Of Errors In Microstepping System

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Abstract— This application note discusses microstepping and the increased system performance that it offers. Some of the most important factors that limit microstepping performance, as well as methods of overcoming these limitations, are discussed. It is assumed that the reader is somewhat familiar with stepper motor driving and the torque generation principles of a stepper motor. If not, chapter 1 and 2 of this book can be read to get the background information necessary.

Keywords— Microstepping, Stepper Motor, Half Stepping, Full Stepping, Wave Stepping, Sources Of Error In Microstepping System, Sources Of Failure In Microstepping System, Quantization Error, Detent Error, Motor Pole Placement Error, Lead Screw Pitch Error, Sticktion And Backlash Error.

INTRODUCTION

Microstepping is a way of moving the stator flux of a stepper more smoothly than in full-step or half-step drive modes. This results in less vibration, and makes noiseless stepping possible down to 0 Hz. It also makes smaller step angles and better positioning possible.

There are a lot of different microstepping modes, with step lengths from 1⁄3-full-step down to 1⁄32-fullstep or even less. Theoretically it is possible to use non-integer fractions of a full-step, but this is often impractical.

A stepper motor is a synchronous electrical motor. This means that the rotor's stable stop position is in synchronization with the stator flux. The rotor is made to rotate by rotating the stator flux, thus making the rotor move towards the new stable stop position. The torque (T) developed by the motor is a function of the holding torque (T_H) and the distance between the stator flux (f_s) and the rotor position (f_r).

$$T = T_H \times \sin(f_r - f_s)$$

where f_r and f_s are given in electrical degrees

The relationship between electrical and mechanical angles is given by the formula:

$$F_{el} = (n \div 4) \times f_{mech}$$

where n is the number of full-steps per revolution.

When a stepper is driven in full-step and half-step modes the stator flux is rotated 90 and 45 electrical degrees, respectively every step of the motor. From the formula above we see that a pulsing torque is developed by the motor (see figure 1a, which also shows the speed ripple caused by the torque ripple). The reason for this is that $f_s - f_r$ is not constant in time due to the discontinuous motion of f_s.

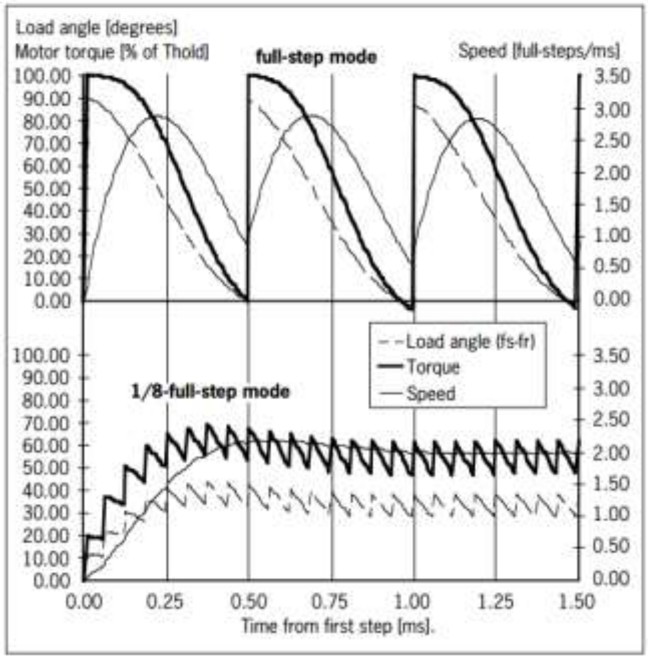


Figure 1. (A)—torque and speed ripple as function of load angle, full-step mode. (B)—torque and speed ripple as function of load angle, microstepping 1⁄8-full-step mode.

Generating a stator flux that rotates 90 or 45 degrees at a time is simple, just two current levels are required Ion and 0. This can be done easily with all type of drivers. For a given direction of the stator flux, the current levels corresponding to that direction are calculated from the formulas:

$$I_A = I_{peak} \times \sin(f_s)$$

$$I_B = I_{peak} \times \cos(f_s)$$

By combining the Ion and 0 values in the two windings we can achieve 8 different combinations of winding currents. This gives us the 8 normal 1- and 2-phase-on stop positions corresponding to the flux directions 0, 45, …, 315 electrical degrees (see figure 2a). If we have a driver which can generate any current level from 0 to 141% of the nominal 2-phase-on current for the motor, it is possible to create a rotating flux which can stop at any desired electrical position (see figure 2b). It is therefore also possible to select any electrical stepping angle— 1⁄4-full-step (15 electrical degrees), 1⁄8- full-step or 1⁄32-full-step (2.8 electrical degrees) for instance. Not only can the direction of flux be varied, but also the amplitude.

