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eng. Emanoil TOMA

Ph-D THESIS

Abstract

OPTIMIZATION OF THE ELECTRICAL DISCHARGE MACHINING TECHNOLOGY IN TERMS OF CONSUMED ENERGY

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keywords:

EDM Pulse Generator, current source, electrical efficiency, microstepping technique, EDM process control.

Introduction

Motivation

Nowadays the electrical discharge machining is considered one of the most fulfill procedure to dimensional processing of hard material and generate complex geometrical shapes in metals. The progress made throughout the years, regarding the understanding and shaping the diversity of phenomenon that occur at the material sampling through electrical discharge, which is linked to the evolution of technology, led to the continuous performance increase of the processing machinery and to the expanding of the applying area of this technological field [85, 117].

The occurrence of new and faster electronic devices of high voltage and high intensity, led to the development of power electronics through new energy converting circuit topologies, based on the switching of power devices. The increase in the computing power of personal computers led among other things to the development of electric circuit simulation programs. Detailed analysis of the behavior of circuits that were subjected to various requests eases up the designing of new circuits with high energy conversion efficiency. This benefits the procedure of electrical discharge machining because the pulse generators are enable to generate high voltage and current pulses with parameters, that were up until now impossible to reach. The developed research into this piece of work complete this step by finding the electric circuit topologies which generate voltage and current pulses with parameters, that can vary between wide limits and high energy conversion efficiency.

Working assumptions and theses goals

The data experimentally obtained by different researchers reinforced by the explanation of the complex phenomena, that take place during the electrical discharge, justify the effort of generating controllable high voltage current pulses of small duration. The reduction or even the absence of white layer allows the processing using only one loop, without the need of further finishing. Although the specific energy causing the material to turn into steaming state is higher than the specific energy for passing into liquid state, the energetic component, which binds through thermal conduction to the object subjected to the processing, is much lower at reduce pulses. The higher attrition of an Electrode Tool determines the use of low pulses especially by the processing with thread-lie electrode and micro-processing. By the processing with massive electrode, the generator must be capable of providing pulses of long duration and large current by roughing and pulses of small duration by finishing. The current's polarity change at the end of each impulse is necessary while using alternative polarity, at high frequency, hundreds of kHz.. MHz, favors the priming of the discharging through additional thermal activation of the dielectric from the interstice thanks to the oscillation of the elementary electric dipoles.

There are two proposed solutions for the pulse generator: one is based on using a series-parallel LCC resonant converter which is behaving like a current source at the commutation frequency of 150 kHz, the other one is based on the synchronous Buck convertor made with the newest MOS transistor versions which are in turn made of substrate of Silicon Carbide (SiC). The first solution, which utilizes the MOS transistors on the Silicon substrate commuting at zero voltage in order to reduce the commutation losses, has an energy recovery circuit which recovers the energy stored in the magnetic field of the spool and presents an easy commutation regime for power rectifier diodes. The second solution resulted from a comparative study, done through simulation, between different types of Buck convertors, a study that highlights the superior efficiency of the Buck converter with SiC-MOS. By combining two Buck converters in one symmetrical structure you get an H Bridge convertor, capable of providing widely controllable pulses parameters.

In the electric erosion processing, the automatic adjusting of the active gap is of great importance. A fulfill system ensures that the time necessary for processing through the reduction of the share of abnormal pulses is reduced, the movement speed is adequate and variable, the resolution is at its best for the movement of the electrode tool. The focus of the study was the making of fulfill circuits used for commanding stepper motor by microstepping technique.

Thesis structure

The thesis is structured in five chapters, the first one being the result of the bibliographical study and the other three being, mostly the result of personal research.

Chapter One presents the Electrical Discharge Machining principle, the main electrical erosion machining techniques, the short history and state art of domain. In this chapter are presented the main theories referring to the ignition and the evolution of electrical discharge phenomenon, the EDM pulses types in the real process, the material removal mechanism, the gap energetically account, processing characterization of materials, and technological characteristics. Finally, there are showed same examples of EDM machines.

Chapter 2 is an extensive chapter, in which are presented in a proper manner the aspects of different stepper motor's commands. The phenomenon presentation and electrical circuits behavior are usually accomplished by simulation results and electrical schemas conceived by the author for PSpice simulation.

It was attached a great importance to this chapter for a lot of reasons:

- The growing of linear displacement system resolution, correlated with the growing of maximum stepper motor rotation speed, determines the improving of the automatic gap control system performances. This has as a result the reduction of machining time and of the energy consumption.
- The phenomenon analysis of electrical circuits following the improving of electrical energy conversion efficiency, such as the effort in physical realization of PCB, have utility for the next chapter, which refers to the pulse generators.
- The experiments of low voltage, where the electronic devices are low cost and have proved their utility in highlighting of some dangerous functioning situations and in development of some techniques of reduction of the electromagnetically radiation influence.

Chapter 3 deals in the first part with the issue of the pulses generators. The own researches focused on the improvement of electrical efficiency. At first the pulses generator with inductive current limiting technique, based on the Buck converter, realized with MOSFET, was approached, in order to determine the electrical efficiency.

Then, through a comparative analysis of different types of Buck converters, the high electrical efficiency realized with SiC-MOSFET was highlighted, especially at high switching frequency. There was conceived a pulse generator, capable of providing the voltage pulses of both polarities for ignition. Also, the current pulses can be controlled in wide range of magnitude and duration and moreover they can have both polarities. There were developed variants of pulse generator based on current source behavior assured by the peak current feedback technique. By interleaved technique there were obtained a good current pulse shape control and an important ripple reduction.

Then, a systematic analysis of series-parallel LCC resonant converter was made. It was conceived an electrical scheme of pulse generator based on LCC resonant converter and it was observed a good functionality and a high electrical efficiency in all the cases faced in EDM process. There were also conceived two block schemas.

Chapter 4 presents the issue of the automatic gap control brief. There were conceived two block schemas of control, based on digital signal controller. The first schema uses pulse generator with interleaved resonant LCC converter. The second schema uses H bridge Buck converter with SiC MOS FET, command by interleaved technique.

Chapter 5 presents the final conclusions and the perspectives/ outlooks opened for further research.

The Ph-D Thesis contains 263 pages, 271 figures and 9 tables.

Chapter 1. EDM process; Fundamentals and state of art

1.1. The principle of electrical erosion processing

The action of dimensional electro-erosion process is based on the effects produced by an electric discharge of short duration, localized in a very small volume, between the two conducting electrodes separated by a dielectric medium.
Erosion processing fits into one general category of processing methods using concentrated energy in which the removing of material occurs discontinuously and cumulative, the dimensional processing is the cumulative result of incremental erosion processes, concentrated in time and space.
In electrical erosion processing principle, the workspace has the structure shown in Figure 1-1.

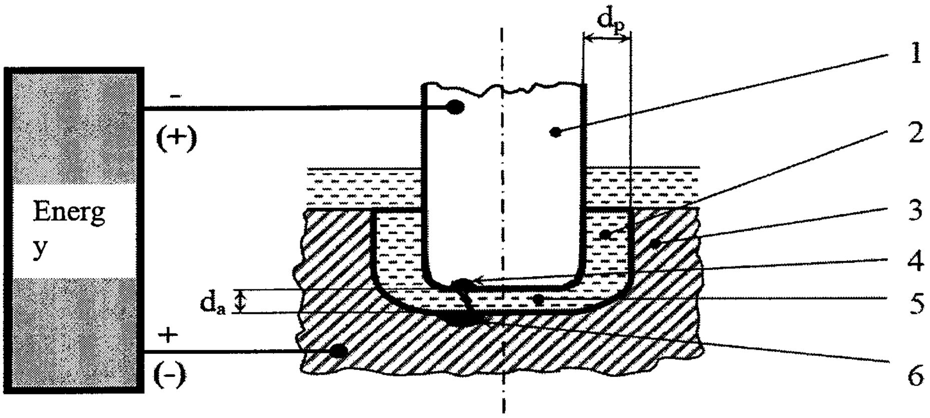

Figure 1.1. The main structure of work space, with electrical erosion processing

The object to be processed (3) is a semi fabricated made of conductive material.
Transfer Object (1) is an auxiliary electrode (electrode - tool), acting as a positioning agent and as a macroscopic localizing
The working environment (2) is a liquid dielectric, acting as location and spatial concentration of discharge, discharge cooling products and electrode erosion.
Agent erosive electrical discharge pulse is generated by local environmental breakthrough dielectric between the electrode - tool and the object to be processed, among them the application of a voltage pulse from a source of electricity.
Energy is likely to effect the thermal, mechanical and electromagnetic (mainly the thermal component). This local energy destroys the integrity of the electrode surfaces and removes material from the resulting material, creating crater erosion (6) on the surface of the object to be processed, respectively crater wear (4) on the surface of the electrode tool.
Elementary processes of erosion is actively engaged in the gap (5). As the process evolves between the electrode - tool and work piece forms a passive gap (2) which discharge the products of erosion and refreshes gap dielectric liquid
The cumulative effect of elementary processes of erosion is the the reproduction, with a certain precision of the spatial shape of the electrode-tool, in the target object's volume.

1.2. Variants classification of the electro-erosion machining process.

Depending on the lightning priming, the electro-erosion machining processes are as follows:
- Electrical discharge machining by erosion primed by piercing a dielectric medium

• Electrical discharge machining by electrical pulses primed by breaking micro-contacts (break contact with electric erosion). This variant is characterized by a large amount of material removed per time unit on the surface of the object to be processed. However, this variant has experienced a substantial industrial development because the surface's roughness is rather big and considerable big structural changes caused by thermal very intense micro sources.

Electrical Discharge machining erosion primed by piercing a dielectric medium

It is characterized by the absence of direct contact between the object and the electrode-tool, as shown in Figure 1-1. Erosive gap size is maintained at a value of 0.005 ... 0.5 mm by the automatic feed system of the technological system, being dependent on the conditions and parameters .The thermal energy component leads to local melting and vaporizing of some material micro volumes on the surface of the two interacting objects.

The Mechanical Component of the disruptive energy causes the expulsion of liquid phases formed as a result of previous actions with specific formation of craters on the surface of objects in interaction. The selective sequence of these sequences leads to a formation of craters crowds statistically evenly distributed over the entire surface of the two interacting objects. This mode of removal of material explains the anisotropic surface roughness processed by erosion.

From the point of view of the electrode- tool's shape, the electrical erosion by piercing a dielectric medium is sub-classified in:

Electrical Erosion with massive electrode

It is known as the electric erosion by copying the electrode's shape. The final shape to the object being processed is obtained by copying the conjugate, achieved by the electrode-tool. In case of processing without an additional automatic feed equipment of the electrode, provides its penetration in the object being processed by simply moving straight and constant. When using additional generation equipments, remains the same principle of automatic feed overlapped with additional movements in a law-like dependence of the main movement of the feed.

Electrical erosion with filiform electrode

It is known under the name of electrical erosion by wire cutting. Filiform shaped electrode diameter (less than 0.5 mm) with an axial motion is usually led by industrial computers, after a certain profile, which can be very complex, without impacting the processing parameters.

1.2. Process productivity

Thermal processes have the decisive role in the material removal. Processability of different materials can be characterized by thermo-physical properties. The Palatnik's criterion is expressed by the formula 1.1:

$$\pi = c \cdot \rho \cdot \lambda \cdot \theta_t^2 \tag{1.1}$$

Where:

• c: specific heat
• ρ: density
• λ: thermal conductivity
• θ: absolute melting temperature

Electrical erosion workability of a material is inversely proportional to the criteria of Palatnik [36, 117].

Productivity processing can express the simplest formula

$$Q_p = K \cdot P_m \cdot f(d_m) \tag{1.2}$$

Where:

Q p = processing productivity
K = a constant dependent on the PO and ET materials, the nature of the dielectric, etc.
Pm = average power developed in the workspace
dm = mean value of the asset gap

Sampling of material is possible with the condition of enrollment size "d" of the asset gap in a narrow range of values (Figure 1.2.) Because: - For values of d < d_{min} - short circuit occurs between OM and ET
- For values of d> demine - discharge does not occur (blank discharge).

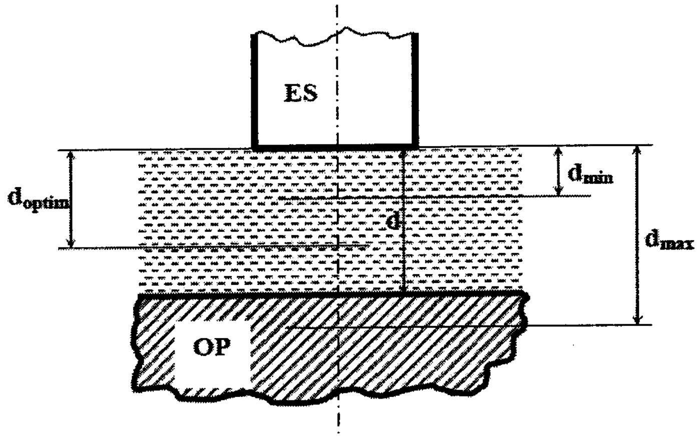

Figure 1-2 Values domain of the active asset gap

Material sampling from a single discharge increase the local gap, resulting in discharge location in other areas of the electrode surfaces. Thus is obtained the removal of material from the surface layer of PO or ET, accompanied by increasing the average value of the average gap around the optimum value, followed by the removal of a new layer of material. The described mechanism also leads to reproduction in the OP's volume of the ET's shape, in time. [36, 116, 117].

1.4 The evolution of the domain

The development of the dimensional processing through electric erosion was determined on one hand by the fundamental theoretical researches of scientific domain, and on the other hand by the perfection and development of certain industrial branches, such as power electronics, automation of processing technique, machine tools design, microelectronics, technology information.
The first alerts of industrial use of this process dates back to World War II when the Boris and Natalia Lazarenko husbands propose "reversing" the breaking of electric contacts and direct utilization of erosion contacts. Thus the foundations were laid for a new industrial application process which was about to revolutionize the concept of workable technology.
We continue by summarizing below the important moments in the history of dimensional manufacturing process development through erosion.
Between 1950-1960:

- The emergence of the first technological processing systems..
- Development of relaxation generators.

Between 1961 1960-1970:

- The emerge of the first industrial commanded pulse generators.
- First processing machinery through electric erosion with wire electrode.

- NC command introduction at processing machinery through electric erosion with wire electrode. The emerge of first industrial commanded pulse generators.

Between 1971-1980:

- The application of CNC controls at the processing machinery through electric erosion.
- Development of electrical erosion processing by adoption specific technological equipment (planetary motion of the tool-electrode, automatic feed after two or three directions, conical cuts with wire electrode, etc).

Between 1981-1990:

- First attempts to equip the electro-erosion processing machines with automatic feeding electrode-tool storage.
- Using stepper motors for automatic feed systems to electrical erosion processing machinery by copying the shape of the electrode-tool.

Between 1991-2000:

- Using the processing machines through electric erosion within the flexible manufacturing lines (including technological systems of electrode-tool processing)
- Using CAD, CAM, CIM systems for electric erosion processing.

