A Comparison of Different Input Values for Gap-Width Controllers used in Electro-Discharge Machining[1]

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Abstract

The operating efficiency of an Electro-discharge (ED) machine is strongly influenced by the gap-width controller. For the multiple cases in which ED-machining is used in practice the gap width controller has to provide a stable and efficient removal process. Most of modern ED-machines make use of the ignition delay time (t_d) as input value for the gap width controller. A disadvantage of t_d for control operations is it's considerable variance. As consequence of this fact a flutter movement of the electrode often may be observed. In case of finishing even micromotions influences the removal rates because of the very small geometrical gap width. Therefore a gap-width controller was developed which uses the relative frequency of short circuits and open circuits during an inspected period as input values. In finishing and micro erosion operations much higher removal rates and reduced electrode wear was observed. A further improvement was achieved by implementing the controller algorithm using fuzzy computation technology.

Key Words: *electro-discharge machining (EDM); gap-width controller; fuzzy-logic*

1. Introduction

The gap width controller is a significant part of the process control system in electro-discharge (ED) machines. The strategy of the controller should fit to the employed generator technology and the machine should include a facility to detect „arcs" [1], in order to realize and react early to tendencies of process corruption. An optimal electrical gap-width must be realized by the gap-width controller to achieve a stable and highly efficient erosion process for the multiplicity of EDM applications [2]. The electrical efficient gap width can not be measured directly during ED-processing [3] yet, because of the surface roughness of the electrodes and the local different distribution of the dielectric properties in the gap zone. So in industrial use of EDM other controller input parameters must be applied.

Most of modern ED-machines make use of the ignition delay time (t_d) as input value for the gap width controller [4], [5], [6]. Especially if using a microcomputer based control system, t_d as controller input has many advantages. It is easy to measure, the comparison to a t_d-target value can easy be realized and t_d can characterize the most important kinds of ignitions [7]. Another disadvantage of t_d for control operations is it's considerable variance. Especially if the EDM-process is carried out without external flushing this variance is very high.The reason for this is the permanent growth of gap pollution during the ongoing process. This pollution influences the electric field strength and promotes conditions precedent to an ignition [8]. Figure 1 shows the big variance of t_d-values recorded at a constant geometrical gap-width.

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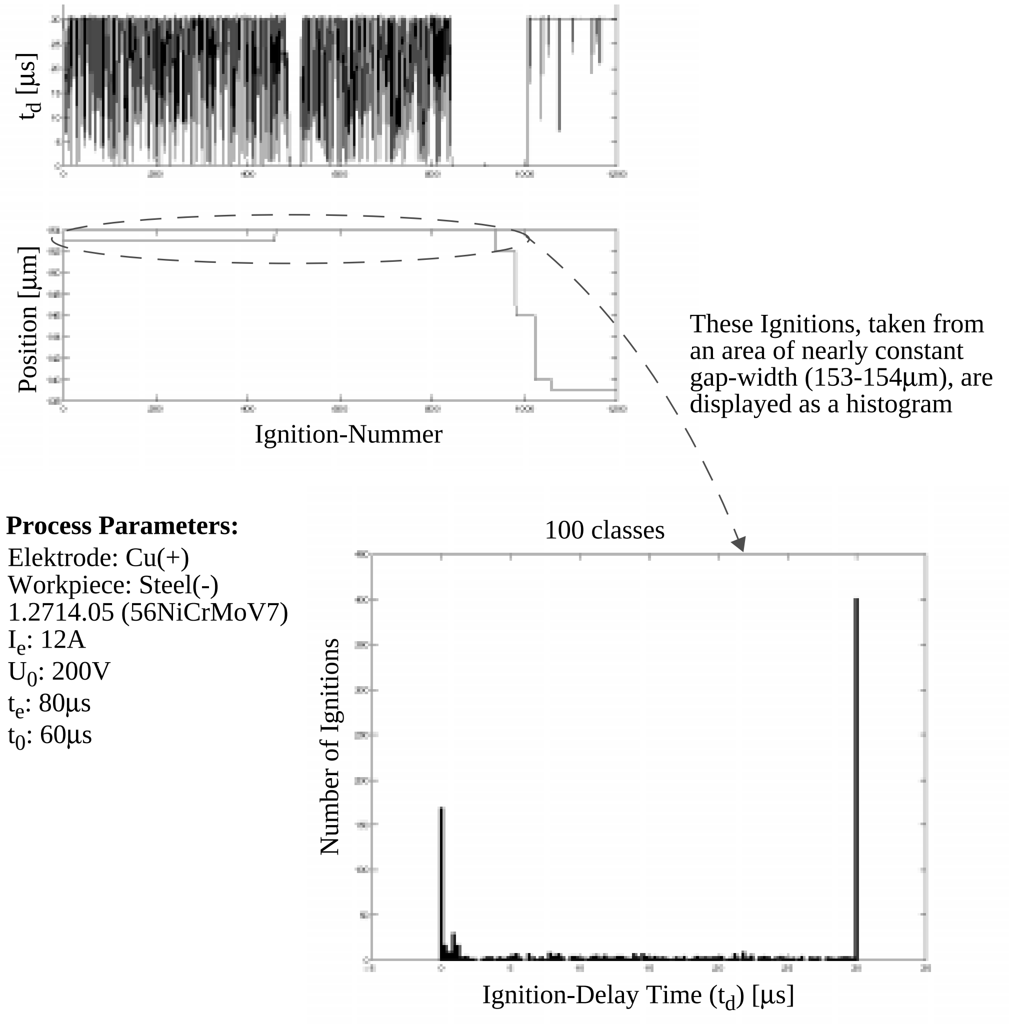


