Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Procedia Technology 12 (2014) 90 – 97
Procedia Technology

The 7th International Conference Interdisciplinarity in Engineering (INTER-ENG 2013)

High performance microstepping driver system based on five-phase stepper motor (sine wave drive)

Zsolt Albert Barabas[a], Alexandru Morar[b,*]

[a] Abbott Products Romania SRL, Calea Floreasca, No. 169A, 014459, Bucharest, Romania
[b] Department of Electrical and Computer Engineering, "Petru Maior" University of Tg.-Mureş, No.1, N. Iorga St.,540088 Tg.-Mures, Romania

Abstract

This paper presents the implementation of microstepping in five – phase hybrid stepper motor. The proposed drive system, in microstepping mode, achieves standard full step angles on five – phase stepper motor in the range of 1, 2, 4, 5, 8, 10, 20, and 40. Low vibration, low noise and improved controllability are achieved using microstepping. A dedicated new lower cost 5 phase pentagon stepping motor controller IC was developed to create a small but powerful package for use in high volume applications. This IC has all the drive functions of a sequencer and can control motor phase currents accurately and efficiently. The step motor driver circuitry consists of four parts as follows: micro-step sequencer, pre-driver and current control, P-channel MOS array and N-channel MOS array. The paper presents the operation of the system in both clockwise and counter clockwise direction at various speeds which is an important need in the field of robotics, automation engineering and textile industries

Selection and peer-review under responsibility of the Petru Maior University of Tirgu Mures.

Keywords: five-phase hibrid stepper motor; P-channel MOS array; N-channel MOS array; micro-step sequencer; dedicated IC; power down circuit; Pulse Width Modulation (PWM); dedicated IC; high performance drive.

* Corresponding author. Tel.:+40-728-191-897; Fax: +40-265-233-212.
E-mail address: alexandru.morar@ing.upm.ro

Selection and peer-review under responsibility of the Petru Maior University of Tirgu Mures.
doi:10.1016/j.protcy.2013.12.460

1. Introduction

Stepper Motors are used to obtain the motion profiles in the field of Robotics and Automation Engineering. Stepper motors are preferred in applications where high precision controls in position and velocity, is important such as in aerospace, printers, scanners, copiers, faxes, word processors, optical and magnetic disk devices, medical equipment, X-Y plotters, CNC machines, semiconductor fabrication equipment, agricultural automation applications, textile equipment's and telescope.

Moreover reliability, lack of contact, aging, mechanical ruggedness and availability of torque at zero speed are the attractive features of Stepper Motors. Among the various types of stepping motors, the hybrid stepping motor has a permanent magnet rotor and a toothed magnetic structure on both the stator and rotor, so that a permanent-magnet torque as well as reluctance torque can be generated [1]. Two – phase stepper motors are commonly used, but five-phase stepper motors have the superior characteristics of resolution, vibration and performance compared with two phases motors. When both stepping motors are operated in half step mode, two phase motor provides a resolution of 400 steps per revolution while a five phase motor has a resolution of 1000 steps. This resolution is 2.5 times higher when compared with two phase stepper motor. The applications where high precision, low vibration and low noise is required, five-phase hybrid stepper motor can be employed compared to two-phase hybrid stepper motor. Five-phase stepper motors are superior in dynamic performance [2]. A high precise position control using five-phase hybrid stepper motor is achieved in open loop control achieves. The higher the number of phases, smaller will be positioning deviations. Microstepping is a technology that achieves low resonance, low noise operation, at extremely low speeds by controlling the flow of electric current fed to the motor coil and thereby dividing the motor's basic step angle into smaller steps. Pulse Width Modulation (PWM) technique is usually used to excite the driver to operate the motors.