From 2001 up to now:

- The development of CAD, CAM, CIM systems for electric erosion processing.
- The emergence and development of process simulators.
- Improvement of control algorithms (fuzzy controllers, neural networks, genetic algorithms)
- Diversification of EDM applications in micromachining, deposit of materials (micro and nanotechnologies).
- Further development of technological systems; linear motor drives

The main technological performance achieved today in the electrical wire erosion processing

- minimum gap 5 μm
- roughness (Ra): 0,05 μm
- minimum internal radius: 5 μm
- graphite electrode wear: 0,02%
- copper electrode wear : 0,05-1%

The main technological performance achieved today in the electrical wire erosion processing:

- form deviation: ±1,5 μm
- roughness (Ra): 0,05 μm
- minimum internal radius: 15 μm

For this procedure there are already specific fields of application, where the use of other dimensional processing methods is not required, the electric erosion is, by itself, able to complete all the processing requirements for the roughing to finishing or super finishing [85, 117].

1.5 Fundamental

1.5.1 Classification of the main phenomenon that occur during electrical erosion processing

Electrical discharge in pulse is characterized by energy development in a highly spatial and temporally concentrated form. A short duration discharge (10 ... 100μs) and a low gap (10...50μm) lead to energy densities on the order of 300000 W / mm3, respectively energy densities on the order of 30000 J/mm3 in the cvasi-stable phase of elementary discharge.

The developed energy from the unloading column is transmitted to neighboring environments (OP surface, ES surface and working environment) leading to physical and chemical transformations.

The main phenomenon that are occurring during the discharge into impulse and also the consequences on the technological process can be summarized as:

a) Phenomenon at the surface of machined part:

- local changes of the state of aggregation of material
-expulsion of material with the formation of erosion craters
-structural changes of the surface layer of OP.
-emergence if micro deforming and micro crack in the surface layer due to rapid local temperature variation.

Effects:
-local corrosion of OP surface
-change in the material properties of the surface layer of OP

b) Phenomenon in dielectric working environment:

- local dielectric piercing
- generating a shock wave that propagates in the fluid volume
- local fluid temperature increase
- thermal decomposition of dielectric liquid

Effects:

- discharge of erosion products from the gap
- modifying the composition and properties of the dielectric liquid
- general worming of the liquid

c) Phenomenon on the surface of the electrode-tool:

- local changes of the state of aggregation
- expulsion of material with the formation of crater wear
- changes in the structure of the material surface layer
- pyrolysis products deposit on the ES surface

Effects:

- wear through erosion for the surface of electrode-tool
- changing the material properties of the surface layer of ES
- formation of protective film on the ES surface.

1.6. Types of discharges in actual processing conditions

The phenomenons that contribute to the removal of material, to the evacuation of the erosion products and maintaining the dynamic balance of the overall process is highly complex, so that the conditions in which the individual electrical discharges are occurring are different from an impulse to another. Thus, the effects of individual discharge are variable, not all the voltage impulses applied to the electrodes are producing effects to individual discharges are reflecting in modification of the waveform of electric characteristics (voltage and current)

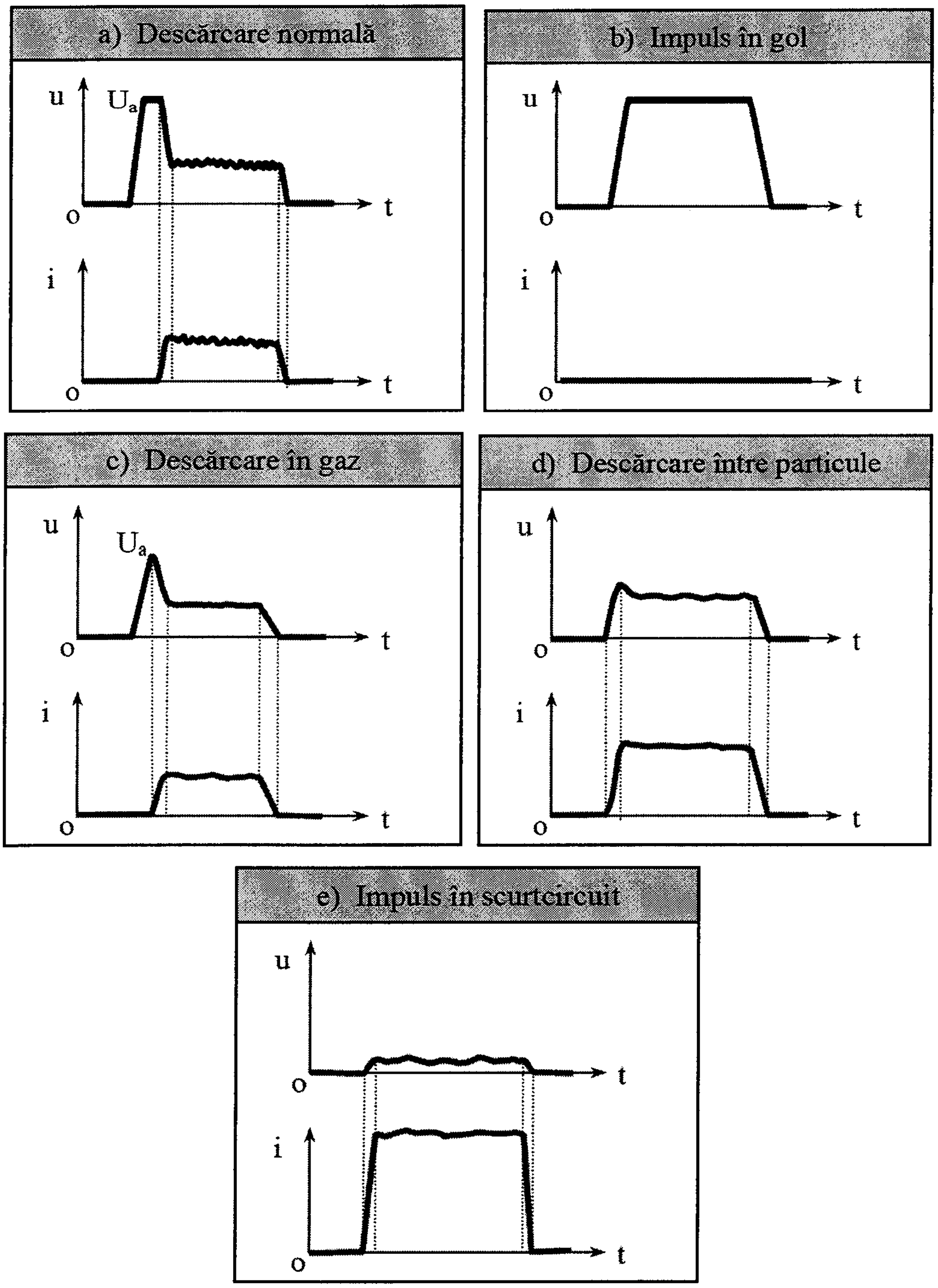

Figure 0-1. The pulses type in real EDM process

Figure 1-23 shows the main types of pulses:

- Normal discharge pulses (figure 1.23.a.)
- Open circuit pulses (figure 1.23.b.)
- Abnormal discharge pulses
    - Gas discharge (figure 1.23.c.)
    - Discharge between particles (figure 1.23.d.)
- Short circuit pulses (figure1.23.e.)

1.9.2. Material Expulsion

The material expulsion from the surface of the active electrode's material occurs as a result of the cumulative effects of a wide variety of phenomena. The mechanisms that lead to extraction (removal) of material are systematized on the nature of the underlying phenomena, such [117]:

- Expulsion of thermodynamics;
- Expulsion (breaking) thermo mechanical;
- Expulsion (plucking) electrostatic;
- Expulsion electrodynamics

The large diversity of activating -expulsion leads to a pronounced dependence of sampled material quantity to the pulse duration, as well to the polarity. In Fig. 1.30, this dependency is represented, in un interval of 1 minute, for constant energy discharges. Material sampling from the Anode is maximum in case of pulse value around μs [36]. In other researches, the maximum is reached with a much smaller pulse duration, the chart is quite similar thought, dependent of the materials and work conditions [4,5]

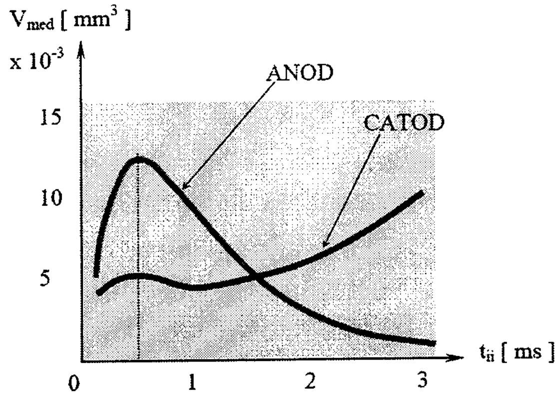

Figure 1. 30. Dependence of average volume, sampled by the pulse duration and polarity, at elementary discharges with constant energy [36]

Chapter 2. Research on increasing the performance of the electric drive subsystem for linear motion

Objectives

In the processing through electric erosion, the automatic control system of the tool electrode advance plays an important role. The performance of the control system is decisively influenced by the performance of the actuator: DC brush motor, stepper motor, linear motor, piezoelectric actuator, ferroelectric actuator, magnetostrictive actuator, hydraulic actuator.

The stepper motor is the optimal solution for processing electro-erosion with massive electrode, due to the advantages: the ability to correlate the incremental operation of the motor with discrete evolution of electrical erosion processing, storing momentary position through electromechanical blocking of the rotor at the last control impulse applied, wide speed control range by simply changing the control frequency, good dynamic, possibity to rapidly reverse the direction of movement.

This chapter aims the increasing efficiency of energy conversion from the power supply to the electric drive process, improving movement resolution and increasing the maximum speed by finding solutions / high performance electric circuits for controlling the stepper motor.

The Problem of electrically operated with stepper motor

A stepper motor use in electrode tool displacement system has some advantages in comparison to the other types of motors:

- Possibility to assures correlation between incremental functionally of motor and discrete character of process evolution.
- Possibility to memorize the position by electromagnetic break after the last pulse applied to the motor.
- Rapid change of revolution's direction.
- Simplified of cinematic chain with a good resolution for linear displacement.

The most used type of stepper motor is the hybrid motor, which is a constructive combination between the permanent magnet stepper motor and variable reluctance stepper motor.

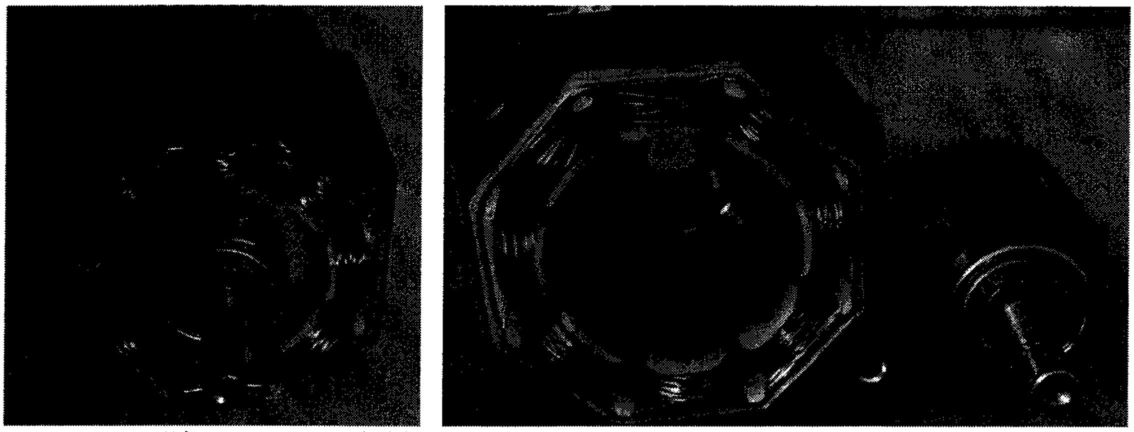

Figure 2-18. Hybrid stepper motor used in experimental research

For experimental set a so called "eight wires" stepper motor was used. This can be configured as unipolar or bipolar connection. Bipolar connection assures high speed for current modification trough the motor coils (both for increase and decrease the current value) by using a high voltage of power supply ($V_{alimentare}$) and two H-Bridges. In this case a current limiting technique is necessary .

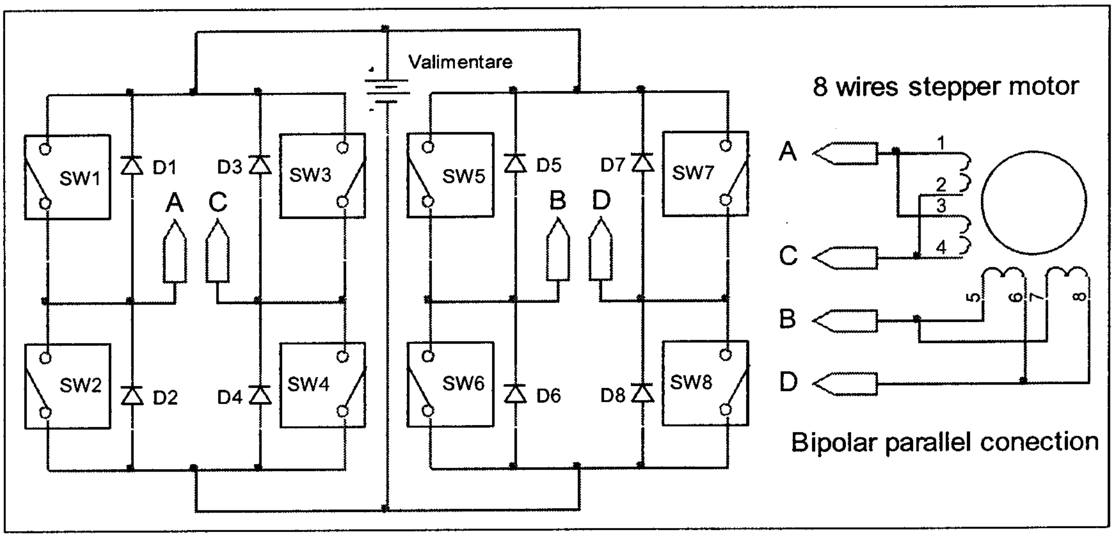

Figure 2-22 Command of bipolar eight wire stepper motor with two H Bridges

Looking at the figure2-22, for power supply which haves a nominal voltage gives by equation 2.1, a positive nominal value for current trough phases A-C is assures for switches SW1, SW4 in "ON" state and switches SW2, SW3 in "OFF" state.

$$V_{alimentare} = I_{motor} \cdot R_{motor} \tag{2.1}$$

For motor used in experimental set which haves R_{motor}=1.1Ω, I_{motor}=3A, results $V_{alimentare}$=3.3V .

For simplified permanent stepper motor, the states of motor coils and chronograms of current for wave command are showed in figure 2-5. Red color for wire suggests the north magnetic pole, blue color suggests the south magnetic pole, and black color suggests an inactivated coil. The other types of command are showed in the next figures. For microstepping high value for $V_{alimentare}$ and current limiting technique is necessary .

