Fuzzy Logic Based Controller for Micro-Electro Discharge Machining Servo Systems

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Abstract— **In this paper, a tunable fuzzy logic based servo controller for monitoring and control of the micro-electro discharge machining (micro-EDM) process has been developed, which uses the behavior of discharge pulses. The fuzzy logic applies a heuristic approach in dealing with the non-linear and time varying nature of the micro-EDM process. The control parameters affecting the performance of micro-EDM include gap voltage and gap current discharge pulses. It is important to discriminate between different levels of pulses for proper operation of micro-EDM. Discrimination of pulses from an RC-type power source is still an ill-defined problem relying on heuristics. The choice of appropriate values of discharge pulses is generally based on the knowledge and experiences of operators. In this study experiments were carried out to distinguish the discharge pulses, which were then classified into open, sparking, arcing, off and short circuit. The classified pulses were utilized as the input fuzzy sets of the fuzzy logic based controller that drives the servo system to maintain the desired gap width. The simulated results obtained demonstrate that the fuzzy logic controller is able to provide stable machining and improve the performance of the micro-EDM process.**

Keywords- Micro-EDM; discharge pulse; RC-type pulse generator; Fuzzy logic; FLC

I. INTRODUCTION

As micro-parts, micro-structures, and micro-transmission mechanisms are becoming the current trend of the products in areas such as medicine, telecommunication, and micro-electro mechanical systems (MEMS), there is a growing demand on miniaturization in a variety of manufacturing processes. Micro-EDM is one of the most valuable techniques for micro machining because of its high precision in the fabrication of micro-holes, micro-mechanical parts, and complex microstructures on difficult-to-machine materials. Micro-EDM is mainly applied for making micro and miniature parts due to its special material removal mechanism and high precision attainable. At present, an RC-type pulse generator is generally used as the power source of micro-EDM. A schematic of an RC-type generator used in micro-EDM is shown in Fig.1. Such a pulse generator provides highly concentrated discharge energy suitable for precise machining. However, the charging characteristic of the capacitor as well as the ineffectiveness of the servo feed control of the micro-EDM process lead to very low machining efficiency. As the discharge takes place in a very narrow gap (10 ~ 100μm) between the electrode and workpiece, it is conceivable that the machining process is closely related to the gap discharge conditions. Therefore, identification of the gap discharge conditions is essential to enhance the performance of micro-EDM operations. Micro-EDM operations are rather slow and therefore significant power is consumed during the process leading to high costs of machining.

Open circuit discharge pulses occur when the gap width is too large so that there is no current conduction through the gap. These pulses do not produce any erosion but may lead to damage of the power supply due to an over-voltage. Arcing takes place when the dielectric fluid is not completely de-ionized. This situation implies that the generation of sparks within a concentrated small area may damage the workpiece and the tool electrode. Short circuits occur when the electrode makes physical contact with the workpiece. Again there is no material removal and there is a risk of welding the tool onto the workpiece, leading to low productivity.

Micro-EDM is a complicated and stochastic process whose working conditions are difficult to monitor and control effectively due to lack of adequate knowledge of the discharge mechanism.

The gap voltage and gap current discharge pulses were analyzed and the discharge pulses were classified as open,

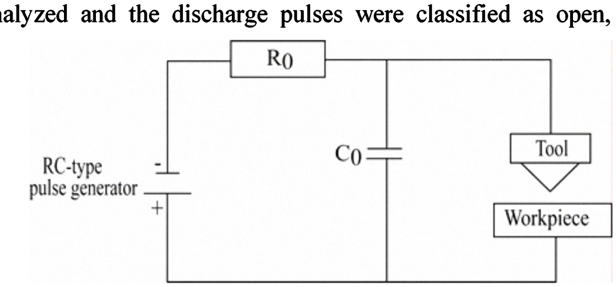

Figure 1: Micro-EDM process

spark, arc, off and short circuit pulses.