2. Structure of five – phase stepper motor

The five-phase hybrid stepper motor is developed with high resolution with no low speed resonance problems. The five-phase stepper can also be classified under permanent magnet hybrid stepper motor[15]. The stator windings are energized in the proper sequencer to produce a rotating magnetic field which turns the rotor. The significant advantage of the five-phase stepper motor is its excellent torque retention capability at high operating speed. The motor used for implementation is a five-phase hybrid stepper motor and it is shown in figure 1 and figure 2. The figures above show two cross-sections of a 5-phase hybrid stepping motor. Hybrid stepping motors are composed primarily of two parts, the stator and the rotor. The rotor in turn is comprised of three components: rotor 1, rotor 2 and the permanent magnet. The rotors are magnetized in the axial direction, with rotor 1 polarized north and the rotor 2 polarized south. The stator contains 10 magnet poles with small teeth, each of which is wrapped in wire to form a coil. The coil is connected to the facing magnet pole and is wound so it becomes magnetized to the small pole when current is run through it. (Running a current through a given coil magnetizes the facing poles to the same magnetism, either North Pole or South Pole.). The two facing poles form a single phase. Since there are five phases, A trough E, the motor is called a 5- phase stepping motor. There are 50 teeth on the outside of the rotor, with the teeth of rotor 1 and rotor 2 mechanically offset from each other by half a tooth pitch.

Figure 3 and figure 4 help to describe the relationship on the positions of the stator and rotor teeth when magnetized. When phase A is excited, its poles are polarized south. This attracts the teeth of rotor cup 1, which are polarized north, while repelling the teeth of rotor cup 2, which are polarized south. Therefore, the forces on the entire unit in equilibrium hold the rotor stationary. At this time, the teeth of the phase B poles, which are not excited, are misaligned with the south-polarized teeth of rotor 2 so that they are offset at 0.72°. When excitation switches from phase A to B shown in figure 4, the phase B poles are polarized north, attracting the south polarity of rotor 2 and repelling the north polarity of rotor cup 1. In other words, when excitation switches from phase A to B, the rotor rotates by 0.72°. As excitation shifts from phase A to phases B, C, D and E, then back around to phase A, the stepping motor rotates precisely in 0.72° steps. To rotate in reverse, the excitation sequence is reversed as phase A, E, D, C, B, then back to phase A. High resolution of 0.72° is inherent in the mechanical offset between the stator and rotor, accounting for the achievement of precise positioning without the use of an encoder or other sensors [1].