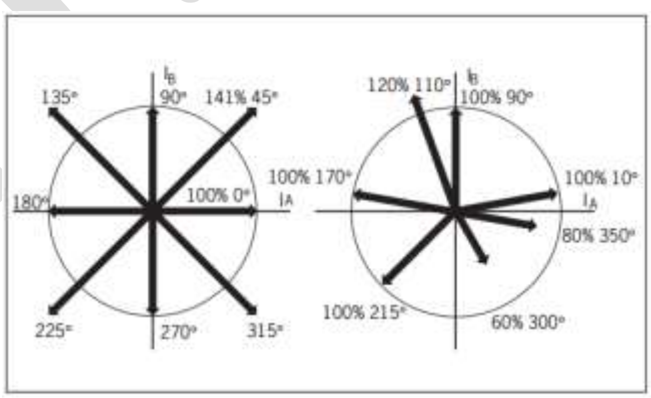


Figure 2. (A)—flux directions for normal half and full-step stop positions. Length is proportional to holding torque. (B)—microstepping flux directions. Direction and length are variable.

From the torque development formula, we can now see that the effect of microstepping is that the rotor will have a much smoother movement on low frequencies because the stator flux, which controls the stable rotor stop position, is moved in a more-continuous way, compared to full and half-step modes, (see figure 1b).

With frequencies above 2 to 3 times the system's natural frequency, microstepping has only a small effect on the rotor movement compared to full-stepping. The reason for this is the filtering effect of the rotor and load inertia. A stepper motor system acts as a low pass filter.

REMAINING CONTENTS

I. WHY MICROSTEPPING

In many applications microstepping can increase system performance, and lower system complexity and cost, compared to full- and half-step driving techniques. Microstepping can be used to solve noise and resonance problems, and to increase step accuracy and resolution.

- **Running at resonance frequencies**

The natural frequency, F_0 (Hz), of a stepper motor system is determined by the rotor and load inertia,
$J_T = J_R + J_L$ (Kgm^2), holding torque, T_H (Nm), (with the selected driving mode and current levels) and number of full-steps per revolution (n).

$$F_0 = (n \times T_H \div J_T)^{0.5} \div 4\pi$$

If the system damping is low there is an obvious risk of losing steps or generating noise when the motor is operated at or around the resonance frequency. Depending on motor type, total inertia, and damping; this problems can also appear at or close to integer multiples and fractions of F_0, that is: …, $F_0/4$, $F_0/3$, $F_0/2$, $2F_0$, $3F_0$, $4F_0$, … . Normally the frequencies closest to F0 gives the most problems.

When a non-microstepping driver is used, the main cause of these resonances is that the stator flux is moved in a discontinuous way, 90 or 45 (fullstep and half-step mode) electrical degrees at a time. This causes a pulsing energy flow to the rotor. The pulsations excite the resonance. The energy transferred to the rotor, when a single step is taken, is in the worst case (no load friction) equal to:

$$(4T_H \div n) \times [1 - \cos(f_e)]$$

T_H and n are as above and f_e = electrical step angle, 90 degrees for fullstep, 45 degrees for half-step. This shows that using half-steps instead of full-steps reduce the excitation energy to approximately 29% of the full-step energy. If we move to microstepping 1/32-full-step mode only 0.1% of the full-step energy remains (see figure 3).

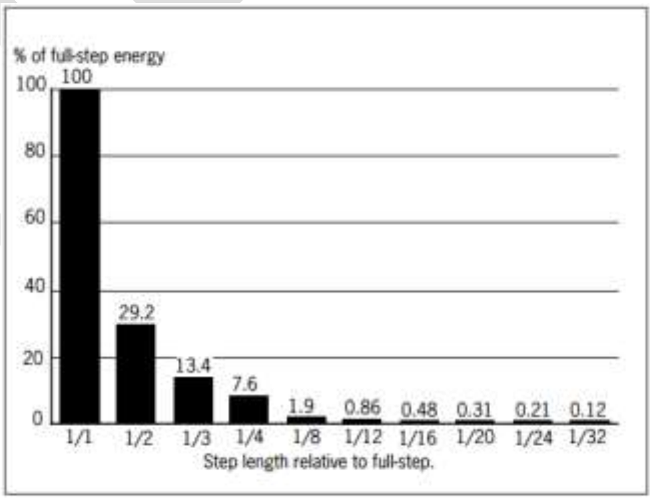


Figure 3. Relative excitation energy as function of electrical step length.