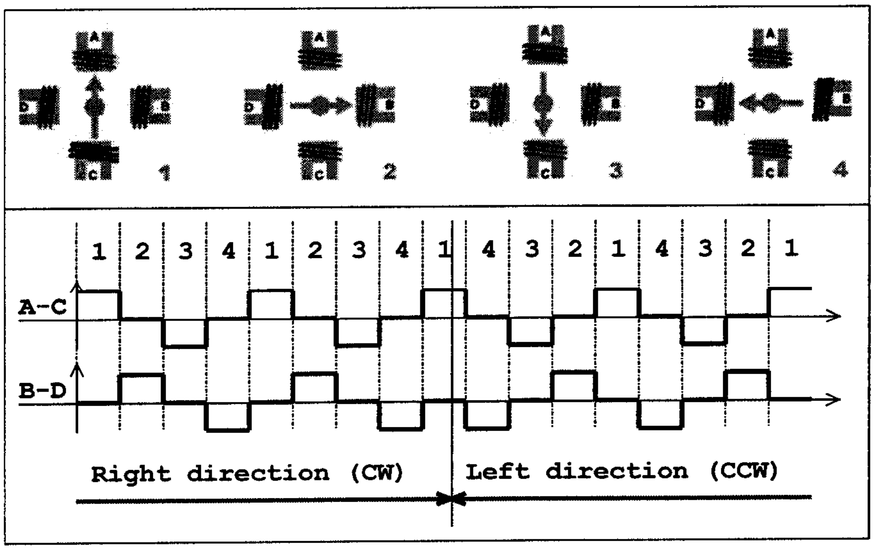

Figure 2-5 Wave drive: the states of motor's coils and current evolution

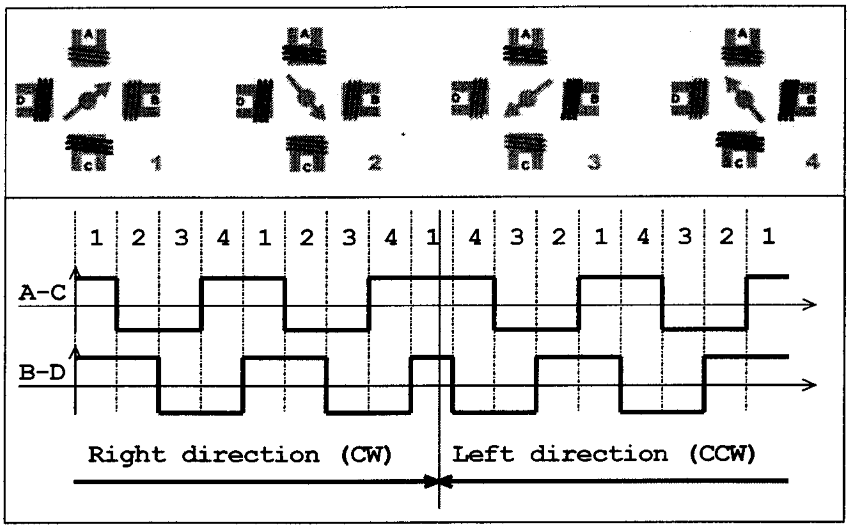

Figure 2-7 Full drive: the states of motor's coils and current evolution

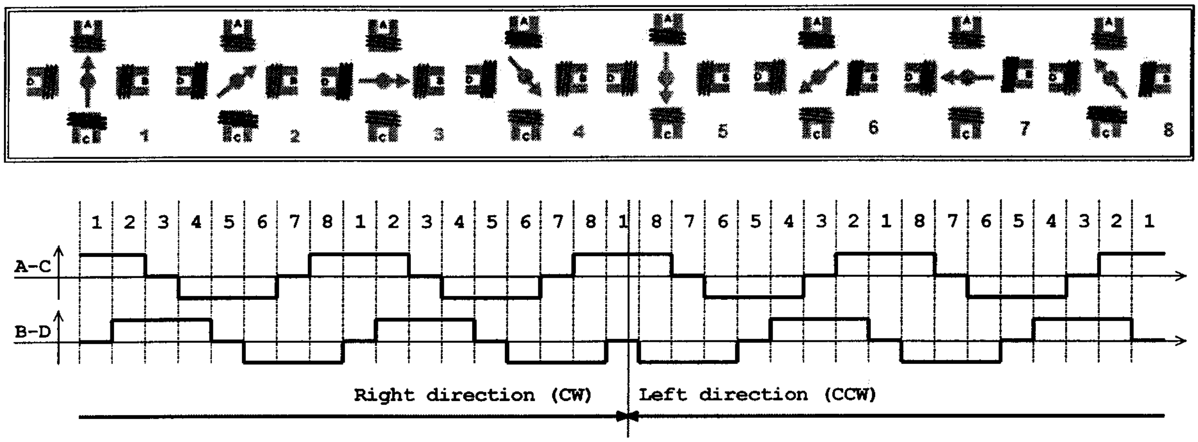

Figure 2-8 Half step drive: the states of motor's coils and current evolution

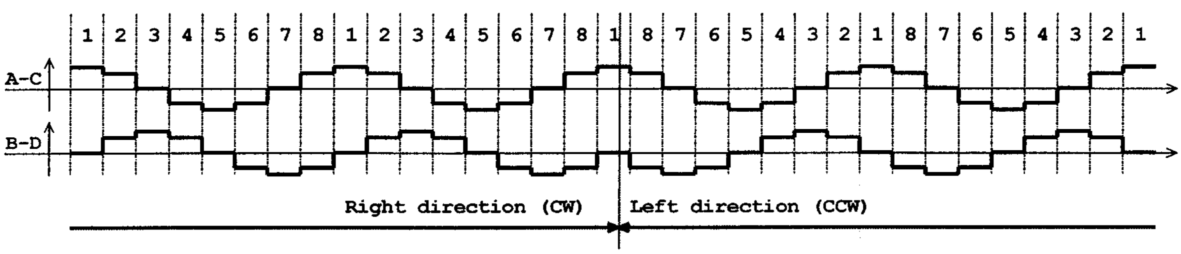

Figure 2-10. 1/2 micro-stepping sin-cosine drive: the evolution of current through the motor's coils

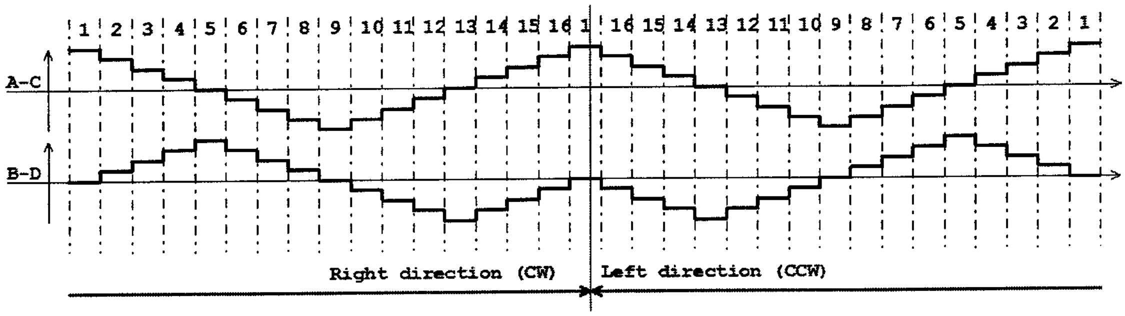

Figure 2- 11. 1/4 micro-stepping linear drive: the evolution of current through the motor's coils

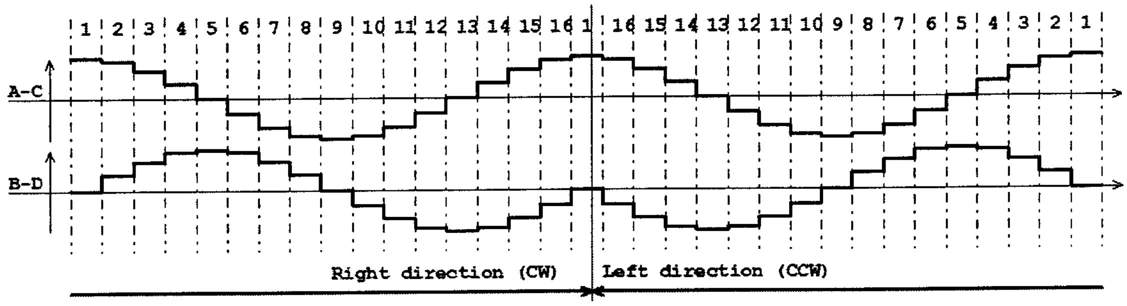

Figure 2-12. 1/4 micro-stepping sin-cosine drive: the evolution of current through the motor's coils

For simplified permanent magnet stepper motor presented above, the magnetic force is constant in every state for sine-cosine drive. Maximum of force is obtained in full step command and minimum in linear command.

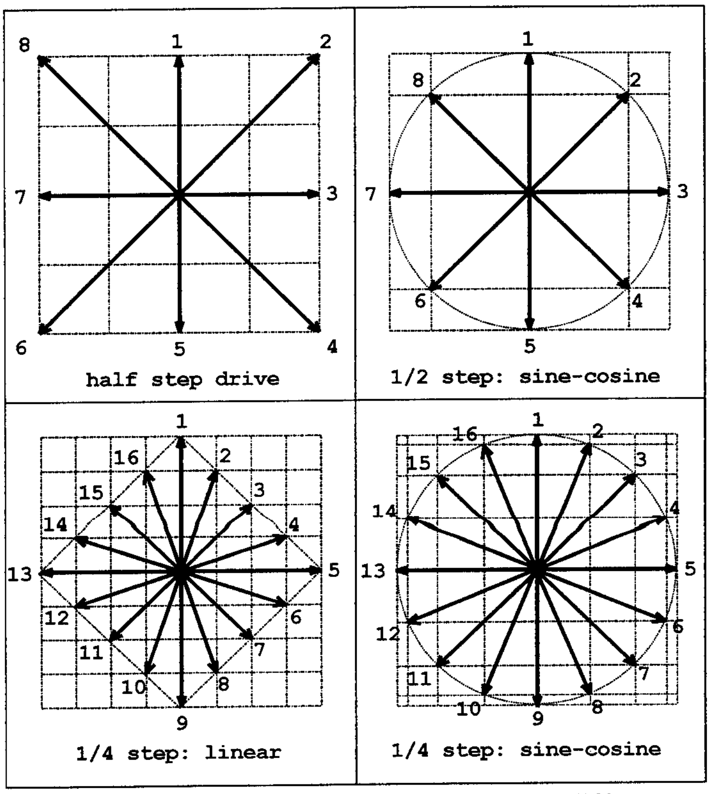

Figure 2-13. Synthesis of magnetic force in every state for different types of drives

Peak Current Control

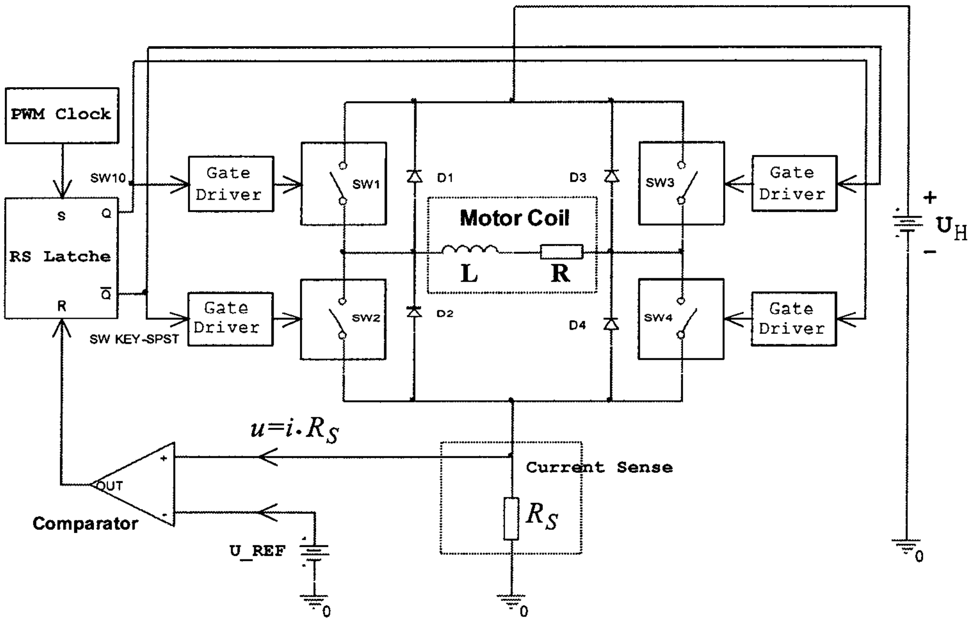

Figure 2-60. Peak current limiting principia schema for one phase of bipolar stepper motor

In figure 2-60 is showed the principia schema to limit current trough the motor coil, using digital and analog circuits. The current sense resistor gives a voltage proportional with the current trough the motor coil. This value is compared with the reference voltage. When the current exceeds a maximum imposed value, the output of analog comparator resets Latch, the output Q becomes zero logic, the PWM pulse is finished and switches SW1, SW4 is turned "OFF" and switches SW2, SW3 is turned "ON". The voltage applied on the coil inductance becomes negative (approx $-V_H$) and current trough the motor coil becomes decrease.