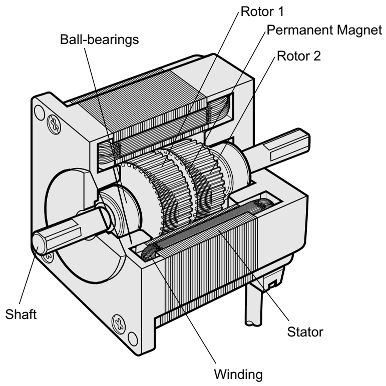

Fig. 1. 5 Phase Stepping Motor Cross-Section Parallel to Shaft

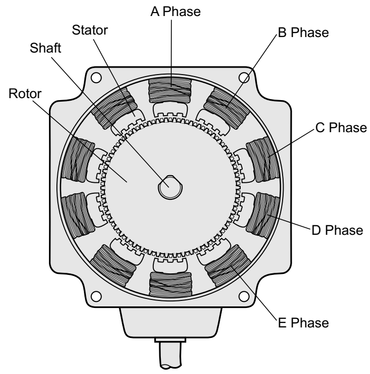

Fig. 2. 5 Phase Stepping Motor Cross-Section Perpendicular to Shaft

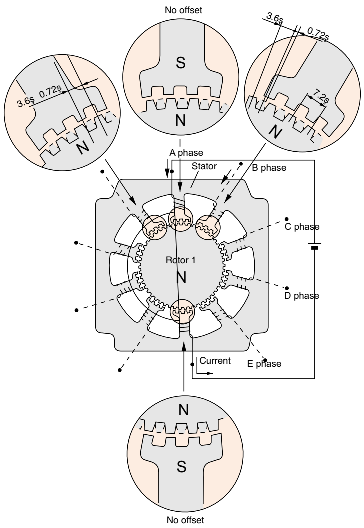

Fig. 3. When Phase A Is Excited

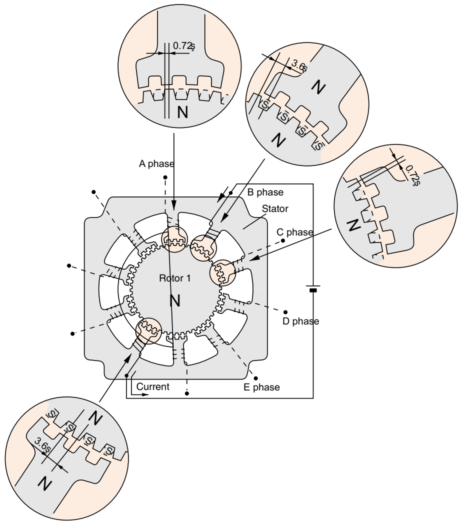

Fig. 4. When Phase B Is Excited

3. Constant current driving technology

The driving technology with constant current is shown in figure 5. The constant current drive, on the other hand, is now the most commonly used drive method, since it offers excellent torque performance at high speeds. The stepping motor rotates through the sequential switching of current, flowing through the windings. When the speed increases, the switching rate also becomes faster and the current rise falls, resulting in lost in torque. The chopping of a DC voltage that is far higher than the motor's rated voltage will ensure that the rated current reaches the motor, even at higher speeds. The current flowing to the motor windings, detected as a voltage, through a current detecting resistor, is compared to the reference voltage. Current control is accomplished by holding the switching transistor 2, ON when the voltage across the detecting resistor is lower than the reference voltage. That is when it hasn't reached the rated current or tuning transistor 2, OFF. When the value is higher than the reference voltage that is when it exceeds the rated current, thereby providing a constant flow of rated current. [16] Voltage – Current relationship in constant current chopper drive is shown in Fig. 6.