Note: Due to the engaged generator technology all pulses which did not show an ignition after 30 µs are classified as open-circuits and switched off. As a consequence open-circuits can be found in the histogram by an ignition delay time of 30 µs.

Figure 1: Variance of ignition-delay time in the case of constant geometrical gap-width

The histogram in figure 1 shows that even when geometrical gap-width is constant pulse characteristics can vary from short-circuit (t_d = 0 µs) to open-circuit (t_d = 30 µs) and ignition-delay time is varying in a wide range. To smooth this variance t_d-values are filtered before using them as controller input. This filtering once can simply be done by calculating the average value of several ignitions but also more complex methods of filtering are applied. Much research work has been spent to design optimal filter algorithms for the t_d-values in sequence in order to obtain smooth t_d-parameters for the gap width controller [9], [10]. Nevertheless the fluctuating controller input t_d leads to a flutter movement of the electrode. For roughing erosion those flutter movements are unproblematical, because in these cases the stability of the erosion process does not depend much on the actual gap width.

In case of finishing or micro erosion a stable process can be maintained only in a very small geometrical gap distance. Even micromotions can lead to process corruption.

The modern generator used in our experimental erosion machine works as a controlled current source [11]. The hard rise of the gap voltage produced by this kind of generator at pulse beginning creates ignitions with very small t_d-values (figure 2). This reduces the significance of t_d-values as controller input even more.The disadvantages initiate the search of alternative controller inputs which are more suitable to the employed generator technology and provide a stable erosion process even at finishing conditions.

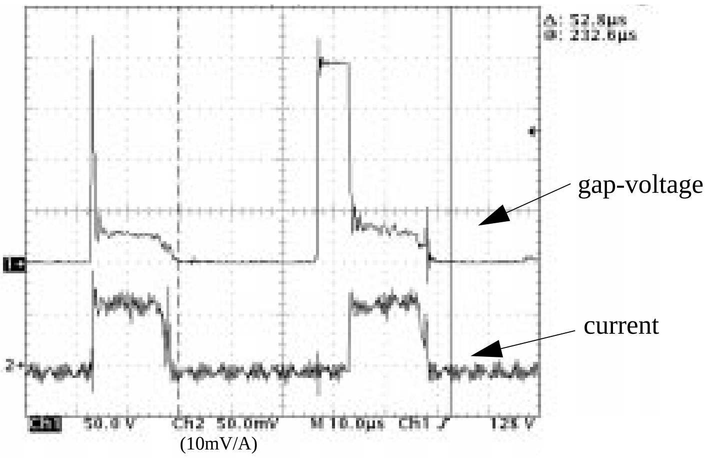


Figure 2: Hard rise of gap-voltage at pulse beginning

The solution are input parameters derived from the relative frequency of short-circuits and open-circuits during an inspected period. A highly efficient removal process shows a very low number of these pulses. As demonstrated in figure 3 the mentioned two parameters mark two undesirable process conditions, namely the dominance of open-circuit and short-circuit pulses.