It appears that, by using microstepping techniques, this excitation energy can be lowered to such a low level that all resonances are fully eliminated.

Unfortunately this is only true for an ideal stepper motor. In reality there are also other sources that excite the system resonances. Never the less, using microstepping will improve the movement in almost all applications—and in many cases microstepping will alone give a sufficient reduction of the noise and vibrations to satisfy the application.

- **Extending the dynamic range towards lower frequencies**

When running a stepper motor at low frequencies. in half- or full-step mode. the movement becomes discontinuous, shows a great deal of ringing, and generates noise and vibrations. The stepping frequencies where this happens are below the system's natural frequency. Here microstepping offers a easy and safe way to extend noiseless stepping frequencies down towards 0Hz. Normally it is not necessary to use smaller steps than 1⁄32-full-step. With this small electrical step angle the energy transferred to the rotor/ electrical step is only 0.1% of the fullstep energy, as described above, and is so small that it is easily absorbed by the internal motor friction—so no ringing or overshot is generated by the stepping (see figure 4). The deviation of the microstepping positions from a straight line is due to the use of uncompensated sine/cosine profiles.

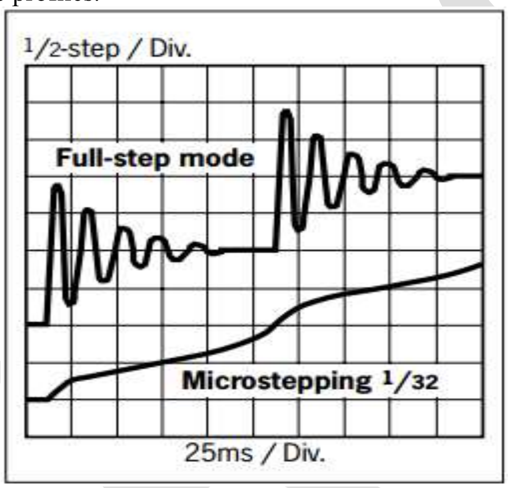


Figure 4. Rotor position as function of stepping mode.

- **Electronic "gearbox"**

In some applications, where small relative movements or higher step resolution are required, microstepping can replace a mechanical gearbox. In many applications, this is often a better and less-complex solution—even if a larger motor has to be used. To get the best results in this type of application careful motor selection and development of customized sine/cosine profiles are recommended.

- **Improved step accuracy**

Microstepping can also be used to increase stepper motor position accuracy beyond the manufacturer's specification. One way to do this is as follows. Design a microprocessor based microstepping system. Use the motor at 2- phase-on stop positions, $|I_a| = |I_b|$ (these are normally the most accurate rotor stop positions). Use a factory calibration process (manual or automatic) to store a correction value for each stop position on every motor used. The correction value is used to output "adjusted" full-step positions to the motor (see figure 5b). The adjusted positions have slightly changed current levels in the windings to compensate for the position deviations at the original stop positions (see figure 5a). This technique can be used when optimum step accuracy is the most important design criteria.

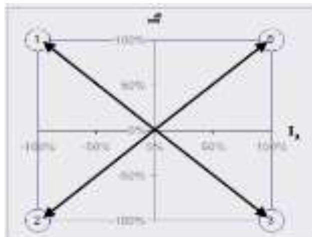
If this technique is used, the system has to use a rotor home position indicator to synchronize the rotor with the compensation profile.

- **System complexity**

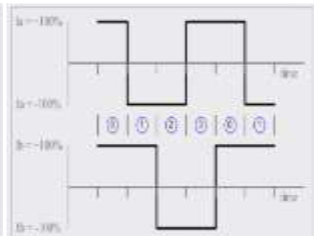
Even though the electronics for generating microstepping is more complex than electronics for full- and half-step ping, the total system complexity including motor, gearbox and transmission is less complex and costs less in many applications. Microstepping can replace or simplify gearboxes and mechanics for damping of noise and vibrations. Also motor selection becomes easier and more flexible. In a microprocessor,based microstepping application it is possible to use software and PWM-timers or D/A-converters internal to the microprocessor to replace an external microstepping controller to achieve lowest possible microstepping hardware cost. It is then possible to achieve the same hardware cost as in full- and half-step systems for similar motor sizes.