A. Pulse-type Discrimination

A number of studies have been carried out to discriminate discharge pulses in micro-EDM processes. The discharge pulses were classified into open circuit, normal discharge, arcing and short-circuit pulses [1]. The effects of pulse types on metal removal rate (MRR) and relative wear ratio were investigated and classification of pulse types in die sinking EDM based on two voltage threshold values obtained through many investigations [2 – 4]. The correlation between MRR and other EDM process control parameters is given by the following equation [4]:

$$\upsilon = \frac{\alpha K I_g V_g T_{on}}{T_{on} + T_{off} + T_d} \tag{1}$$

where; υ is material removal rate, K is a dimensionless constant, V_g is gap voltage pulse, I_g is gap current pulse, T_{on} is pulse on-time, T_{off} is pulse off-time, T_d is ignition time and α is material constant. In [5], the open circuit voltage, discharge voltage and current were compared with pre-determined corresponding values and the pulses were classified into normal spark, transient unstable arc, harmful arc and short circuit. Furthermore, studies on pulse discrimination for wire-EDM were carried out under various machining conditions [6, 7].

All the above-mentioned pulse discrimination studies used a transistorized power source and therefore are not applicable in the pulse discrimination for an RC-type power supply commonly employed in micro-EDM and micro wire-EDM. In a study carried out by [8, 9] the RC-type power supply was found to give better results in micro-EDM process compared to transistorized type.

This paper presents the analysis of the characteristics of the gap voltage and gap current pulses of an RC-type power supply leading to the classification of discharge pulses into open, spark, arc, off and short circuit pulses. The classified pulses were used as the input data to a fuzzy logic controller (FLC) for the servo system in order to obtain stable machining and to improve micro-EDM operations.

B. Fuzzy Logic Control

Fuzzy logic proposed by Lotfi Zadeh [10] in 1965, emerged as a tool to deal with uncertain, imprecise, or qualitative decision-making problems. Fuzzy logic control is based on fuzzy set theory and fuzzy logic. Several studies have shown that fuzzy logic control can be applied in a variety of control applications since it provides a convenient method for design and implementation of nonlinear controllers via the use of heuristic information [11 – 15].

An FLC comprises four functional blocks: fuzzification, inference engine, rule base and defuzzification. The fuzzification interface modifies the inputs so that they can be interpreted and compared to the rules in the rule-base. The inference engine evaluates which control rules are relevant at the current time and then decides what the input to the plant should be. The rule-base holds the knowledge in the form of set rules of how best to control the system. The defuzzification interface converts the conclusions reached by the inference mechanism into the inputs to the plant.

Basically, the FLC can be viewed as an artificial decision maker that operates in a closed-loop system in real time. Many researchers have tried to monitor and control EDM process by using fuzzy logic [13 – 14]. However micro-EDM operation is still an ill-defined problem that generally relies on use of heuristic techniques or experiences of machining operators. In this study a fuzzy logic based servo controller utilizing classified discharge pulses as control parameters was designed and simulated. Several experiments were carried out in order to obtain input data (discriminated pulses) to the FLC. Expert knowledge was integrated in the control system for improvement of the micro-EDM operations.

II. EXPERIMENTAL WORK AND DESIGN OF FLC

In order to design the fuzzy logic based servo controller for the micro-EDM operations, experiments were carried out to determine the required inputs by classifying the discharge pulses. The classified discharge pulses are treated as input fuzzy sets of the FLC.

A. Classification of discharge pulses

Experimental work to classify the gap voltage and gap current pulses was carried out in the micro machining research laboratory of Technical University of Kaiserslautern. Since the gap width was too narrow (10 ~ 100μm), for purposes of measurement and classification of pulses, the gap voltage during micro-EDM operation can be used to represent the gap width. The experimental setup for the measurement of gap voltage and current discharge pulses is shown in Fig. 2.