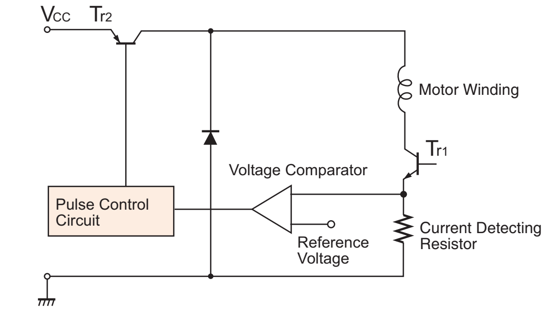

Fig. 5. Constant current control

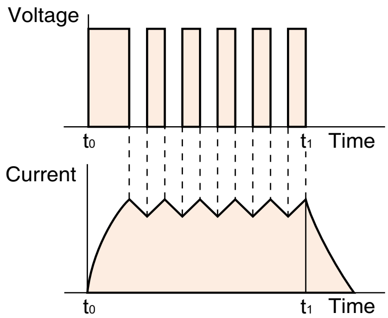

Fig. 6. Voltage – Current relationship in constant current chopper drive

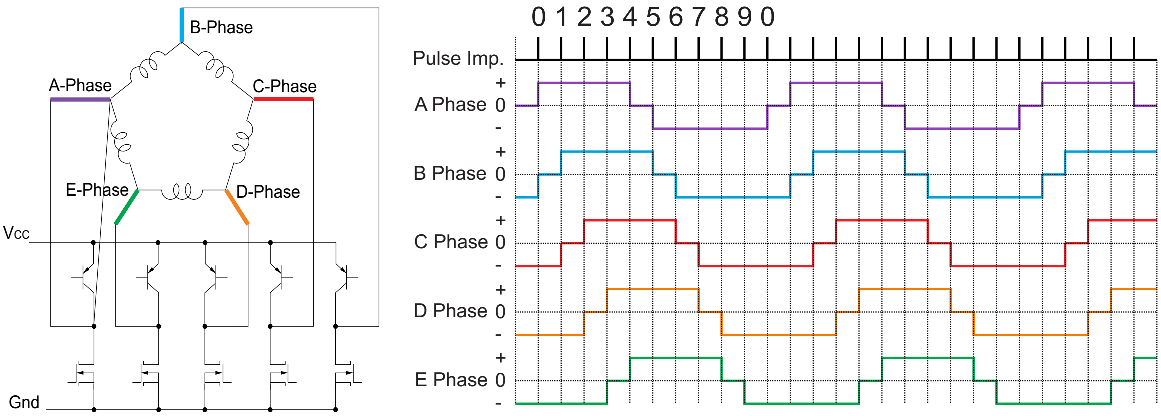

Fig. 7. Pentagon 4-phase excitation sequence

4. Driving and controlling five phase stepping motor

The 5 phase stepper motor control use a simple 4 of 5 phase excitation (pentagon configuration) which employs a simpler and well balanced current control scheme. Pentagon 4-phase excitation sequence (full step – 0.72º/ step) is shown in figure 7. This is system to the 0.72º stepper motor, in which four phases are excited. The step angle is 0.72º. It offers a great damping effect, and therefore stable operation. Pentagon 4- 5 -phase excitation sequence (half step – 0.36º/step) is shown in figure 8. A step sequence of alternating the 4-phase and 5-phase excitation produces rotation at 0.36º per step. One rotation may be divided into 1000 steps.

The 5 phase stepper motor control use a simple 4 of 5 phase excitation (pentagon configuration) which employs a simpler and well balanced current control scheme. Pentagon 4-phase excitation sequence (full step – 0.72º/ step) is shown in figure 7. This is system to the 0.72º stepper motor, in which four phases are excited. The step angle is 0.72º. It offers a great damping effect, and therefore stable operation. Pentagon 4- 5 -phase excitation sequence (half step – 0.36º/step) is shown in figure 8. A step sequence of alternating the 4-phase and 5-phase excitation produces rotation at 0.36º per step. One rotation may be divided intro 1000 steps. In a general pentagon driving system, the current flows as shown in figure 9. The relation between I_0 and I_{0M} is as follows: $I_0 = 4 \times I_{0M}$. With some driving system, the relation can also be as follows: $I_0 = 2 \times I_{0M}$.

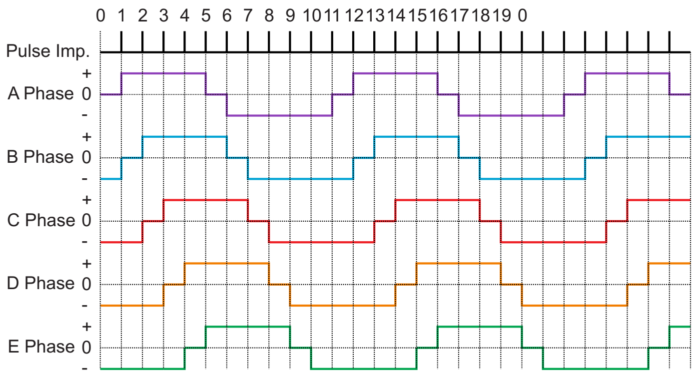

Fig. 8. Pentagon 4-5-phase excitation sequence

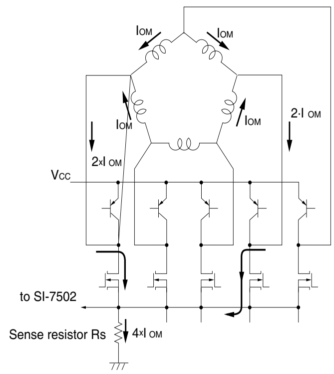

Fig. 9. Coil current flow at pentagon driving

5. Micro - stepping drive system

One of the advantages of microstepping operation of the stepping motor is much higher resolution of the motor shaft positioning. This is achieved without complex and expensive rotor position feedbacks or gear box. Another advantage is improved single-step response of the motor by substituting one big step for multiple micro-steps [5]. Microstepping operation of the stepping motors is achieved by suitable changes of the values of the phase currents [5]. There are two basic ways for microstepping control. The first way is to vary the currents in sinusoidal law. In this case the maximum static torque is constant and theoretically any step angle can be achieved. This method is used for stepping motors with permanent magnet rotors. The second way is to use the standard control with rated phase currents and only during the commutation the new values in small steps so as the natural step is divided into several micro-steps- so called vernier control[3] [4]. The aim of the paper is to develop a first method. This paper presents a 5-phase stepping motor driver with dedicated IC with built-in micro-step controller having a bipolar constant current PWM system, in which a power MOSFET is employed an output stage,