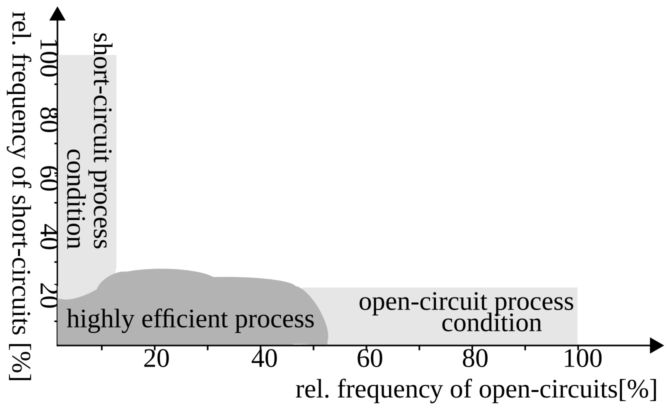


Figure 3: Different process conditions characterized by the relative frequency of short-circuit and open-circuits

2. Comparison of Different Methods for Gap-Width Controlling

The used ED-machine configuration allows the implementation and comparison of different gap-width controllers and optimization strategies by programming their algorithms into a VME-bus-based computer system [12]. Moreover the ED-control system can measure and record various process parameters for further statistical analysis. These are conditions for extensive testing of different control strategies under the same conditions. In the following a t_d-based gap width controller is compared to a controller that uses only the relative frequency of short-circuits and open-circuits as input parameters (SC/OC-based). Both controllers were inspected at roughing as well as at finishing operations. The efficiency of the controller strategy was proved by the resulting electrode wear and the removal rate.

The characteristic function of the t_d-based gap-width controller has a split devolution (figure 4). Both forward and backward amplification can be changed separate from each other. As an input parameter the average value of t_d is used.

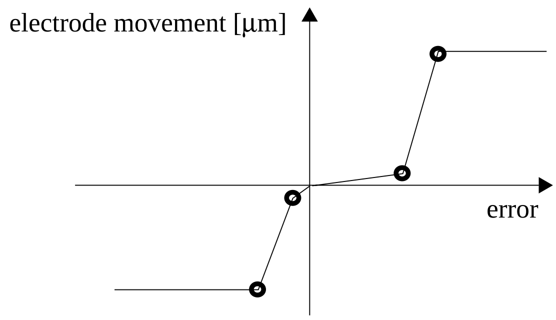


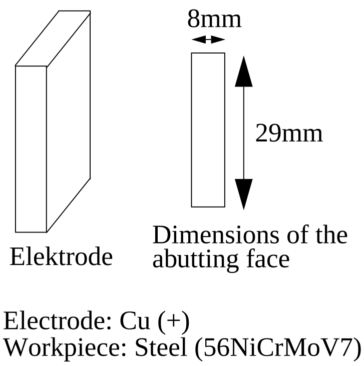
Figure 4: Characteristic function of the t_d-based controller

The SC/OC-based controller achieves a process with a small amount of short-circuits and open circuits. For that threshold values for short-circuits and open-circuits can be preselected as controller parameters. If the measured relative frequency of open-circuits and short-circuits is below the defined thresholds the electrode position will not be changed. If one of the relative frequencies is above its threshold, the electrode position is changed proportional to the absolute amount of its exceed. The parameters of this controller are:

- OC-threshold: Threshold for relative frequency of open-circuits
- SC-threshold: Threshold for relative frequency of short-circuits
- P-OC: Proportional factor used, if the rel. frequency of open-circuits is above its threshold to release a gap reduction
- P-SC: Proportional factor used, if the rel. frequency of short-circuits is above its threshold to release a gap enlargement.

Figure 5 shows the machine parameters and the electrode geometry that were used to carry out the comparison of the gap-width controllers. The controller parameters were varied systematically in each test.

Machining Parameters:



	Finishing	Roughing
I_e [A]	6	40
U_0 [V]	200	160
t_e [µs]	10	200
t_0[µs]	30	20
Number of Arcs for flushing	10	100
deepness	variing	10 mm
Time for testing	60 Min.	variing

Figure 5: Machining parameters and electrode geometry used for comparison of the different gap-width controllers.