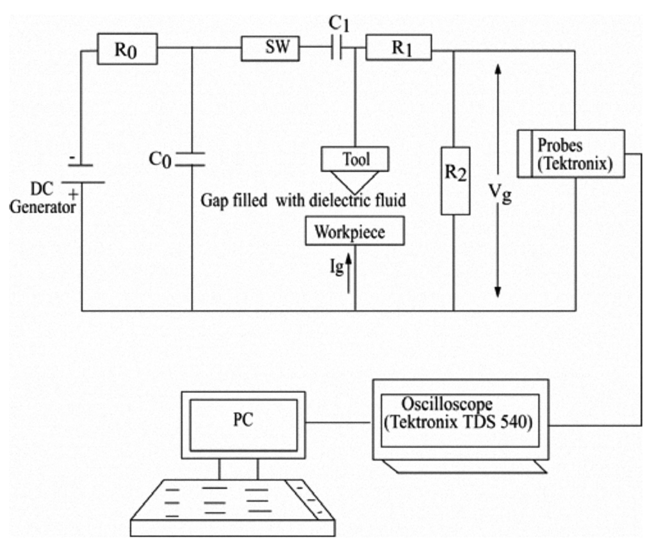

Figure 2: Measurement of gap voltage and current pulses

The gap voltage and current discharge pulses were measured by using the Tektronix probe and the data obtained was viewed using an oscilloscope (Tektronix TDS 540) and then recorded in LabView. The current helped in distinguishing between the various pulses.

In this experiment, a high voltage DC generator was used instead of the existing RC-pulse generator in order to increase the supply frequency from 4 MHz to about 100 MHz. The frequency was raised by using a high frequency switch to modulate the DC voltage. Various capacitors were integrated as spark gaps and a voltage divider was used to facilitate the measurements using the Tektronix probe. The equipment used a conventional PID controller. Table 1 shows the specifications of the devices used.

A number of measurements of gap voltage and current were obtained and used to classify the discharge pulses into five categories namely, open, off, spark, arc and short-circuit. The measured gap voltage and current discharge pulses are shown in Figs.3 and 4. The averages of these measured values are shown in Figs. 5 and 6.

TABLE I : SPECIFICATION OF THE EQUIPMENTS

Item	**Specification**
Power supply (DC Generator)	Max. output voltage: 500V Min. output voltage: 100V Internal resistance: 100KΩ
Tektronix voltage probe	Maximum voltage: 100V
Coaxial cable RG58	C_o : 100pF/m and R_o: 50Ω/m
Spark capacitor	C_1: 200pF
Resistors	R_1: 100KΩ and R_2: 9 KΩ Frequency: 100MHz
Dielectric fluid	De-ionized water
Workpiece and tool electrodes	Tungsten carbide
Oscilloscopes	Tektronix TDS 540 (Max. bandwidth): 500MHz
Software	LabView 7.0 Express
Electrical switch (SW)	Frequency: 100MHz

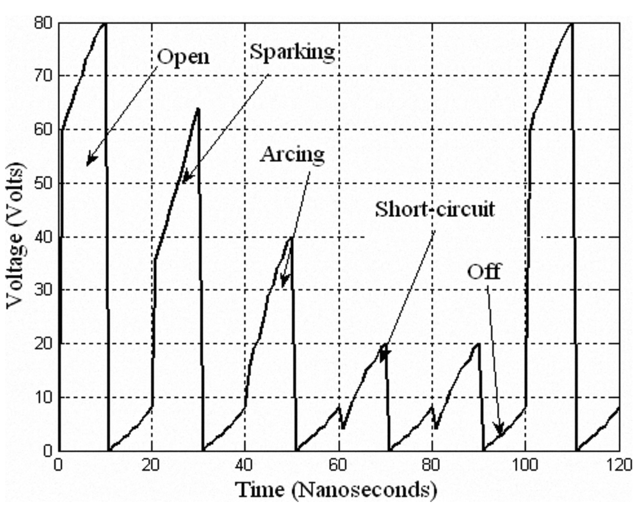

Figure 3: Measured gap voltage discharge pulses

B. *Design of Fuzzy Logic Based Controller*

In the design of the fuzzy logic based servo controller for micro-EDM, three inputs are used. These are the gap voltage