II. FULL STEPPING

In full stepping operation, the current required in each winding is either $-I_{max}$ or $+I_{max}$. A step sequence of 4 full steps makes up one complete step cycle. Note that these full step positions are the same as the odd numbered positions from the half stepping sequence.



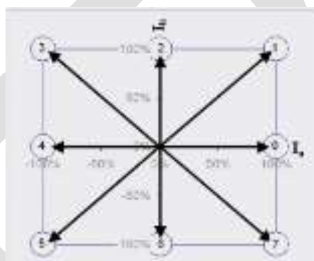
Phase Diagram



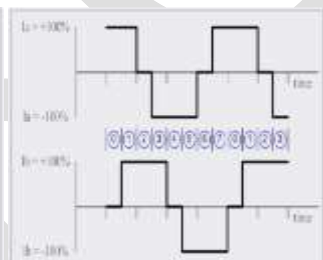
Timing Diagram

III. HALF STEPPING

In a half stepping operation, the current required in each winding is either $-I_{max}$, 0, or $+I_{max}$. A step sequence of 8 half steps makes up one complete step cycle.



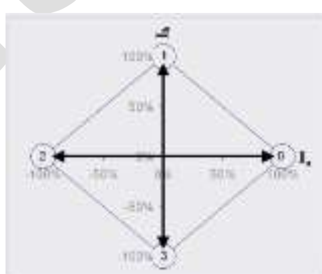
Phase Diagram



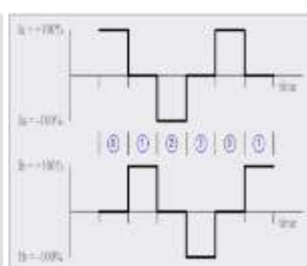
Timing Diagram

IV. WAVE STEPPING

Wave stepping is another method of full stepping, but with reduced power requirements (and corresponding torque output) since only one winding is powered at a time. The current required in each winding is either $-I_{max}$, 0 or $+I_{max}$. A step sequence of 4 full steps makes up one complete step cycle. Note that these full step positions are the same as the even numbered positions from the half stepping sequence.



Phase Diagram



Timing Diagram

V. TYPES OF MICROSTEPPING

- **Square Path**

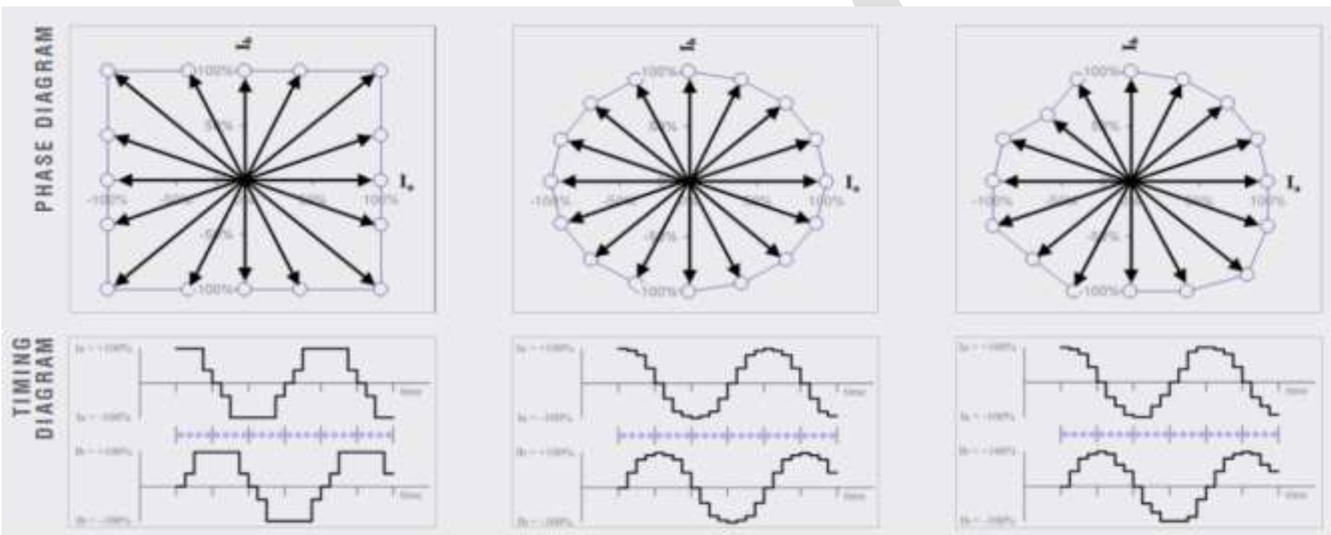
This method of microstepping provides the highest peak torque if you are limited by available supply voltage.