The typical IC uses P channel MOSFETs to the high side and N channel to the low side of the power bridge circuit used to drive a motor. This configuration allows the pre-drive circuit to employ an equivalent circuit structure represented by figure 10. A typical drive IC composed of a monolithic IC circuit (for current control) and a hybrid IC circuit consists of discrete signal transistors and resistors. The monolithic IC, which controls phase current, uses a bipolar process. It was not reasonable to include a separate middle scale logic circuit to be used for sequencing functions due to its negative characteristics, higher cost and more importantly, its larger size (real estate). Because of this situation, an exclusive C-MOS gate array was used for the sequencing control circuitry. The stepper motor driver circuitry consists of four parts as follows [15][16]:

1. Micro-step sequencer (ex. EIC 0231)
2. Pre-driver and current control (ex. EIC 0241)
3. P channel MOS array (ex. SLA 5012)
4. N channel MOS array (ex. SLA 5011)

This drive configuration is the most current 5 phase stepper motor drive currently in use today.

The design procedure of this driver is described detailed as follows. For compact design consideration, a five phase stepping motor driver chips EIC 0231, EIC 0241, SLA 5012and SLA 5011 is adopted. EIC 0231 is a special designed IC that imbedded a function sequence (micro-step) circuit to control the pre – driver. (EIC 0241). When this chip receives an input clock, the sequence circuit generates proper phase sequence to drive the output stages. The chip EIC 0241 (pre-driver and current control) operated with current feedback to achieve a constant current driver. A constant current driver can drive a motor according to the winding current of the motor.

EIC 0241 is also equipped with a dedicated circuit to drive gates of P-channel MOSFETs and N- channel MOSFETs so as to simplify the design of driving stages. The configuration of the proposed driver is illustrated in figure 11. EIC 0231 can operate in 8 different modes (A 3 bit D_0, D_1,D_2 signal input allows a 8 step change in motor resolution). Table 1 shown the motor resolution selection. A 4 bit signal input (I_0, I_1, I_2, I_3) set the motor current (min. 0.5A, max. 3A).

The resolution can be selected simply with a DIP switch. DIP switch D_0, D_1, D2 select the micro-step angles in the range of 1, 2, 4, 5, 8, 10, 20 and 40 . In a normal condition, the drivers were controlled by two signals termed as clock (CLOCK) and direction (DIR) pulses. In this design, PCL-838 ISA Stepping Motor Control Card PC –Lab Card was used to provide a self-test function. The PCL-838 has been specifically designed as user-friendly solution for your stepping motor control application. It's on-board 80C31-CPU, along with a 16MHz clock crystal, and two 8254 programmable timers, controls up to three driver axis (one motor/channel) independently and simultaneously. Digital pulse and directional output signals control each motor by step rate and clockwise/counter-clockwise (CW/CCW) direction.

Table 1 Motor resolution selection

D2	D1	D0	Step Angle (division/ step)
H	H	H	0,72º (1)
H	H	L	0,36 º (2)
H	L	H	0,18 º (4)
H	L	L	0,144 º (5)
L	H	H	0,09 º (8)
L	H	L	0,072 º (10)
L	L	H	0,036 º (20)
L	L	L	0,018 º (40)