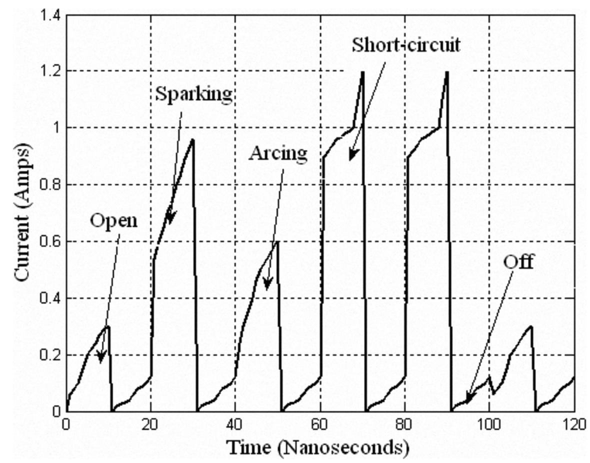

Figure 4: Measured gap current discharge pulses

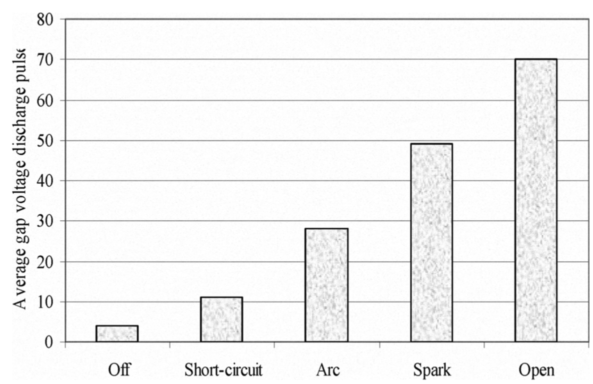

Figure 5: Average of measured gap voltage discharge pulses

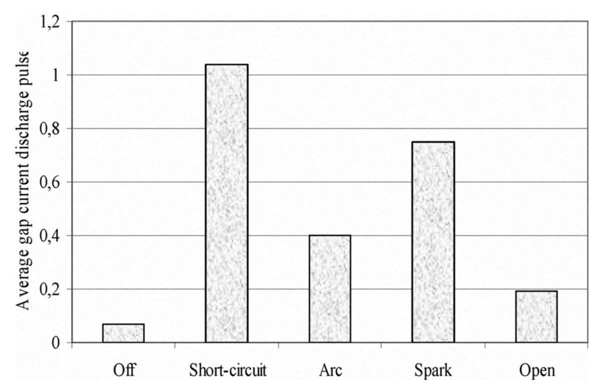

Figure 6: Average of measured gap current discharge pulses

and current, which are in form of the five classes of discharge pulses, and the differences between the reference and the actual gap voltage, that is, the gap voltage error. As an example, the pulse is considered open when the gap voltage is between 75% and 100% of the set voltage, and the current is between 5% and 25% of the peak gap current. The pulse is considered short-circuit when the gap voltage is between 5% and 25% of the set voltage, and the current is between 75% and 100% of the peak gap current. The experiments carried out on micro-EDM and operator's intuition are used to set these values. The output is the voltage to be supplied to the servomotor. The FLC works in a closed-loop system to regulate the desired gap width by controlling the direction of rotation of the servomotor.

The design of the FLC involves five steps: (i) identification of the inputs, outputs and their ranges, (ii) design of the fuzzy membership function for each input and output, (iii) construction of the knowledge base that contains the fuzzy rules used to operate the system, (iv) the fuzzy decision making or inference mechanism that perform fuzzy reasoning, (v) defuzzification to determine the crisp control output. Fig.7 shows the structure of the designed FLC. In defining the fuzzy subsets for the fuzzy variables, triangular membership functions were used. A membership function for the gap voltage as in input to the FLC is shown in Fig. 8.