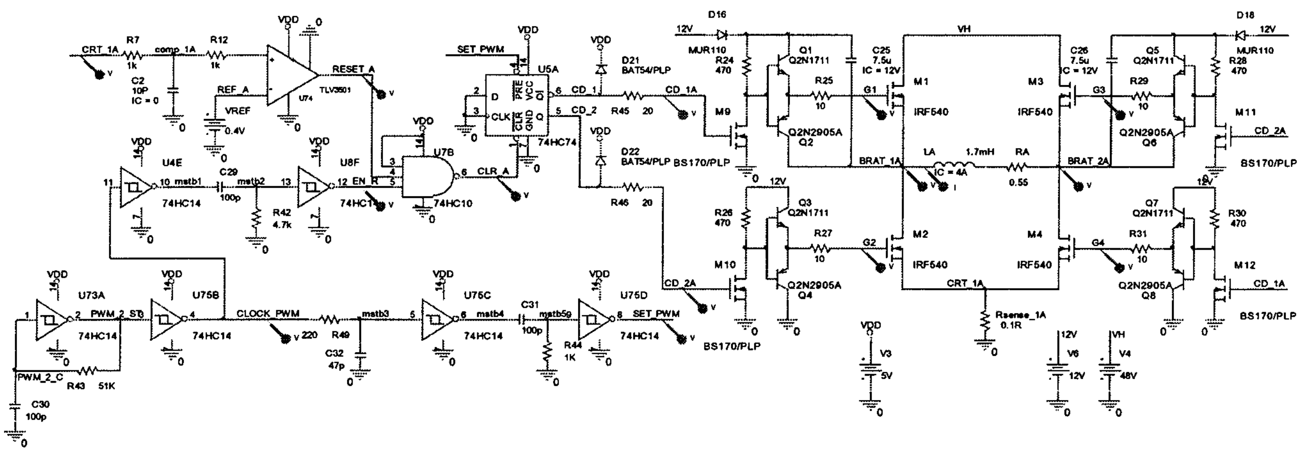

Figure 2-70. Electrical schema, used in Orcad - Pspice simulation for highlighting the peak current limiting principle

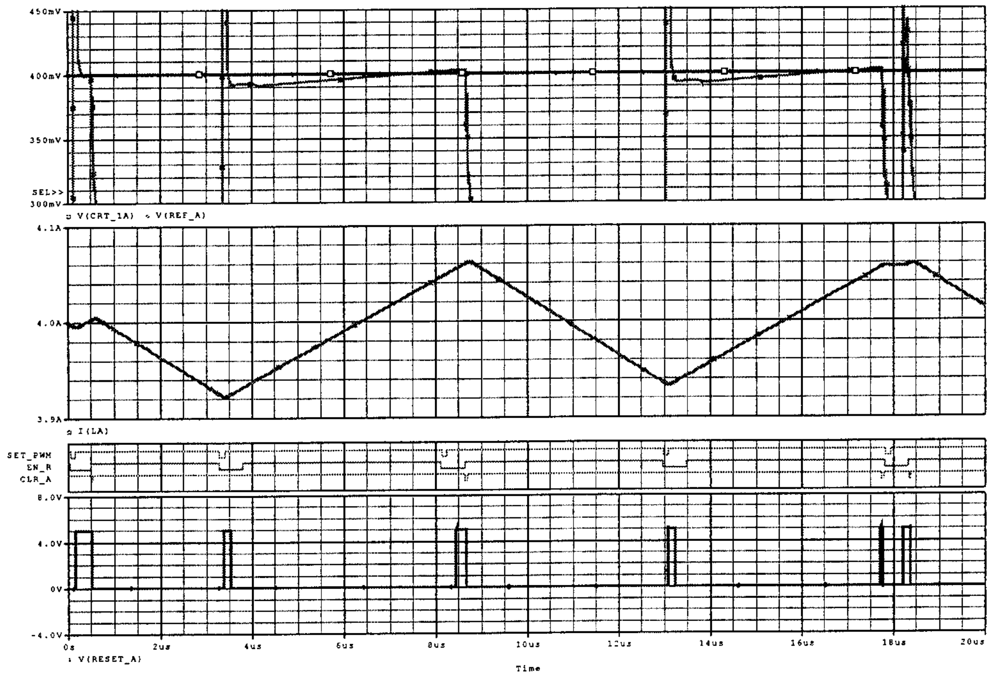

Figure 2-71. Chronograms results from simulation

The author was conceived an electrical schema which is presented in figure 2-71. By electrical simulation in Orcad Pspice, result the chronograms showed in figure 2-76. In central plot we can observe the evolution of current trough the motor coils. The motor coil was emulated by an inductance in series with a resistor, back electromagnetic force doesn't appear, but errors are negligible. Modifying the value of reference voltage (VREF), applied to the analog comparator TLV3501, determines the modification of average value of current trough the motor coil.

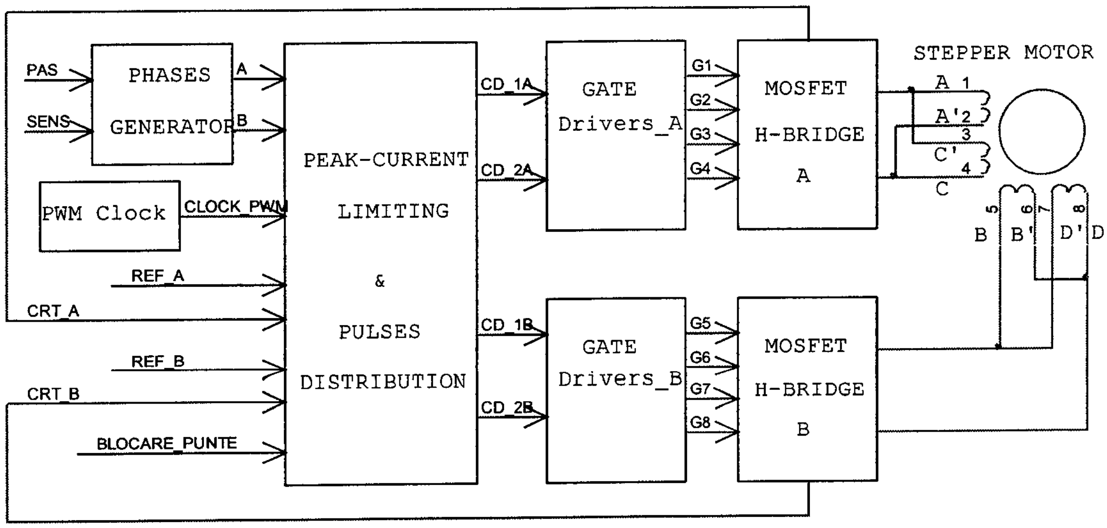

Figure 2-71. Block diagram of conceived bipolar motor driver schema for electrical simulation

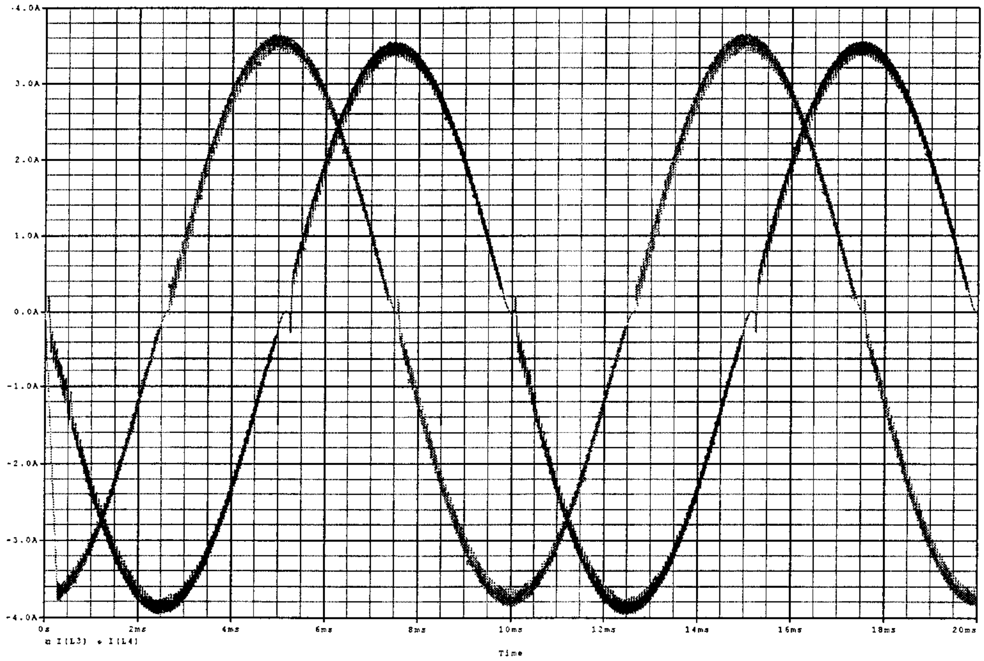

Figure 2-76. The evolution of current through the motor's coils gives by electrical simulation

Peak current control using digital signal controller

Spectacular evolution of semiconductor's technology and microelectronics was bringing to apparition of the very complex circuits which include analog and digital functions. Microcontroller is a computer on chip, which includes digital processing functions and peripheral blocks. Digital Signal Controller (DSC) has supplementary facilities to assure digital control in motor drive and switching mode power supply. Peak current limiting technique is easy to realize with DSC as shows in figure 18. A physical prototype was realized and sine cosine drive for stepper motor was performed .

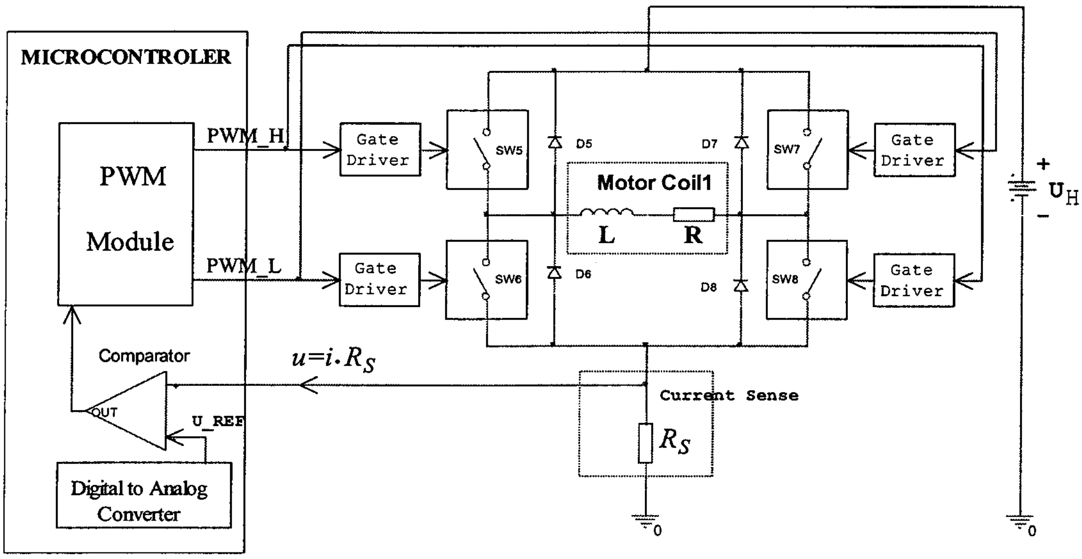

Figure 2-79. Peak current limiting principia schema for one phase of bipolar stepper motor, using DSC with integrated analog comparator

Figure 2-88. Experimental set up with realized prototype

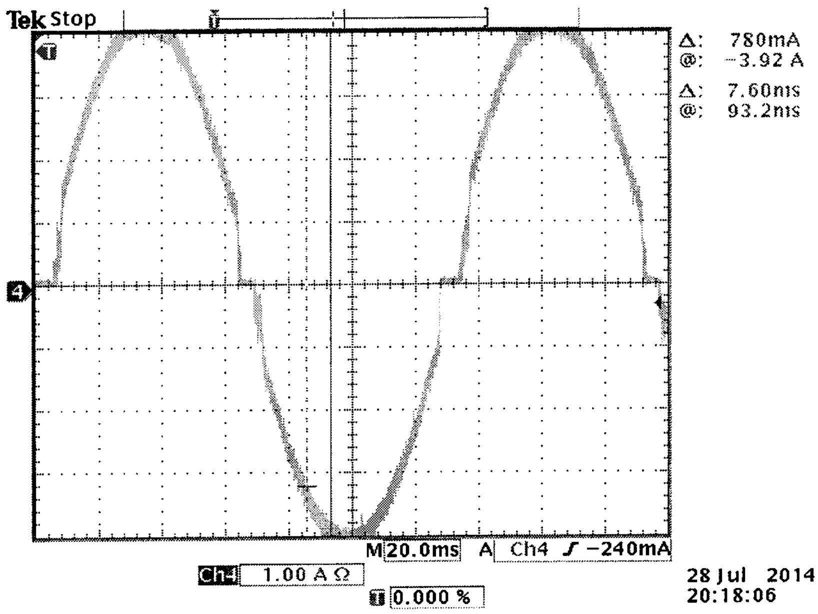

Figure 2-89. The evolution of current through the motor's coils gives by experimental results for 1/64 step sin-cosine drive

In figure 2-89 we see a "dead" interval at zero crossing for current. By splitting the current sense resistor, for every leg of bridge, this problem can be diminishing. Another way to improve the sinus accurate is to put the current sensor in series with motor coil. For reducing the ripple of current trough the motor coil is necessary to have a high frequency of Pulse Width Modulation (PWM), above 100 KHz . Hall Effect sensors are the best option for frequency under 50 KHz. For voltage of motor power supply (V_H) under 60 V, integrated circuits AD8210 can be a good choice.

Another prototype was realized, the drive and current sensing for one coil is presented in figure 2-90. Unfortunately, for switching of leg Brat_1A of H-Bridge, a perturbation during approx. 1.5 μs is presents on the sensor output CT1_OUT.

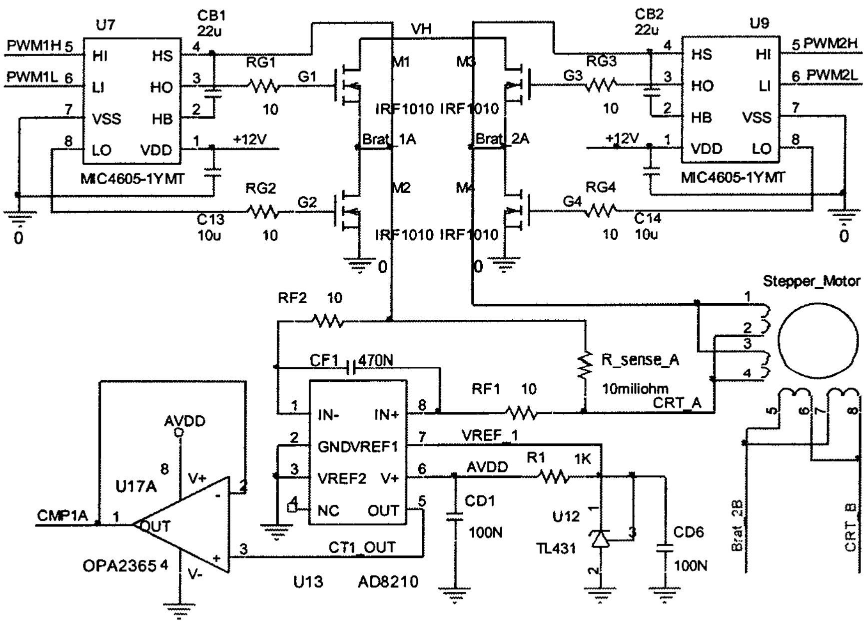

Figure 2-90. NMOS H-Bridge with gate drivers and current sensing based on AD8210 integrated circuit.

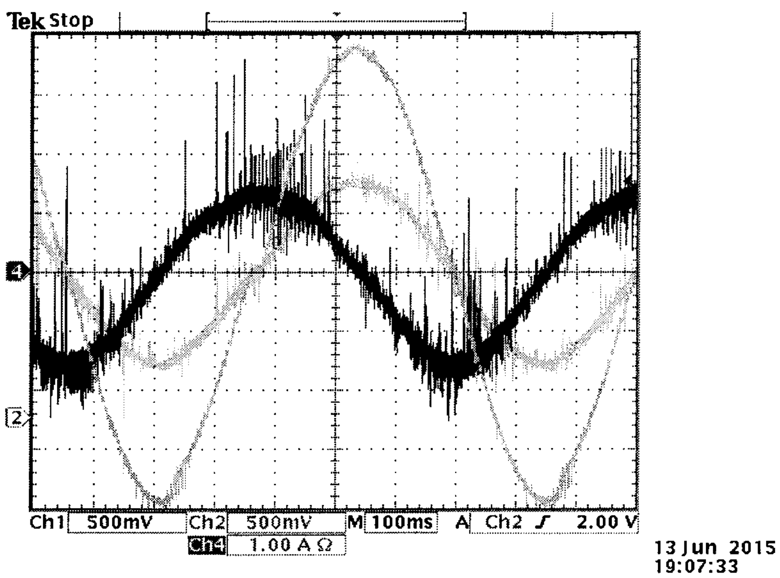

Figure 2-96. The evolution of current through the motor's coils gives by experimental results for 1/32 step sin-cosine drive and 320 KHz PWM frequency.