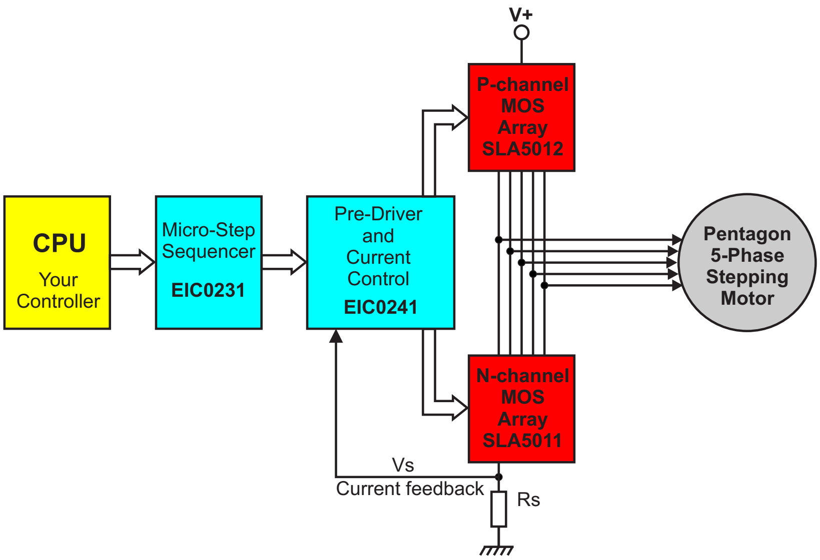

Fig. 10- The block diagram of pentagon five-phase stepping motor micro-step control

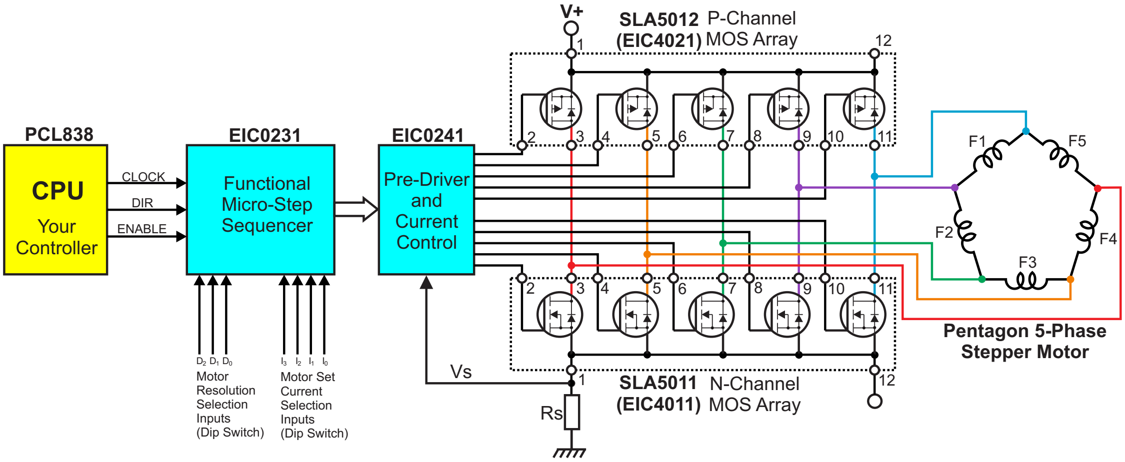

Fig. 11- The configuration of the proposed driver

6. Results

The micro-stepping of five-phase stepping motor driver is obtained. Natural step angles are divided in the range of 1, 2, 4, 5, 8, 10, 20 and 40. The dimension of the driver is approximate 110x80x35 millimeters, which is smaller than a business card in length and width. A positioning card (PCL-838) plugged inside an IBM PC is utilized to test the accuracy and the speed of the driver. For easy implementation, this positioning card was implemented with ISA bus interface. This card output clock and direction signals as inputs to the tested driver. A software package including several functions was designed with C language so as to be feasible to test this driver. The most used function of this package was linear acceleration and deceleration so that the motor may start and stop more smoothly and allow the motor to reach a higher speed that in the case of without acceleration and deceleration. A five – phase stepping motor Model PK566-NB-A8, with a rated current of 1.4A, 1.1Ω, from VEXTA ORIENTAL MOTOR [15] [16], Japan, was used to connect with this proposed driver.