Five fuzzy sets were used for each of the inputs and four for the output. Linguistic terms for the membership functions are; negative small (NS), zero (Z), positive small (PS), positive medium (PM), positive big (PB), and positive very big (PVB). A total of 65 control rules were formulated as shown in Table II. The max-min inference method is used to perform the fuzzy reasoning and the center of gravity (COG) or centroid defuzzification method is used to obtain the crisp output from the FLC.

The rules in Table II are read as follows:

Rule 1: *IF V_g is PM and I_g is PB and ΔV_g is NS THEN V_s is Z*

Rule 2: *IF V_g is PB and I_g is PM and ΔV_g is Z THEN V_s is Z*

The defuzzification carried out in the FLC design is illustrated in Fig. 9. The crisp output quantity of the FLC (a

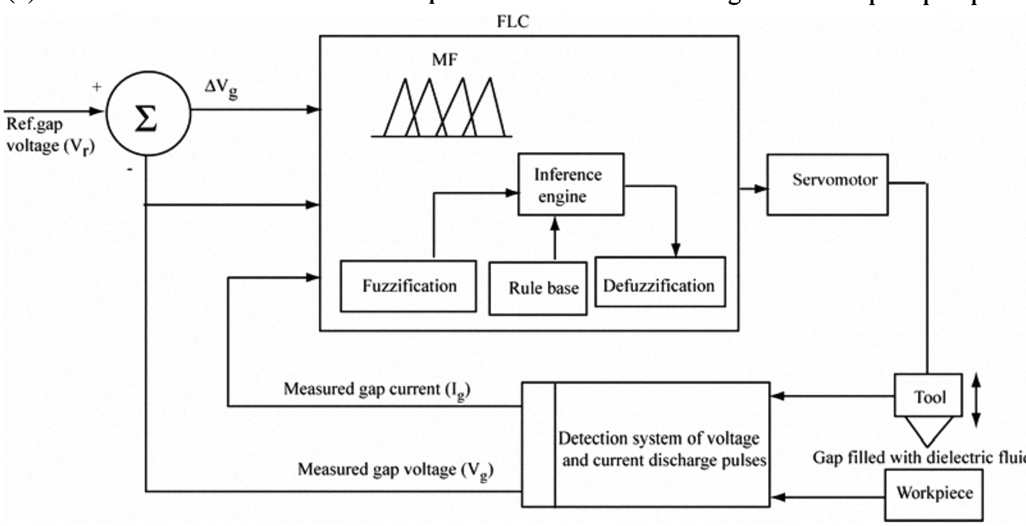

Figure 7: Structure of designed FLC for servomotor

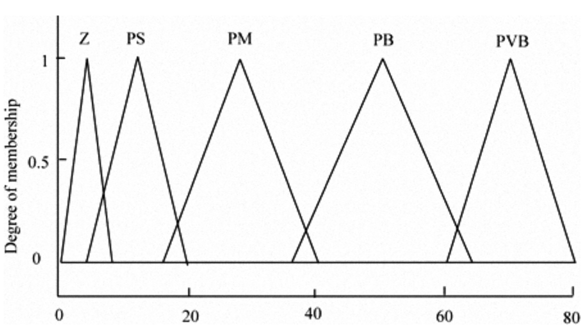

Figure 8: Membership function for gap voltage

TABLE II : RULES OF FLC

Rule No.	V_g (V)	I_g (A)	ΔV_g (V)	V_s (V)
1	PM	PB	NS	Z
2	PB	PM	Z	Z
3	PM	PM	PS	NS
4	Z	Z	PB	Z
5	PVB	PM	NS	Z
6	PVB	PS	NS	PB
7	PVB	Z	PB	Z
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65	PS	PVB	PM	NB