For this reason, the gate drive for NMOS transistors M1 and M2 was modified by adding a DC-DC convertor to supply CB1 (Bootstrap capacitor) and M1 is permanently "ON" for positive current, M2 is permanently "ON" for negative current. In figure 2-96, output voltage of current sensors is showed on CH1 and CH2 and current trough the coil B is showed on channel CH4. The Printed Circuit Board (PCB) requires a careful design for reducing the noise (generated by NMOS transistors switching) and reducing the noise sensitivity of analog part.

Chapter 3. Research and contributions related to increasing performances of EDM Pulse Generators

3.1. Objectives

In the first part of this chapter the author aims to make a comparison between different types of pulse generators described in specialized literature.

In the second part the author aims to find / develop some circuit topologies that generate voltage pulses to the corresponding parameters and assure current limitation through interstice at set points, aiming at increasing electricity conversion efficiency.

Since practical experience working on high voltage circuits and high currents require special attention, with the risk of failure of expensive components, particular importance was given to circuit simulation. For this, models of electronic devices must be found and the interstice has to be emulated in order to highlight the operation in three main cases: idle, the normal discharge and short circuit.

It will be given the proper importance to electromagnetic compatibility problems and will have to take into account the parasitic elements (inductance, capacitance) introduced by the connecting cables and the electrode assembly tool - object to be processed.

PULSE GENERATORS

The Pulse Generator applies the electrical voltage between Electrode Tool and Working Piece, necessary for Electrical Discharge Machining (EDM).

RC pulse generator

This type of pulse generator was used on the earlier EDM machines. When the gap is passive, the current trough the resistor R charges the capacitor at the high voltage. After the ignition is started, the capacitor is discharged trough the active gap.

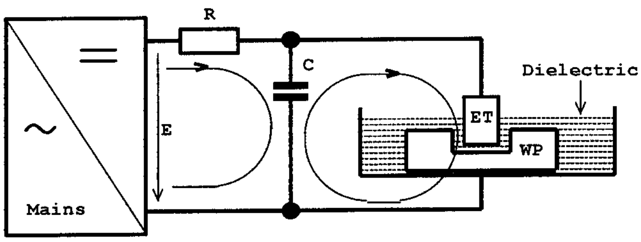

Figure 3-1. RC Pulse generator for EDM

The control of pulse parameters is not realized and electrical efficiency is poor (20..40%). But the frequency of pulses can be high (above 1MHz) and this type of generator is actually used in micromachining.

Controlled Pulse generators

These types of generators are very useful on numerical controlled machines. They use one or more electronic switch and their performances had improved especially by evolution of electronic power devices [117]. One of most important requirements for these types of generators is current limiting. Resistive current limiting technique use in principle a resistor and a fixed voltage power supply, as is shoved in figure 3-2.

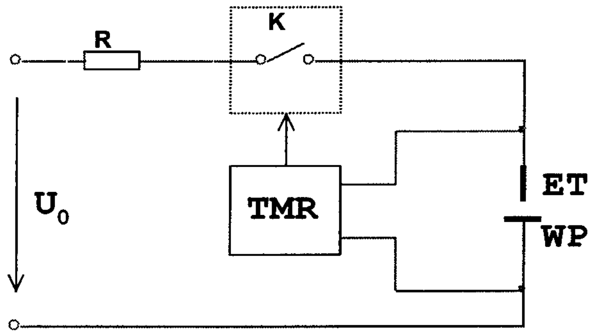

Figure 3-2. Resistive current limiting technique for EDM controlled pulse generator

The timer electronic bloc (TMR) imposes pulse duration and period of repetition. The typical diagram for normal discharge (roughing Die Sinker EDM Technology) is shown in figure 3-3, [117], where:

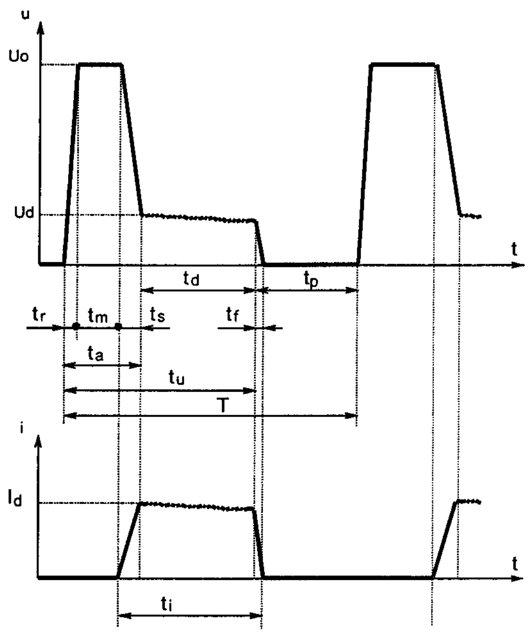

Figure 3-3. RC Pulse generator for EDM

- U_o is the breakdown (ignition) voltage and his value is fixed by power supply. U_o have a value between 100V and 300V.
- U_d is the discharge voltage, and it has a little fall and radiofrequency noise. U_d have a value between 20V and 30V. The radiofrequency noise have maximum power spectrum in 50MHz – 90MHz range.
- I_d is the current value during the discharge (1A.....10A.......200A)
- t_r is the rise time of voltage pulse.
- t_m is the holding time of the ignition voltage.
- t_s is the starting discharge time.
- t_a is the ignition delay time.
- t_d is the discharge time.
- t_u is the voltage pulse width (1...3000μs)
- t_p is the pause time (1...3000μs).
- T is the period of the voltage pulses.

- t_i is the current pulse width.

The energy for one discharge is :

$$w_i = \int_0^{t_u} u(t) \cdot i(t) \cdot dt \tag{3.1}$$

The amplitude of current pulse is:

$$i_d = \frac{U_0 - u_d}{R} \cong const \tag{3.2}$$

Results:

$$w_i = u_d \cdot \frac{U_0 - u_d}{R} \cdot t_i \tag{3.33}$$

where:

$$t_i \cong t_u - t_a \tag{3.44}$$

Delay ignition time t_a is a stochastic variable, depending on the gap state. TMR command bloc defines control mode by imposing parameters t_u or t_i, which, in conjunction with amplitude of current pulse determine the energy pulse. [117]. The principals working mode are: izopulse mode, where t_i and implicit w_i is constant, and izofrequency mode, where t_u is constant. In the izopulse mode the control of process is more accurate and technological results are better.

Analyzing the principia schema (figure 3-2) and the chronograms (figure 3-3), result that difference between ignition voltage U_0 and gap voltage U_d is supported by R during the discharge time period (t_i).

Considering ideal switch (K), dissipated power on the resistor is:

$$p_d = (U_0 - u_d) \cdot i_d \tag{3.5}$$

The consumed power is:

$$P_c = U_0 \cdot i_d \tag{3.6}$$

The utile power is:

$$p_u = u_d \cdot i_d \tag{3.7}$$

Results the electrical efficiency of Pulse Generator:

$$\eta = \frac{P_u}{P_c} = \frac{u_d}{U_0} \tag{3.8}$$

For a small difference between ignition voltage U_0 and gap voltage U_d the efficiency can be acceptable (eq. U_d=24V; U_0=60V, the efficiency is 40%). But for high ignition voltage the efficiency is very poor (eq. U_d=24V; U_0=300V, the efficiency is 8%). Using two power supplies, one has high voltage - low current for ignition, and another having low voltage - high current for sustaining the discharge process, like in figure 3-8, the efficiency can be acceptable. Driver bloc assures properly command for switches, TMR bloc imposes time duration for pulses, Threshold Detector (TD) senses the moment of discharge apparition for starting timers. The efficiency can grow around 50% (eq. for: U_d=24V; U_{01}=300V; U_{02}=45V).

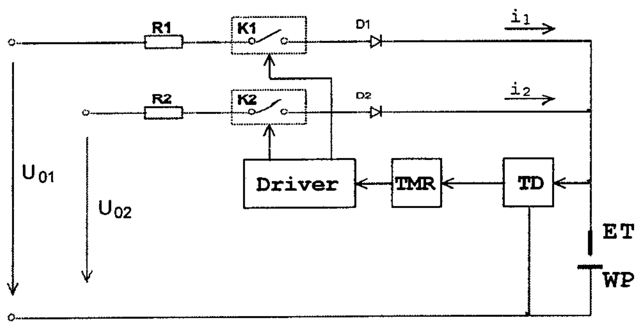

Figure 3-8. Two sources pulse generators for EDM

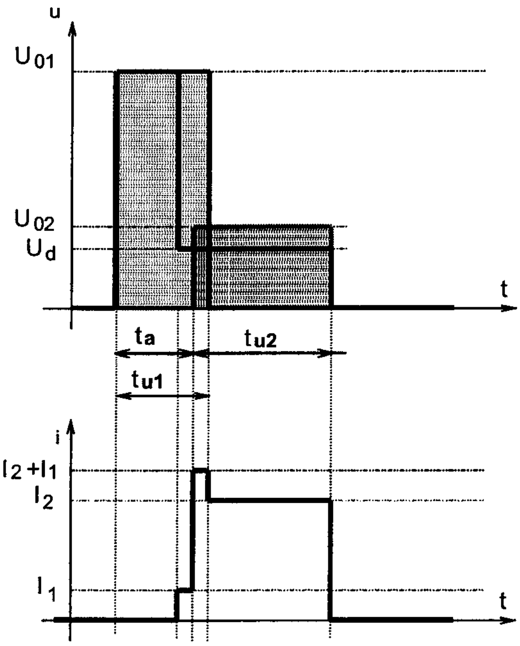

Figure 3-9. Chronograms for two sources pulse generators

Pulse generator with inductive current limiting

For increase the efficiency is necessary to replace the limiting current resistor R by a coil with inductance L and adopt the chopper technique for limiting the current. Step Down (Buck) Converter can be use in a closed loop to control the value of current intensity as is shown in figure 3-20.

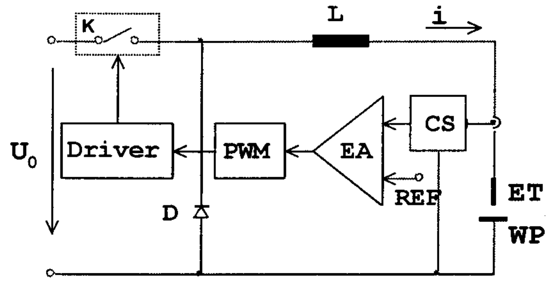

Figure 3-20. Buck Converter as a Current Source for EDM pulse generator

Current sensing bloc (CS) provides a voltage proportional with the current and this value is compared with reference. The error amplifier command Pulse Width Modulation (PWM) module and finally the switch K.

In Continuous Conduction Mode (CCM) there are two situations as shown in figure 3-21:

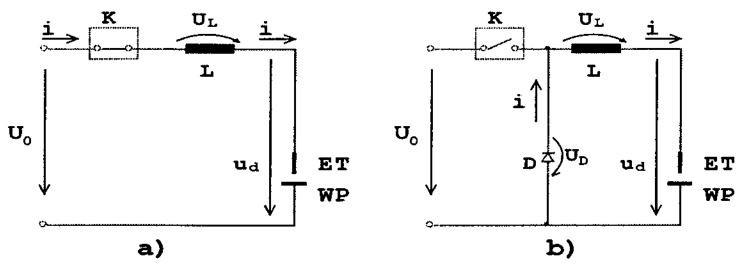

Figure 3-21. The states of Buck Converter in CCM mode

In figure 3-21a) the switch K is "ON", and, assumes ideal circuit elements, results:

$$U_L = U_0 - u_d \tag{3.9}$$

$$U_L = L\frac{di_L}{dt} \tag{3.10}$$

$$\frac{di_L}{dt} = \frac{U_0-u_d}{L} \cong \frac{U_0}{L} \tag{3.11}$$

The current increases with high slope. In figure 3-21b) the switch K is "OFF" and results:

$$U_L = -U_D - u_d \tag{3.12}$$

$$\frac{di_L}{dt} = \frac{-U_D-u_d}{L} \cong -\frac{u_d}{L} \tag{3.13}$$

The current decreases slowly. Because after the EDM pulse is finished current decreases too slowly, a second switch is necessary. Electrical schema is showed in figure 3-23 [87] and chronograms in figure 3-24.

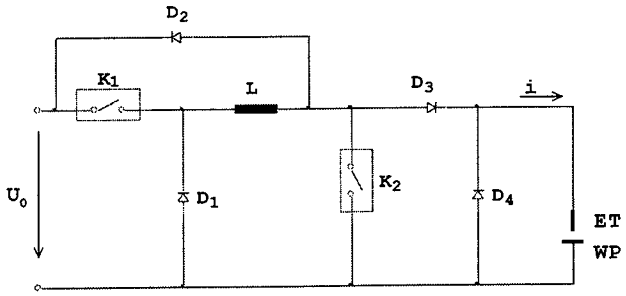

Figure 3-23. Buck Converter based EDM pulse generator[87]

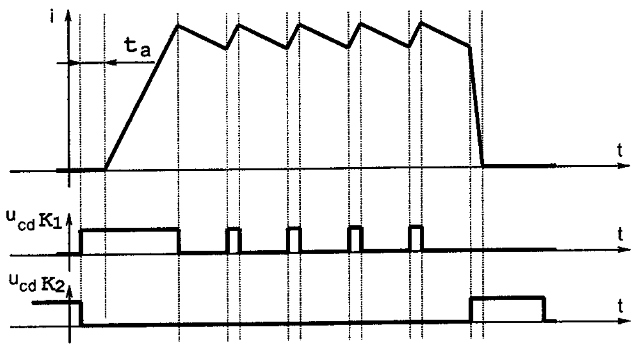

Figure 3-24. Chronograms for Buck Converter based EDM pulse generator

The supplementary diodes prevent undesirable phenomenon: D_2 prevents upper voltage, D_3 inverse current and D_4 inverse voltage. The author has simulated the principia schema by emulating the principal states of gap (high resistor in parallel with small capacitor for pre-ignition state and switch in series with small resistor for discharge state). The efficiency increased to 70..75% for high input voltage U_0=300V. The most important power losses are during the switching time when an important voltage and current appears on the power electronic devices (especially for K_1 and D_1). The efficiency can be improved by decreasing U_0 at 100V, recovering the energy stored on the core's magnetic field and adopting interleaving technique [38,131]. We can increase the efficiency by adopting Synchronous Buck Converter With low R[on] switches. And, finally, we can use the novel silicon carbide transistors (SiC) eg. C2M0080120D, MOSFET transistor which have: R[on] = 80mΩ and switching time much lower than silicon devices. These novel devices don't have yet Pspice model for simulation. An experimental setup is necessary for research and this will be treated in the future work.