- **Circular Path**

This method is also referred to as sine cosine microstepping and is usually what people are referring to when they talk about microstepping, though in fact it is only one method.

- **Arbitary Path**

There would be little reason to use a method such as this. It is presented only to illustrate the possibilities. Although it looks very strange compared to the other two methods, in theory it will produce the same angular rotation of an ideal motor. Only the available thrust would differ.



Square Path *Circular Path* *Arbitary Path*

VI. SOURCES OF ERROR IN MICROSTEPPING SYSTEM

Stepper motor control systems are usually open loop. That is, the controller does not have position feedback and
position being different from the calculated position.

Therefore is not aware of the "actual" position of the motor. Therefore, it is important to be aware of possible sources of error that will result in the actual

- **QUANTIZATION ERROR**

In any digital controller, it is impossible to achieve infinitely variable I_a and/or I_b. Only discrete or "quantized" values are possible. The number of discrete values depends on the resolution achievable by the controller. For example, if the maximum current output of the controller is 1 A, and the controller has a resolution of 0.1 A, then there are 10 possible current values for I_a and/or I_b, not including 0. The number of discrete values possible determines how close mathematically the phasor can be set to a particular length and microstep angle. The error between the desired phasor angle and the actual phasor angle achieved is the quantization error. A maximum quantization error equivalent to 0.5 microsteps is a typical design requirement in any microstepping control algorithm. Note that by adusting the phasor end point to a nearby I_a ,I_b point rather than sticking to a strictly circular or square profile can often reduce the quantization error, but may add some torque ripple. Thus, the current resolution you require for I_a and I_b will be determined by the number of microsteps per step you want to achieve, the quantization error you can tolerate, and the torque ripple you can tolerate.

- **DETENT ERROR**

Detent torque is the maximum torque that can be applied to an unenergized stepper motor without causing continuous rotation. If you plotted torque versus shaft angle as you slowly rotate the stepper motor with no current in either winding, then you would find that the torque is approximately sinusoidal with shaft angle. The detent torque is just the amplitude of the sine curve. In an ideal motor, the torque curve would be perfectly sinusoidal. What is commonly referred to as "detent error" isn't due to the existence of the detent torque per se but due to the non-sinusoidal component of the detent torque. The shape of the torque curve is affected by motor pole geometry. In that sense, detent error is really pole geometry error. Because different motor manufacturers use different pole geometries, this error can vary from one manufacturer to another as well as from one motor to another.

- **MOTOR POLE PLACEMENT ERROR**

Motor pole placement error results in a varying step size. There is typically an error that repeats every 4 steps (one complete step cycle), as well as an error that repeats every full revolution. This has an obvious effect on microstepping. The microstep size within large steps will be proportionally larger than the microstep size in small steps. Pole placement error in a typical motor is less than 0.5 steps of cumulative error over half a revolution of the motor. Given that a typical motor has 200 steps per revolution, that translates to an error in step size of roughly +/- 0.5%. It is possible to eliminate pole placement error in any application simply by moving in increments of one full revolution of the motor. If that is not possible, then some error can be eliminated by moving in increments of 4 steps. However, moving in increments of 4 steps or full revolutions is clearly not microstepping. Therefore, all microstepping applications invariably suffer from some pole placement error.

- **LEAD SCREW PITCH ERROR**

Many motorized systems convert rotary motion to linear motion via lead screw. Stepper motor applications are no exception. In these types of systems, any error in the lead screw pitch will contribute to the total system error.