All tests were carried out without external flushing. The normal cleaning of the gap is performed only by the electrode lift-off movement triggered by a separate arc detection module. Arcs were treated separately first by switching off the current and, in case they don't disappear when restarting, a gap flushing is released by a combination of an oscillating and retrieval movement of the electrode in order to clean the gap [4]. The arc detection and flushing mechanism is independent from the gap-width control.

Figure 6 and figure 7 display the results for the roughing application:.

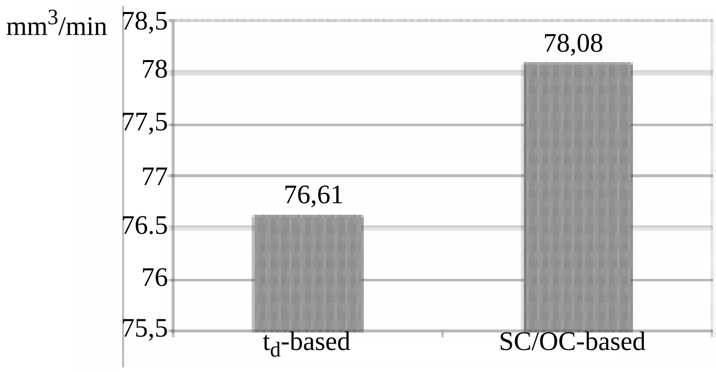


Figure 6: Removal rate for roughing application

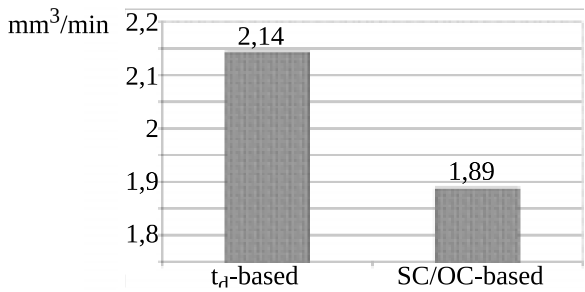


Figure 7: Electrode wear for roughing application

From the experimental results for roughing (figure 6 and figure 7) it can be seen that the SC/OC-based controller can only slightly improve the removal rate in comparison to the t_d-based controller. Because of the higher gap-width in a roughing EDM-process a fluttering electrode movement can be tolerated. For this reason no great improvement can be achieved by SC/OC-based control strategy.

Figure 8 and figure 9 display the results for the finishing application:

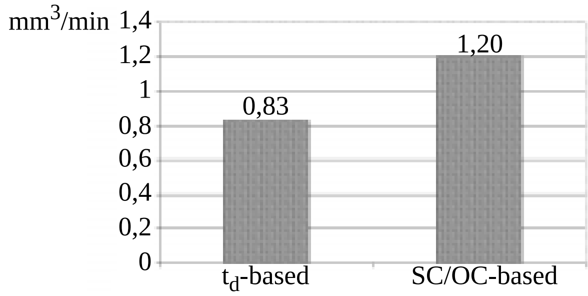


Figure 8: Removal rate for finishing application

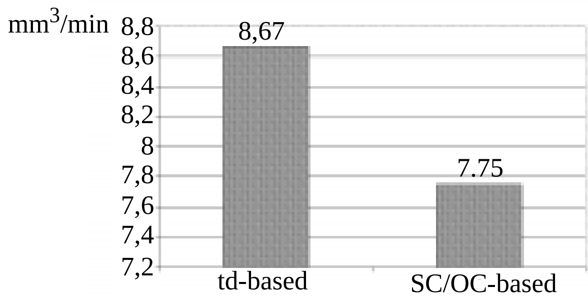


Figure 9: Electrode wear for finishing application

Comparing the removal rates from both controllers in a finishing application (figure 8), it can be recognized that an improvement of about 40% is achievable using the SC/OC-based controller. An additional improvement of the SC/OC-based controller is the reduction of electrode wear in both finishing and roughing (figure 7 and figure 9).

By systematic variation of the SC/OC-controller parameters it turned out, that better removal rates can be achieved, if the OC-threshold parameter is kept high (50%). From this it follows that a relatively high rate of open-circuits can be tolerated before moving the electrode towards the workpiece. Figure 10 shows the distribution of t_d-values during ED-processing using the SC/OC-controller with an OC-threshold of 50%. This random sample shows an increasing number of open-circuits (t_d = 30μs).