EDM Pulse Generator based on LCC resonant Converter

The efficiency can be improved for a high value by minimizing the switching stress for power electronic devices. The resonant and quasi-resonant converters ensure commutation on low voltage (ZVS-Zero Voltage Switching) or on low current (ZCS-Zero Current Switching), but not for all load conditions. In EDM process the equivalent load resistance for power supply has different values, dependant on the gap state (open-circuit in pre-ignition state, low resistance on normal discharge (dependant on the programmed current) and very low resistance on short-circuit conditions). The resonant circuit which have two capacitors, one in parallel with load (or equivalent resistance load) and one in series, presents an interesting property to be an AC current source at ω_0 resonant frequency, [25] where:

$$\omega_0 = \sqrt{\frac{1}{L\frac{C_S \cdot C_P}{C_S + C_P}}} \qquad (3.14)$$

In figure 3-69 is presented circuit used for Pspice AC simulation:

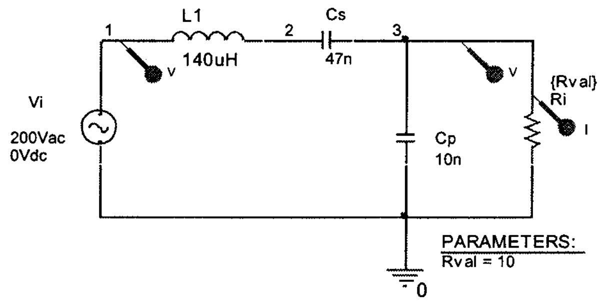

Figure 3-69. Series-parallel LCC resonant circuit for AC analyze

In figure 3-70 is shown the results of simulation, where you can see the frequency f_0=148KHz that circuit have current source behavior.

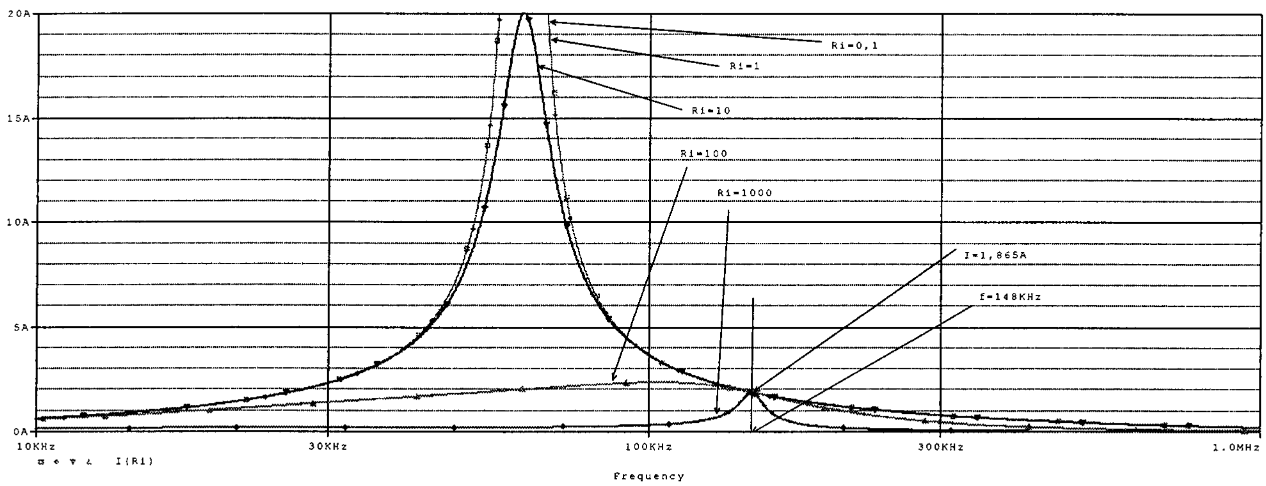

Figure 3-70. The frequency behavior of series parallel LCC resonant circuit

The complete schema for EDM pulse generator simulation is shown in figure 3-77. The independent sources V1A and V1B assure command sequences for both diagonals of MOSFET Bridge. The source V6 permits or inhibits command for bridge's transistors and determines EDM pulse durations t_u and t_p. The voltage dependent sources EG1...EG4 command transistors X1...X4 between gate (G) and source (S). The source V5 command switch transistor X5 and determines duration t_i. The resonant inverter has load a high frequency transformer (U1), that have a null point rectifier with diodes D5 and D6 in secondary. Because we use an ideal model for transformer, magnetizing inductance L_M is added in exterior and also a leakage inductance L_{lk} . For 3F3 ferrite core type the working frequency in 100KHz.. 200KHz is ideal for a good volume-losses performances, we used 150KHz frequency command for resonant LCC bridge inverter. In figure 3-78, is showed the results of simulation; the ignition voltage is not applied very fast. For eliminate this inconvenient the switch X7 is ON during t_p duration and remains ON in the first microseconds in that we apply command for bridge switches. The current through the L resonant tank increased and the energy stored in magnetic field will be capable to increase rapidly the voltage applied to the gap when X7 becomes OFF. In figure 3-104 is showed the results of simulation for two interleaved LCC resonant Converters with X7 action. Also X7 in ON state solves the problem of slow decreasing gap current when the EDM pulse is in t_p time interval. The discharge current has a shape near to ideal "DC" shape when the number of interleaved converters increased. In figure 3-106 we have conceived a schema for the future experimental set-up. A digital signal controller assures the commands for all the converters and has implemented software control strategy.

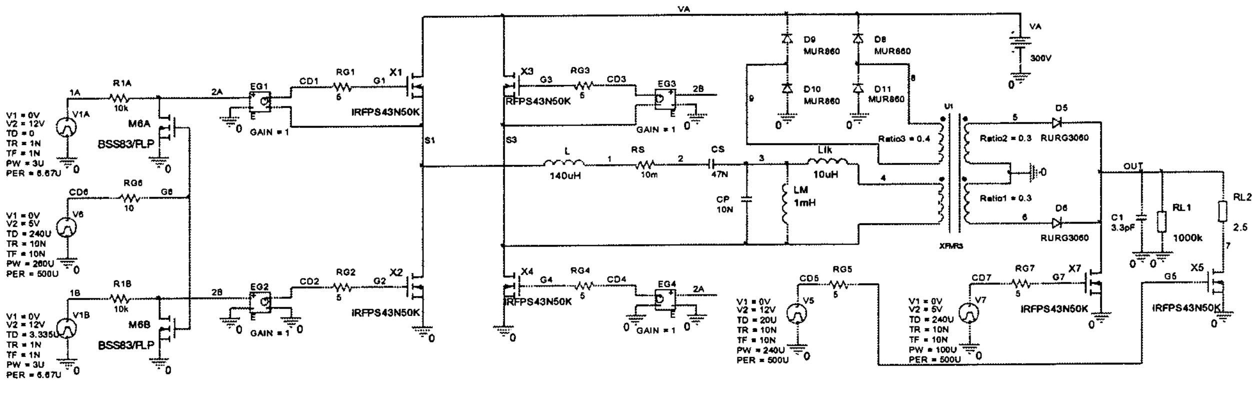

Figure 3-77. Electrical schema used in PSpice simulation of EDM-LCC Pulse Generator

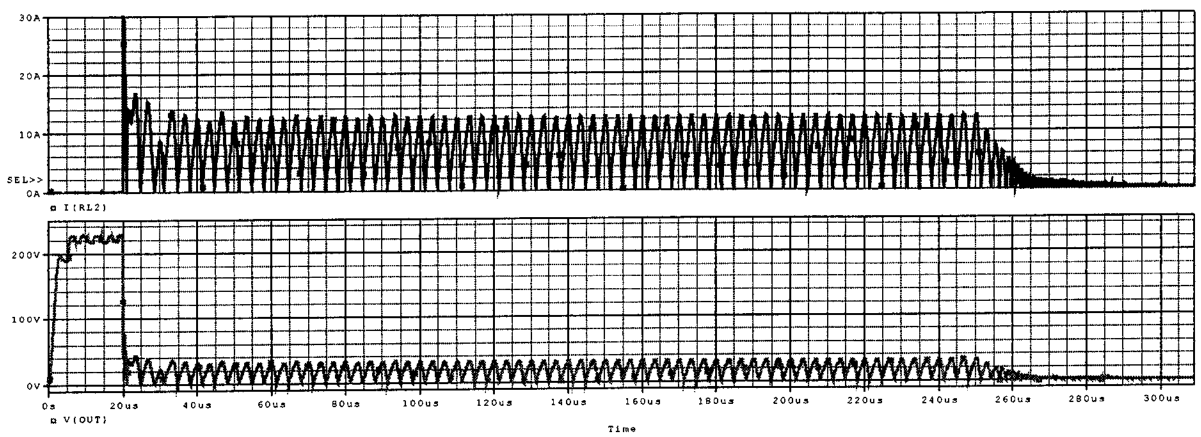

Figure 3-78. The EDM pulse for one stage of LLC converter without action of X7.

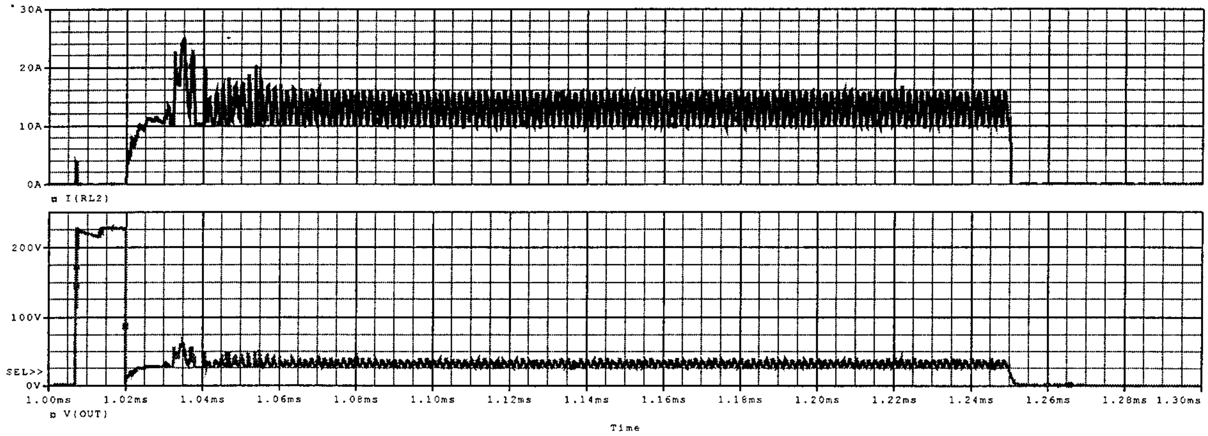

Figure 3-104. The EDM pulse for two interleaved stage of LLC converter with the action of X7.

The Power Supply for EDM can be connected at Mains using an EMI filter, a diode bridge and a bulk filter capacitor or using a PFC module with fixed output voltage (typical 390V).

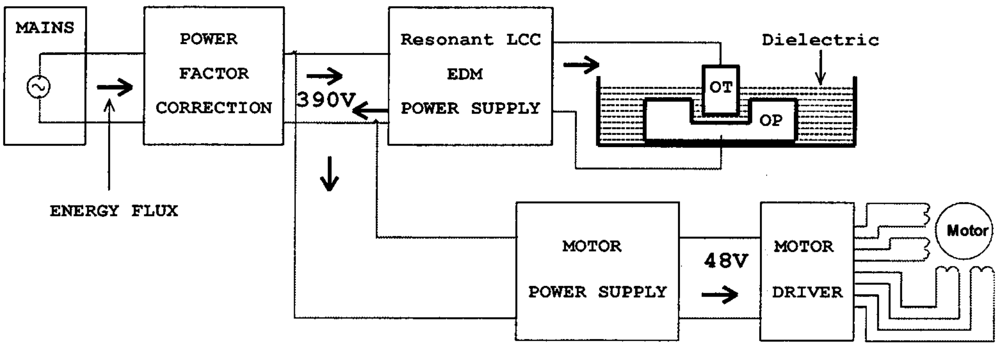

Figure 3-106. The conceived experimental set-up bloc schema for LCC pulse generator.

If we used a PFC module followed by a Full Bridge Phase Shift source with output voltage adjustable, we can modify, (in a specific interval), the discharge current that is proportional to the input voltage. For adjusting separately the ignition voltage is necessary an adjustable auxiliary voltage source. That must be followed by another source for motor drivers' voltage. But that is a much complicated solution.

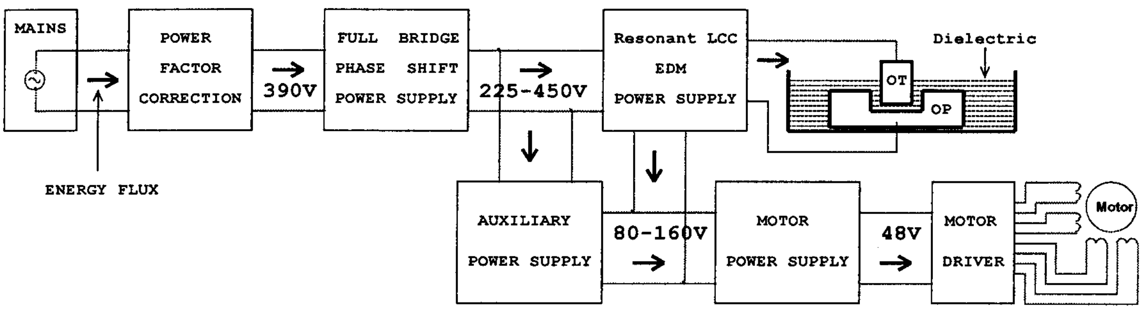

Figure 3-107. The conceived experimental set-up bloc schema for adjusting pulses parameters.

Chapter 4. Research on implementation of the automatic advance system on Z axis

4.1. Bibliographical research on the issue of automatic gap adjustment

In the electrical discharge machine processing, the gap adjustment is made by advance control system (SRA), which prints a relative movement between the electrode-tool (ES) and the processed object (OP), after that ensure maintenance (quasi) of constant gap thickness throughout the processing [85].

Besides this first role, in the modern machinery, the SRA ensure the kinematic generation of the processed surface, by making the advance on two or more axes (flat shaping, spatial processing), using the numerical control equipments [85, 117].

4.1.2.3. Automated step based on the interstitial characteristic through trunk delay

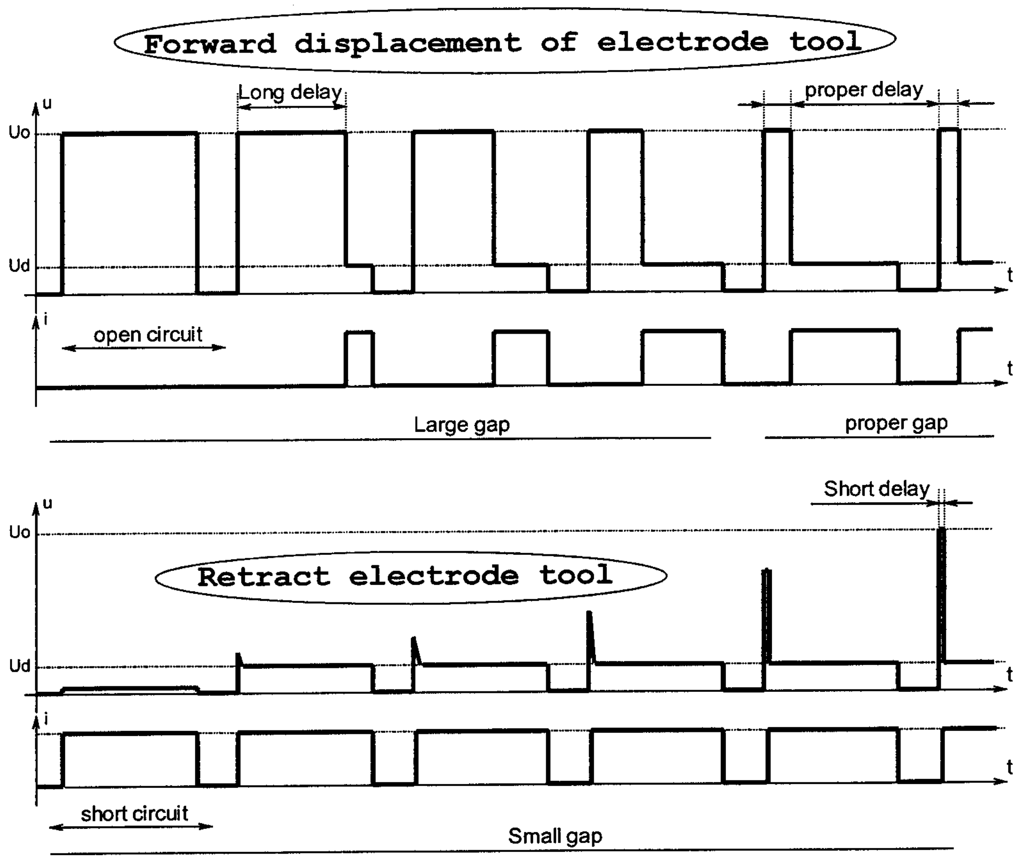

Figure 0-1. Principle of gap control based on ignition delay, idealized.