- **STICKTION AND BACKLASH ERROR**

In microstepping systems, mechanical sticktion and backlash are frequently much larger than the microstep resolution. There are many systems on the market capable of microstepping at 256 microsteps per step, but there is little point to this if mechanical sticktion in the system will be on the order of 5 to 10 microsteps at that microstep resolution.

VII. SOURCES OF FAILURE IN MICROSTEPPING SYSTEM

This discussion has centred on the challenges of designing a microstepping system, but there are also challenges when implementing a system. If the load on a stepper motor exceeds its maximum torque, then the motor poles will not follow the changing magnetic field and the motor stalls. To avoid this type of failure, microstepping systems must either keep the load below the maximum torque, or include position sensors to detect and compensate for stalls.

CONCLUSION

There are still compelling reasons other than high resolution for microstepping.

They include:

1. Reduced Mechanical Noise.
2. Gentler Actuation Mechanically.
3. Reduces Resonances Problems.

In summary, although Microstepping gives the designer more resolution, improved accuracy is not realized. Reduction in mechanical and electromagnetically induced noise is, however, a real benefit. The mechanical transmission of torque will also be much gentler as will a reduction in resonance problems. This gives better confidence in maintaining synchronization of the open loop system and less wear and tear on the mechanical transmission system.

In fact, taking an infinite number of microsteps per full step results in two-phase synchronous permanent magnet ac motor operation, with speed a function of the frequency of the ac power supply. The rotor will lag behind the rotating magnetic field until sufficient torque is generated to accommodate the load.

REFERENCES:

[1] "Handbook Of Small Electrical Motors" by William H. Yeadon and Alan W. Yeadon, McGraw-Hill, c2001. LC number: TK2553, H34 2001.

[2] "Microstepping Mode For Stepper Motor Control" by Baluta, G.(Gh. Asachi Tech. Univ., lasi) E-ISBN: 1-4244-0969-1, Print ISBN: 1-4244-0969-1, Publisher: IEEE.

[3] "Novel microstepping technique for disc rotor type stepper motor drive" by A. Patel, K.S. Denpiya , S.H. Chetwani in IEEE.

[4] Z. Xiaodong, H. Junjun, and S. Chunlei, "An approach of micro-stepping control for the step motors based on FPGA," in Proceedings of the IEEE International Conference on Industrial Technology(ICIT'05),pp.125–130,December2005.

[5] T. Takahashi and J. Goetz, "Implementation of complete AC servo control in a low cost FPGA and subsequent ASSP conversion," in Proceedings of the 19th Annual IEEE Applied Power Electronics Conference and Exposition (APEC '04), pp. 565–570,February2004.

[6] H. K. Bae and R. Krishnan ,"A study of current controllers and development of an over current controller for high performance SRM drives," in Proceedings of the 31st IEEE Industry Applications Society Annual Meeting(IAS'96),pp.68–75,October1996.

[7] S.-M. Yang and E.-L. Kuo, "Damping a hybrid stepping motor with estimated position and velocity," IEEE Transactions on PowerElectronics,vol.18 ,no.3,pp.880–887,2003.

[8] Botson , M., Sat J.S. and Silver S.R. (2006) Spontaneous Speed Reversals in Stepper Motor,IEEE Trans. Control Systems Technology, vol. 14, No. 2, pp. 369-373.

[9] McGuiness J. and Lahr B. (1994) Advantages of Five Phase Motors in Microstepping Drive, in Proc. 1994 IEE Colloquium on Stepper Motors and Their Control.

[10] Bellini, A., Concari , C., Franceschini G. and Toscani A. (2007) Mixed-Mode PWM for High-performance Stepping Motors, IEE Trans. Industrial Electronics, vol. 54, No. 6, pp. 3167- 3177.

[11] Weerakoon, T. S. and Samaranayake, L. (2008) Development of a Novel Drive Topology for a Five Phase Stepper Motor, In Proc. 2008 IEEE Industrial and Information Systems Conf., pp.1-6.

[12] Morar, A. (2001) Sisteme electronice de comandă şi alimentare a motoarelor pas cu pas implementate pe calculatoare pesonale (Electronic systems for stepping motor control implemented on personal computer), Teză de doctorat, Universitatea Tehnică din Cluj- Napoca.

[13] Berrezzek, F., Omeiri, A., (2009), A Study of New Techniques of Controlled PWM Inverters, European Journal of Scientific Research, Vol. 32 No. 1, pp.77-87.