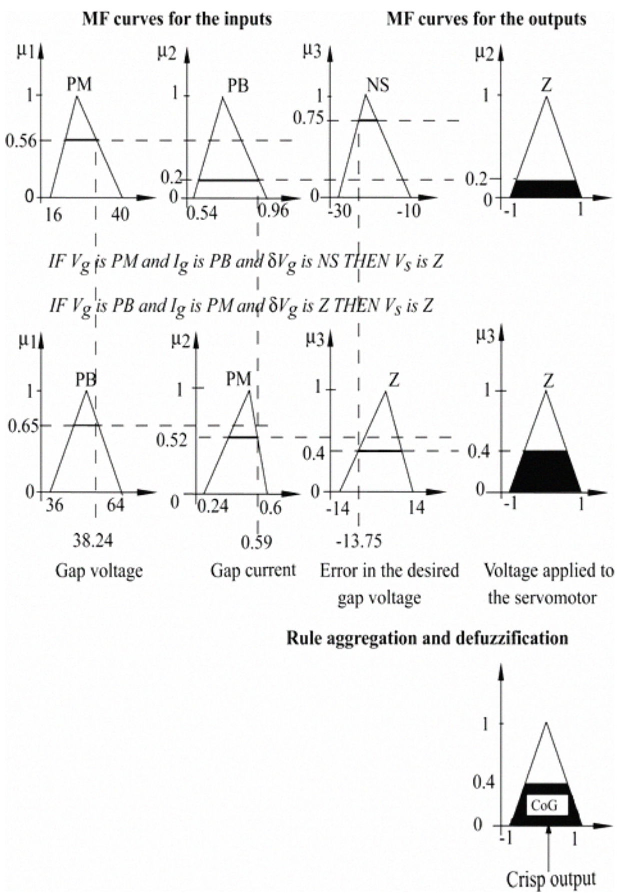

Figure 10: Defuzzification method

voltage) is used as the input voltage to the servo system to control the rotation of the servomotor which in turn controls displacement of the tool electrode in the Z-direction. The upward or downward displacement and the speed are determined by the value of the voltage applied to the servo system.

III. Results and Discussions

The effectiveness of the designed fuzzy logic based servo controller for micro-EDM operations was tested using computer simulation in Matlab/Simulink environment. Table III shows samples of voltages and currents for the different discharge conditions and the resulting voltages to the servomotor. In this table, V is the gap voltage, I is the gap current, ΔV_g is the error in the desired gap voltage, V_s is the voltage to the servomotor. When V_s is positive (open-circuit) the servomotor will rotate clockwise, thus lowering the tool. When it is negative (arcing or short circuit), the servomotor rotates anticlockwise, thus raising the tool. The servomotor will not rotate when V_s is zero (off and sparking conditions). The lowering and raising of the tool will help maintain the gap width at the desired levels. The simulated results for servomotor action are depicted in Fig. 10.

The plots of the numerical results for all the discharge conditions are shown in Figs.11 and 12. It can be seen in these figures that the gap voltages and currents are for off and

TABLE III: INPUT VOLTAGE TO SERVO SYSTEM FOR OPEN PULSE

Discharge condition	V (V)	I (A)	ΔV_g (V)	V_s (V)
Open	71.39	0.18	-19.40	1.92
	64.88	0.10	-13.99	1.93
Off	0.11	0.08	45.42	0.00
	3.70	0.06	49.92	0.00
Arc	21.36	0.36	29.58	-1.5
	38.25	0.39	18.37	-0.70
Spark	56.45	0.75	6.76	0.00
	38.24	0.59	-13.75	0.00
Short circuit	18.75	1.10	39.03	-1.81
	11.82	1.19	33.26	-2.18