It is a method often used, involving an analogical comparator and a digital time measurement circuit. The delay in priming t_a is compared with optimum value t_{a_opt}, experimental results. If $t_a > t_{a\_opt}$, the electrode has an advance movement, and if $t_a < t_{a\_opt}$ the electrode has a withdrawal movement [85]. The regulator determine the speed, depending on the size of difference (error) between t_a şi t_{a_opt} . This type of advance control is easy to implement for driving stepper motor. As the state changes randomly gap, especially by the presence of impurities, resulting an typical hazard in the phenomenon of delay in priming, which translates into a stirred advance-withdrawal movement of electrode.

4.2. Research on creating a system for regulating the gap with stepper motor

The proposed block diagram is showed in figure 4-9:

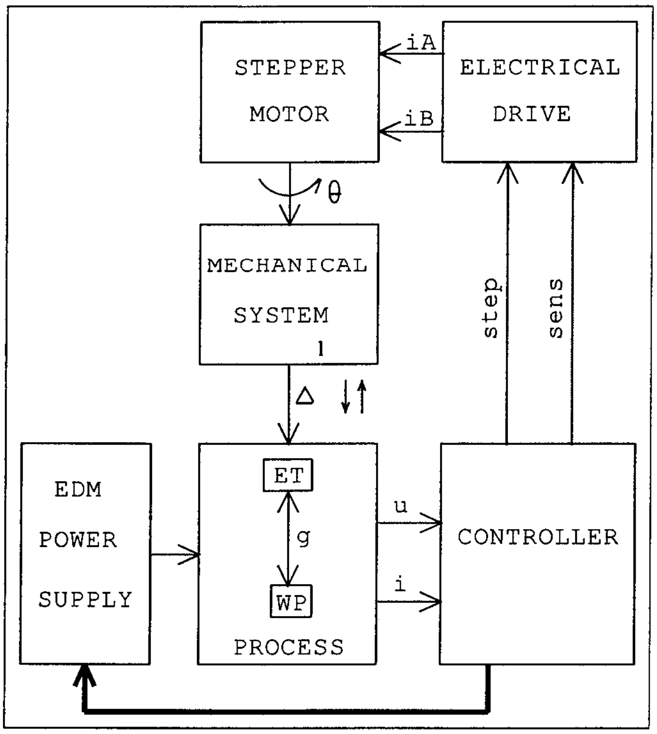

Figure 0-2. Block Schema of gap control system

Using MPP as actuators in advance control systems, to the electrical discharge machine it is based on the advantages of these.

- The possibility of relating the incremental operation of the motor with the evolution of discrete electrical discharge machine processing;
- The memorization of the momentary position through the electrochemical locking of the rotor, to the last command impulse applied;
- The possibility of using the motor so that execution element, and also as a displacement transducer;
- Large range of speed control, simply by changing the control frequency;
- The driving directions reversals can be done in a very fast way;
- It needed s simple kinematic chain for the adaptation of the rotation incremental sizes to the linear discrete movement;
- The order changing of pulse distribution, determine change direction of rotation;
- With a incremental operating, these can be implemented in the digital automate systems;
- Can realize resolutions very small and acceptable speeds through microstepping;
- It has a dynamic operation very good;
- Acceptable price.

Some of the techniques of control have been presented in the report nr 3. Here we limit to control technique based on measuring time t_a, called priming delay.

If the trunk voltage has only one polarity, a resistor voltage divider followed by a fast analogical comparator is the simply solution for deliver pulse duration t_a to a microcontroller on one of CAPTURE input. Taking the information of the current, also knowing the moment when the comand is given for high voltage application, can discriminate impulses to remove quickly the short-circuit situations. The digital control made with DSC sets the direction of movement and the speed for kipping the range time t_a between the limits set, considered optimal for processing.

4.3. Electrical schematic of the movement system on Z axis for processing through electric erosion pulse generating circuit having LCC

The author proposes the block diagram 4-10 for the automatic adjustment system of advance based on the block diagram proposed in figure 4-9 and making use of the pulses generator running with the LCC resonant convertor and described in 3.6.4 paragraph. Using stepper motor drived with micro steps and one of the authors designed and tested circuits , paragraphs 2.11, 2.12, 2.13, 2.14, grants a good resolution and a big enough velocity.

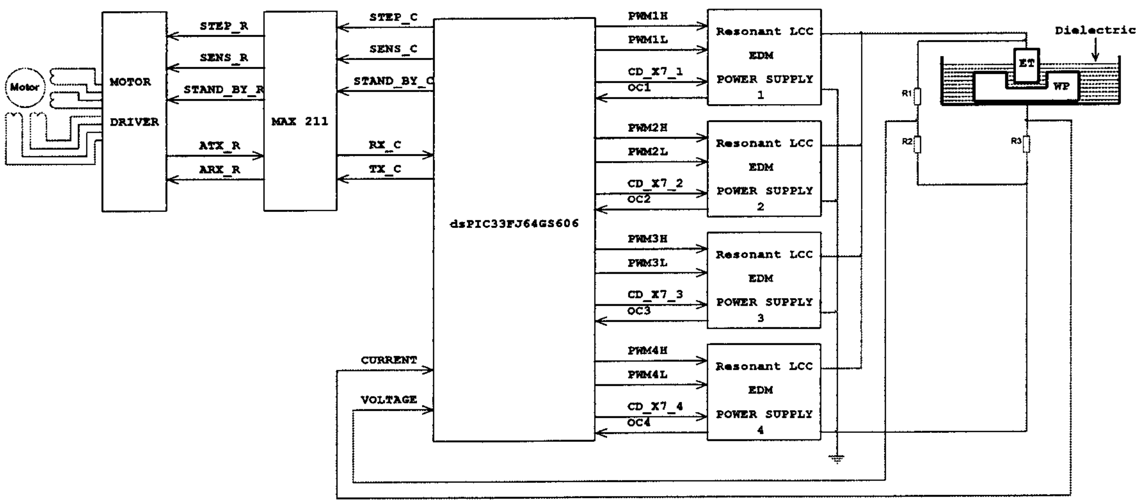

Figure 0-3. Block schema of process control using Z axis displacement with stepper motor and four Pulse generator based on LCC resonant converters.

The GIC command with LCC resonant circuit doesn't create problems when controlling the current because the current is naturally limited due to his current source circuit behavior. Therefore it is enough only one PWM module with two complementary outputs, PWMH and PWML, and ½ duty cycle (dead time). To provide high speed rise time for ignition voltage applied to interstice it was connected the additional transistor X7 driven by one of the digital outputs of the microcontroller. To avoid overcharging X7 transistor, every module has connected this transistor and it was assigned one microcontroller pin for driving him.

Four generators could be driven by the same microcontroller using the "interstice" command technique, if DSC microcontroller has enough pins and enough PWM modules with complementary outputs. The DS dsPIC33FJ64GS606 fulfills these requirements. Furthermore he has two fast independent analog to digital converters, with successive approximation registers, that allows the simultaneously voltage conversion after the resistive divider R4-R5 – information about voltage and voltage drop on R6- information about current. Having these two numeric information cached repeatable in a short time period, it can be realized the digital control for pulses used for process of roughing implemented according to a specified algorithm.

For short time pulses a comparator has to be used that commands a CAPTURE input for ignition delay determination and the implementation of control technique that was described in the preceding figure.

4.4. Electrical schematic of the movement system on Z axis for processing through electric erosion using pulse generators with H bridges using SiC-MOS transistors

The pulse generator usage for electrical erosion processing with transistors SiC-MOS, described in 3.7.2 paragraph cand be done according to the block diagram from figure 4-11.

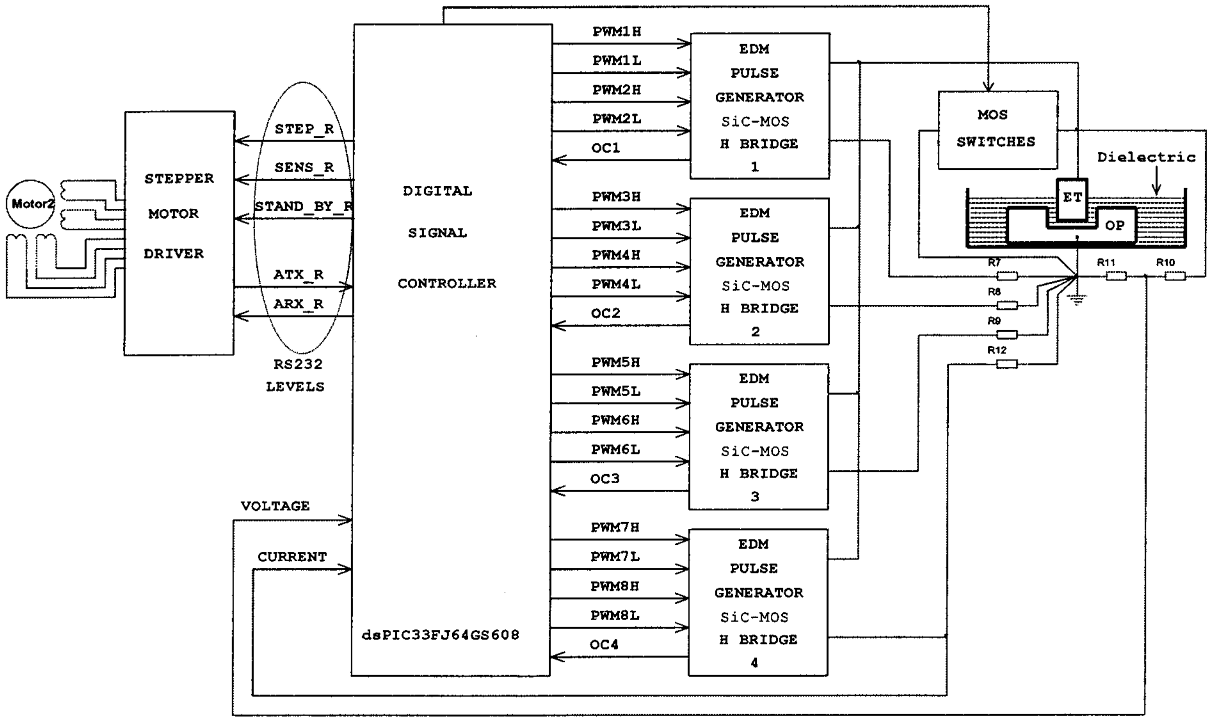

Figura 0-4. Schema bloc a controlului pe axa Z utilizând motor pas cu pas şi patru generatoare de impulsuri cu tranzistoare SiC-MOS în punte H folosind tehnica de "întreţesere" a comenzilor pentru tranzistoarele din punte.

Every GIC module needs two PWM modules each with two outputs and an analogic comparator integrated or not on a „chip" that can allow current control through pick value. The current information is catched by the agency of resistor that is series connected with each module: R1 for module 1, R2 for module 2 and so on. The microcontroller must have eight PWM modules for driving and control the current produced by that four GIC modules. The DSC dsPIC33FJ64GS608 fulfill these requirements. Furthermore it has two analog to digital converters that allow the simultaneously voltage conversion after the resistive divider R5-R6 - the information about voltage and about voltage drop on one of the current transducer resistor.

The microcontroller has to drive using on digital pin, the set of MOS transistors connected as a switch that has to ensure short circuit on the space electrode tool-object used for processing when pulse break. It is enough using only one pin because the gate command for MOS transistors is realized with galvanic isolation with optocouple.

Very important are the problems regarding the electromagnetic emission. The PWM command routes have to be the same length to not have forbidden delays between signals. The cables whereby the signal is brought from the current transducers has to be bifilar, twisted and coated with electromagnetic protective shield, or double shielded.

4.5. Microcontrollers used to achieve digital control of the processing by electrical erosion

To achieve automatic control of advance and command / control pulse generators, microcontrollers family "digital signal controllers - DSC" provides the facilities with integrated "chip" blocks with special functions and performance.

	dsPIC30F2020	dsPIC33FJ64GS606	dsPIC33FJ64GS608	TMS320F28335	F28M36P63C	
					Master ARM-M3	DSC
Number of pins	28	64	80	176	289	
Packege	DIP28 SO28	LQFP64	LQFP80	LQFP176 BGA179	NFBGA289	
Program Memory (Flash)	12k	64k	64k	256k	1024k	512k
Data Memory (RAM)	0,5k	9k	9k	34k	128k	36k
Number of bits	16	16	16	32	32	32
Maximum frequency	30MHz	40MHz	40MHz	150MHz	125MHz	150MHz
High resolution PWM module	4x2	6x2	8x2	3x2	-	8x2
PWM resolution	4ns	1ns	1ns	0,15ns	-	0,18ns
Analog comparator	4	4	4	-	-	6
Floting point operation	-	-	-	YES	YES	YES

Tabel 0-1. Comparison between some digital signal controller (DSC)

In the table 4-1 are shown some representative microcontrollers. Are noticed the superiors performances of microcontroller F28M36P63C. But the large pin number of microcontroller and the capsule BGA (Ball Grid Array) make it impossible to use without the adequate technology of mount for PCB circuits. For this reason the manufacturer provides users a printed circuit board that is mounted microcontroller and circuitry for programming, debugging and USB /Ethernet communications. The PCB can be connecting to the application through a standard memory socket with 168 pins. In figure 4-6 is represented the picture that contain the PCB with microcontroller. Terminals of microcontroller are available on motherboard, the rows of pins shown in figure 4-7.
Using this development board, open multiple avenues for further research. The realization of the system from figure 4-4 or figure 4-5, using this board for control block allows implementation/development of digital control algorithms, handled in many papers [6, 29, 40, 60, 89, 164, 202, 204].

Chapter 5. Research results summary

5,1. Final conclusions

The complexity of the phenomenon that occurs during electric erosion process required a close study of the specialty literature.

Micro volumes of the electrode material are expelled in a way depended by the duration of the current impulse and of the discharged energy.