7. Conclusion

This paper presents a design of a compact and intelligence five-phase micro-stepping motor driver. With special designed IC, the driver is smaller than a business card, although it is a compact driver. The micro-stepping scheme using five-phase stepper motor in both clockwise and counter clockwise direction is implemented under various speeds. Actually the concept of micro-stepping is obtained through current control technique. This method is very cost effective compared to the system available in the market. Self – test function also imbedded inside the PCL-838 (80C31-CPU) [20] of the driver so that engineers can check whether the driver is normal or not without a external equipment. Considering the positioning ability and precise speed control, this proposed driver can provide valuable Robotics and Automation Engineering applications involving either position control or speed control. This type of driver can also be implemented in rotating the camera of the robot, where precise positioning of the camera in both directions is required to capture image or video with minute details.

This type of driver can also implement, in the design of textile material, where both direction of spindle with precise positioning are required.

References

[1] Kenjo T, Sugawara A., *Stepping Motors and Microprocessor Control*, London, Oxford Clarendon Press, 2003.
[2] Acarnley, P.P., *Stepping Motors: a Guide to Modern Theory and Practice*. Peter Peregrinus Ltd.,ISBN: 0 86 341027 8, London, 1992.

[3] Takasaki, K., Sugawara, A., Stepping *Motors and Their Microprocessor Controls*. Clarendon Prsss, ISBN: 019859386 4 hbk, Oxford, 1994.
[4] Morar, A., *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, 2001.
[5] Morar, A., *Comanda inteligenta a actionarilor electrice cu motoare pas cu pas*, Editura MEDIAMIRA, Cluj-Napoca, 2007.
[6] Marc Botson, Jeffrey S. Sat and Stephen R. Silver, *Spontaneous Speed Reversals in Stepper Motor,*IEEE Trans. Control Systems Technology, vol. 14, No. 2, pp. 369-373, Mar. 2006.
[7] J. McGuiness and Berger Lahr, *Advantages of Five Phase Motors in Microstepping Drive*, in Proc. 1994 IEE Colloquium on Stepper Motors and Their Control.
[8] A. Bellini, C. Concari, G. Franceschini, and A. Toscani, *Mixed-Mode PWM for High-performance Stepping Motors,* IEE Trans. Industrial Electronics, vol. 54, No. 6, pp. 3167-3177, Dec. 2007.
[9] T. S. Weerakoon and L. Samaranayake, *Development of a Novel Drive Topology for a Five Phase Stepper Motor,* In Proc. 2008 IEEE Industrial and Information Systems Conf., pp.1-6.
[10] Puran Adhikari and Michael Okaro, *Five-level Five-phase PWM Signal Generation using FPGA,* IEE Trans. Industrial Electronics, vol. 55, No. 5, pp. 1-5, May, 2008.
[11] Berrezzek Farid, Omeiri Amar, *A Study of New Techniques of Controlled PWM Inverters,* European Journal of Scientific Research, Vol. 32 No. 1, 2009, pp.77-87.
[12] Shyh-Ming Jong, Shun-Te Siao, Yuan Kang, *An Implementation of FPGA Based Driver For approaching High Resolution of Five-phase Hibrid Stepper Motor,*Machine Learning and Cybernetics (ICMLC), 2010 International Conference, vol. 5, July 2010, pp.2543-2548.
[13] Baluta, Gh., *Actionari electrice de mica putere-Aplicatii,* Editura POLITEHNIUM, Iasi, 2004.
[14] *** *The Basics of Stepping Motors*, Oriental Motor Co.Ltd, Japan, 2010.
[15] *** *Application Guides of Step Motor,* Oriental Motor Co.Ltd, Japan, 2010.
[16] *** Oriental *Motor-Stepping Motors-General Catalog-2012/2013*.
[17] *** *STMicroelectronics, Motion Control Application Manual*, 2010.
[18] **** LEM Module,* Data Book, Geneve, Switzerland, 2010
[19] *** Portescap: "*Motion Systems*", 2011.
[20] *** PCL – 838 Stepping Motor Control Card,, PC – Lab Card Series Laboratory Manual, 2008