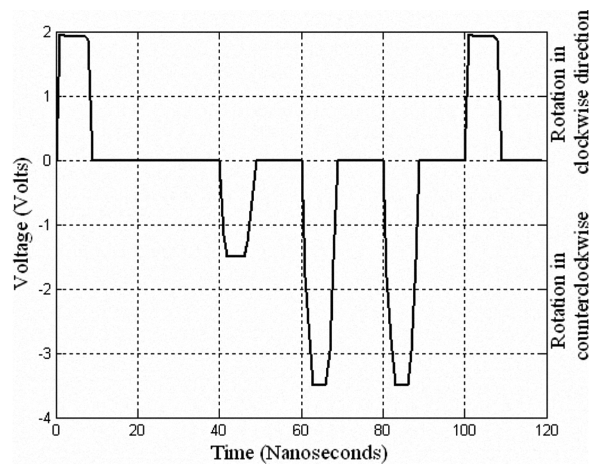

Figure 10: Behavior of servomotor for various pulses

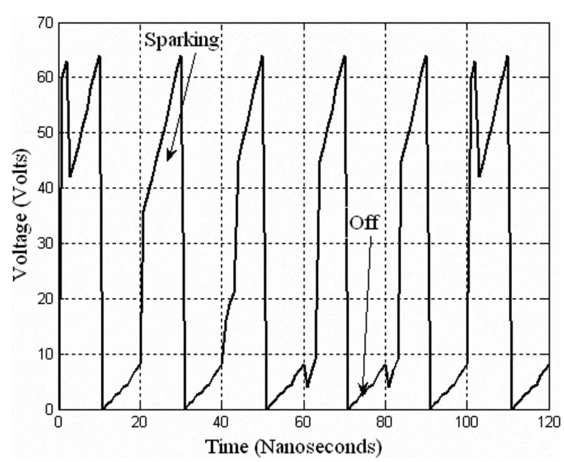

Figure 11: Simulated results for gap voltage discharge pulses

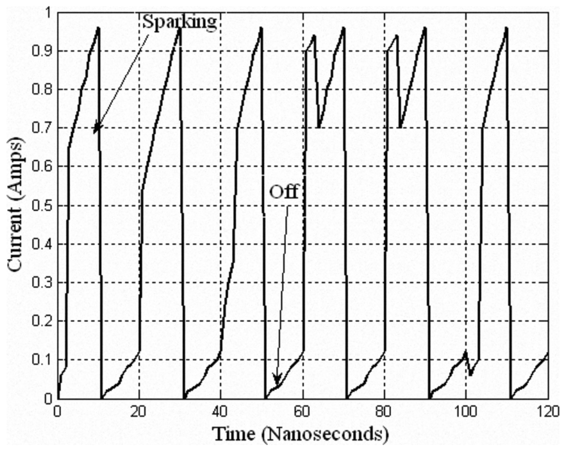

Figure 11: Simulated results for gap current discharge pulses

sparking conditions only. This means that unlike the PID controller, the proposed FLC can effectively eliminate the undesired arc and short-circuit discharge pulses. This indicates that machining with the proposed FLC is more stable than with the PID controller (Figs 3 and 4). Thus, the proposed fuzzy logic based servo controller for micro-EDM process yields better gap discharge characteristics and therefore can improve machining time and minimize loss of the energy due to idle machining or short-circuits.

Furthermore, these results indicate an improvement from those obtained with RC and transistor isopulse [8, 9] under the same conditions in that idle machining is eliminated.

IV. Conclusion

In this paper, a tunable fuzzy logic based servo controller for monitoring and control of the micro-electro discharge machining (micro-EDM) process has been developed. A number of experiments were carried out in order to classify the discharge pulses through measurement and analysis of gap voltage and gap current pulse characteristics. An RC-type discriminating system was used to provide real time behavior of the pulses during the micro-EDM process. The actual gap voltage and gap current of the discriminated pulses were used as the input data to an FLC whose output was used as the control input of the servomotor for maintaining the desired gap width.

The results of this study show that the proposed fuzzy logic based servo controller can improve efficiency of micro-EDM operations.

As an improvement to the already existing micro-EDM machines, these can be modified by incorporating high frequency pulse generators. In addition, there is need to test practically the effectiveness of the proposed controller.

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