For long duration impulses the energy is transferred to the electrodes mostly in the form of heat. The electrode material is thus activated by locally raising the temperature to values higher than the melting point and even trough vaporization. Most of the material is expelled in liquid form. The long impulse duration leads to significant energy losses trough thermal conduction in the material and trough the occurrence of the no exposed, thermally activated surface of a layer that suffers structural changes, the so called white layer. The electrode wear is low if hydrocarbons are used as a dielectric medium, resulting in a long use in the processing for copying the shape of the electrode. Because of the occurrence of the white layer and of the high roughness of the surface an additional finishing process is needed. This is done by using short impulse but extra time and energy is required.

For very short impulses ranging under a few microseconds, the material is largely expelled in gas form. The heating of the not expelled, superficial layer, trough heat conduction is a slow phenomenon and does not happen at a level at which the white layer appears. Therefore it may not be necessary to execute finishing processing. To obtain an acceptable productivity, the energy pulse current needs to be high enough, requiring high amplitude of the pulse. The electrode wear is high, which makes this mode to be used mainly in micromachining and electrical wire erosion processing, where the useful portion of the electrode is continually changing.

Making generators capable of providing pulses with widely parameters, lasting tens of nanoseconds to tens of milliseconds with amplitude from tenths of amps to tens of amps or more, with controllable shape and polarity, allows empirical study of the electro-erosion machining process of various materials using different dielectric environments. In addition, if by using methods of non-resistive current limiting power conversion efficiency of the power supply to the process is close to unity, generators made can be successfully implemented in industrial machines. Based on these considerations the author has focused research to improve the performance of pulse generators, taking into account the development of power electronics and microelectronics. Using small dimension high power electronic devices leads to reduced energy consumption for production.

The appearance of SiC-MOS transistors and PSpice model simulation allowed comparative analysis of elementary Buck converters made with different power electronic devices. The results show higher efficiency of the synchronous Buck converter made with SiC-MOS transistors. This has enabled the design and demonstration of the operation of a pulse generator for electro-erosion processing based on two buck converters in symmetrical H bridge structure. The pulse generator is capable of providing the possibility to change parameters within wide ranges:

- starting voltage can be positive, negative or alternating, the control can be adapted
- the rate of voltage increase for priming can be great if the circuit is designed for low inductances, in the orders of microhenry
- the current can be changed over a wide range, it can be positive, negative, or alternating
- several identical modules, each having its power source may be provided in parallel at the output, provided they respect the voltage polarity
- if the H-bridge transistors are controlled in interwoven PWM pulses the ripple current level decreases, enabling the use of small value inductors

- the PWM frequency of the pulse may be in the order of 500 kHz .... 1 MHz and by using interlacing technique a similar effect is obtained at the output of switching of a frequency multiplied by a number equal to the number of modules placed in parallel

Except for to the limitation of inductive current applied to the pulse generator based on the Buck converter, the resonant property of the LCC circuit can be used as a source of alternating current at a certain frequency. The converters with resonant circuits can provide switching command in voltage and/or current for power MOS transistors, in this way reducing power dissipation while the switching time occurs. The electrical schematic designed and adapted for PSpice simulation, for pulse generator based on LCC resonant converter, confirmed after numerous simulations and analyzes the advantages of this type of generator.

Another important aspect in the electric erosion process is related to the control of the process in order to maximize productivity by reducing the number of abnormal discharges, primarily idle discharges or short-circuit. For this a special attention was given to the advance control systems, starting with the driver from stepper motor. Three main goals were followed:

- increasing of energy conversion efficiency
- increasing the speed of the motor
- improving the resolution.

By increasing the rotational speed and improving the resolution, the stepper motor is the optimal solution to drive the Z-axis for the automatic adjustment of the electrode tool, for much of the technological systems of processing dimensional electro-erosion with massive electrode. An engine control trough microsteps is the solution that yields a wide range in which the speed of rotation of the motor can be changed, by eliminating the phenomenon of mechanical resonance and in the same time to improve the resolution. To eliminate the engine play it can be coupled directly to the linear travel system trough a ball screw. For a larger number of microsteps the resolution it is better than 1 micron. A higher number of microsteps require a higher switching frequency for the power transistors to approximate a sinusoidal current shape at high speeds of rotation of the motor. Reducing power losses in switching transistors becomes an important concern in implementing motor control circuits. For engines of small voltages below 60V, NMOS silicon transistors are power electronic devices with the best performance, because they have very small electrical resistance in the "on state", of the order of mΩ, resulting power dissipation very low while in conduction.

To decrease the switching losses, a "dead time - (DT)" must be introduced between lock control of the conducting transistor and the input control of the other transistor. DSC microcontrollers, used by the author, have the possibility of establishing such downtime with great accuracy. Since the circuits designed by the author to control the engine microsteps have H bridges with NMOS silicon power transistors the greatest power is lost largest while the lower transistor is switching and the higher transistor enters in drive mode. This is because conduction through the lower transistor is provided by PN junction diode existing transistor structure, which has long diode conduction blocking passage of relatively high, given the time of disposal pregnancy stored near the junction barrier region. Further reduction of switching losses diode is achieved by putting extra metal-based semiconductor (Schottky diode) antiparallel across each transistor. Electric current flowing through the Schottky diode is based on just moving the majority charge carriers, free electrons, missing for eliminating pregnancy stored commutation of conduction block. This diode conduction voltage drop having less than the PN diode, it will take over current conduction, switching time being smaller, lower power dissipation and switching in this range.

5.2. Research methods, credibility and argumentation of the results

The method used mainly in research was to simulate electrical circuits designed / developed by the author, where PSpice models for the components could be used.

For circuits where signal generation is made with the use of a microcontroller, the source code is programmed in C language standard. The simulator is used from the IDE, the PCB is designed, the physical PCB is made, the microcontroller is programmed and the circuit operation is tested using an experimental stand.

The simulation results must be viewed with a certain reserve, for several reasons: firstly existing models for components not describe the behavior under all possible operating conditions, exceeding the admissible limit values for voltage, current and / or power, usually it is not detected by the program, being the user's task to find any hazardous situations that might occur in operation. On the other hand the physical realization of the circuit elements introduces additional parasitic inductance such as wires connecting routes and capacity between components / trails, routes resistance. A problem difficult to master is the existence of electromagnetic radiation due to fast current commutation circuits of force and its influence on the analog signal paths and even on routes with a digital signal. Therefore only after physical prototype can be concluded on the functioning and performance of circuits made. In addition the entire circuitry must be within the electromagnetic emission standards in force.

5.3. Original contributions of the thesis

This chapter presents the main original contributions of the author, the results of the research program. These results were validated either by simulation or by measurements done with laboratory equipment.

The thesis contains 231 pages without annexes, 263 pages in total, 271 figures and 9 tables. There are 241 external references. Out of these, 182 represent publications: articles in journals / magazines, at conferences and books in which a total of 10 are the author / co-author. Given that most of the results have materialized in the design / development of electrical and electronic circuits, a total of 36 citations quote application notes of datasheets.

5.3.1. Contributions to the development of methods and control circuits and stepper motor control within the system with linear movement of the object transfer

There were researched and developed modules of command and stepper motor control, aiming at increasing efficiency in the conversion of electrical energy and increasing the performance of the electromechanical advance drive system of the electrode tool focusing on improving and speeding resolution:

- There were highlighted the command modes of the stepper motor, both unipolar and bipolar, on a simplified electromechanical model. For bipolar engine analyzes were made with graphics that represent the force that is attracted to the magnetic pole of the rotor for each step or microstep.
- It was designed and built an experimental stand physically enabling the unipolar motor control, supplied from a source with a nominal voltage in three fundamental ways: simple command - full step, double command - whole step and mixed control –half step. For this it was designed in OrCAD Capture and ORCAD LAYOUT a minimal development board with dsPIC30F4012 microcontroller circuit and another one for the power circuit. For the physical circuitry and experimental stand there was designed a program in C language standard, using microcontroller applications development environment, MPLAB v.8.80. and C30 compiler MPAB v.3.31, the programs were implemented on the "flash" memory of the microcontroller and there were conducted tests and measurements using laboratory equipment.
- In order to increase the maximum speed that the motor can reach, a circuitry was designed to limit the current through the bipolar motor windings, was developed a schematic for the dual command-step command of the bipolar motor circuit , with logic-based standard CMOS IC family, H-Bridges with complementary MOS transistors, and it has been implemented in PSpice simulation program.

- In terms of using motors with a high dispersion of parameter, there was designed a schematic to limit current through the bipolar motor windings, using advanced integrated logic circuit family of HCMOS, quick compensators and H-bridges with NMOS transistors controlled with high frequency PWM pulses circuit, all simulated in PSpice and the proper functioning of the circuit was found
- In order to improve resolution, increase speed and to eliminate the phenomenon of the mechanical oscillation of the stepper motor, it was designed a circuit for controlling the sin-cos, of the bipolar motor, using advanced integrated circuit from the family HCMOS, quick compensators and H-bridges with NMOS transistors controlled with high frequency PWM pulses circuit, implemented in OrCAD-PSpice wiring diagram. It was also determined the correlation between the number of microsteps and minimum required switching frequency of the modulated pulses in duration so that it would be able to reach the maximum speed required and also established the correlation between voltage requirements and the maximum speed required.
- It has been designed, at the level of a block diagram, a circuit with a microcontroller for controlling the microstepping of the bipolar motor , starting from the concept circuit design and analyzed by simulation, in the sub-chapter 2.5. The reference voltages for the current control through the two coils of the motor are obtained through two analog digital converters, with the possibility of obtaining a control of high resolution, converters being on 12-14 bits.
- In order to confirm the physical experiments of the truthfulness advantages of the command in microsteps of the bipolar stepper motor, it has been designed a circuit for controlling the sin-cos using microcontroller DSC dsPIC30F2020 and current resistive transducer in series with H bridge, it was designed and executed thePCB, the circuit was done physically, the microcontroller has been programmed and tests and measurements have been performed on the module developed.
- In order to reduce the error of the approximation of the current sine wave through the motor bipolar windings passage through zero, starting from the circuit mentioned above, the concept of a circuit with the resistive transducer current in series with the motor winding was developed, followed by an dedicated integrated circuit to transducer current, AD8210. It was designed and developed the PCB, physically the circuit was done, the microcontroller has been programmed and test were performed on the module.
- In order to have an approximation as best as possible of the sinusoidal current though the motor windings and at high-speed rotation, thus to increase the switching frequency of the MOS transistors of H-bridge, it was designed and built physical an electronic module having the command on the gates of the transistors using fast galvanically isolated circuit. To enhance the performance of the control circuit, though inrush current limiting, a resistor current transducer has been designed and an differential amplifier with high frequency, correlated with separately power supplies for each H bridge and establishing proper grounding reference.

5.3.2. Contributions to increase electrical efficiency and the performance of the pulse generators for electric erosion processing

They were researched and developed structures for generating electrical pulses to erosion processing aiming at increasing energy conversion efficiency and the possibility of changing the parameters of the impulses widely. They were designed circuits to electrical simulate the operation of generators and there were developed techniques and simulation methods:

- It proposed an electric circuit for emulating the gap, useful both in simulation and testing in electric laboratory conditions, of the pulse generators. The proposed circuit models the gap for both polarities, both in terms of unloading idle discharge and under normal conditions, the short circuit being provided additionally. The circuit provides a good dynamic behavior and appropriate static characteristic.
- The programs were developed, presented in Annexes 7 ... 11 to simulate elementary Buck converters made with the main types of power electronic components, there were analyzed waveforms to determine the components in the range of switching applications and there were determined efficiency switching circuits for different frequencies. Based on the results presented graphically there was highlighted the lower net efficiency synchronous-Buck converter made with MOS transistors on a silicon substrate and superior efficiency of the synchronous converter with MOS transistors on silicon carbide substrate.
- Noticing the superiority of the synchronous-buck converter with SiC-MOS transistors, in terms of yield and high switching frequency operation, there was developed a pulse generator based on two synchronous Buck converters, in H bridge SiC- MOS transistor structure, symmetrical, controlled with peak current limitation technique, with the possibility of changing priming voltage polarity and can change widely the current pulse parameters. Circuit simulation has demonstrated the proper functioning of the pulse generator and allowed the determination of yield.
- • It was designed a pulse generator with a Buck converter with a SiC-MOS deck and seven simple Buck converters. GIC allows current and voltage of both polarities, because of the presence of H Bridge, for the finishing processing. For the roughing processing the other simple Buck convertors are also activated, with interwoven commands, to obtain the large current, in a single direction, with the possibility of changing the parameters in a wide range.
- There were analyzed through simulation in Pspice the behavior of the resonant circuit LCC for different frequencies of sinusoidal voltage applied at the input, highlighting the frequency at which the circuit becomes AC power source and the filtering effect of the circuit in case the input is applied a rectangular voltage source
- • It was designed a circuit for PSpice simulation of the pulse generator with LCC resonant circuit, bridge with MOS transistors, transformer for electrical isolation and double alternation rectifier in the secondary. It was confirmed, through simulation, the pulse generator functionality, and there were analyzed in detail the requests of voltage/current of the resonant circuit components and power components. It was determined the efficiency of the circuit.
- It was developed a voltage limiting circuit priming and recovery of energy stored in the resonant circuit, based on a DC voltage applied coverage through a diode bridge to an additional secondary winding.
- A scheme was developed for the pulse generator with multiple converters LCC resonant circuits with parallel outputs and "interleaved" command highlighting decreasing the current "ripple" and summation of current supplied by the n converters.

5.3.3. Contributions to the development of structures for automatically advance of the transfer object

There were investigated the automatic control structures of advance transfer object and two block schemes have been proposed based on electric drive motor stepping through microsteping. The control block of the advance automatically interacts with the impulse generators for processing through electric erosion.

• It was designed, to a block diagram level, the system for automatic gap control loop stepper motor, highlighting the necessary signals.

• It was developed at a level block diagram, the control structure of the advanced stepper motor and four pulse generators resonant LCC converter, controlled through "interleaved" technique using dsPIC33FJ64GS606 microcontroller.

• It was designed the devise level block diagram the structure of the control system of advanced stepper motor and four pulse generators with buck converter, synchronous SiC-MOS transistor H bridge, symmetrical, ordered by the technique "interleaved" using microcontroller dsPIC33FJ64GS608.

5.4. Outlook and directions of research development

Research conducted in this thesis opens way to the development of an experimental stand for experimental validation of the results of research and development of methods / algorithms of control of the advance electrode tool. The main directions for further research are:

1. The physical making of the circuit for the control in microsteps of the bipolar stepper motor, with microcontroller and digital analog converters for the sinusoidal reference voltage generation, with peak current limit control by using digital circuits and quick comparison of AHC family and resistor current transducer decks on each arm of H bridge
2. Improvement of the DSC module and circuit for drivers with galvanic isolation
3. The physical realization of the pulse generator LCC resonant converter circuit for further research by conducting laboratory bench downloads in the existing engineering faculty
4. Physical realization of the stand with pulse generator based on synchronous SiC-MOS transistors converters and by conducting further research on the laboratory bench single downloads
5. Establishing a physical laboratory stand microcontroller control circuit with F28M36P63C and develop control techniques for the bench made

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