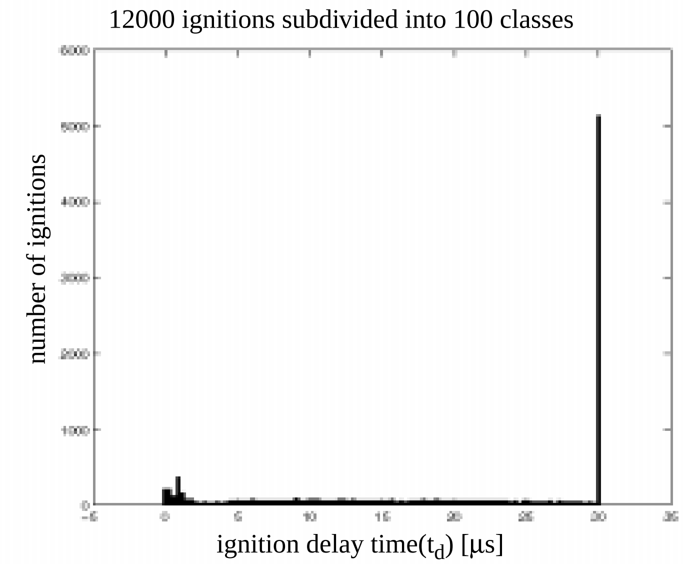


Figure 10: Histogram of ignitions recorded during the ED-process using the SC/OC-controller

This increased portion of open-circuits is responsible for the ascertained reduced tendency toward arcing that can be observed during processing when looking at the number of flushing movements. The reason for tendencies towards process corruption is the increasing contamination of the gap by removed particles. By running the ED-process with a constant geometrical gap-width and without the cleaning influence of flushing there will be a strong tendency towards short-circuit and therefore a high danger of arcing, because of the growing number of removed particles and the resulting reduction of the dielectric-isolation. A better process behaviour can be achieved by running the ED-process with a geometrical gap-width that causes an increased portion of open-circuits. If gap-width is kept constant in this case material will be removed until no further breakdown can happen. The gap-width is continuously increased by each ignition until it is too large (the process will end himself).

With a geometrical gap-width that let the process turn into open-circuits the risk of arcing is definitely reduced. The higher removal rate in spite of the high portion of open-circuits, that might be seen as ineffective time, can be lead back to the reduced tendency toward arcing.

Ignitions classified as „arcs“ are switched off by the separate arc detection module. So they don’t contribute to material removal. Arcs lead to a flushing movement, if they appear in fast succession. Therefore the process is interrupted for seconds during the execution of the flushing electrode movement. This negative influence can be prevented if the gap-width controller avoids tendencies towards arcing by increasing the gap width in spite of augmenting a higher amount of open-circuits.

The loss of time during an open circuit is limited by the improved generator technology with its steep voltage rise at pulse beginning. Breakdown happens at about 90% of the normal ignitions after delay time of 30µs. If the breakdown is not detected after 30µs the impulse is classified as an open circuit. The dielectric isolation will not be influenced very much by an open circuit, therefore pause time (t_0) is automatically limited to the time, that is needed to refill the energy sources inside of the generator (5µs), after such an open circuit. Due to both time limitations the lost time during one open circuit is not more than 35µs.

For the described gap-width controller comparison the implementation was carried out using traditional control-engineering techniques. Fuzzy Logic has obtained much popularity in control applications [13]. Therefore in the following section Fuzzy Logic is included in this comparison.

3. Using Fuzzy-Logic for gap-width control

Fuzzy-technologies has been applied with big success for the control of processes whose transfer functions are unknown or hard to describe [14]. Also in the field of EDM an increasing number of fuzzy process-control systems can be observed [6], [15], [16]. This is supported by the following features of fuzzy logic:

- Fuzzy-Controllers are comprehensible, because their concept is close to human thinking.
- User knowledge can be integrated in the control system
- For controller design it is sufficient to formulate the coherences of the problem domain which even can have contradictory influences.

The gap-width controller based on the rel. frequency of short-circuits and open circuits can be implemented using fuzzy technologies. The strategy of this controller can be characterized as follows:

1. If *little* short circuits and open-circuits don’t move electrode
2. If *more* short circuits move electrode backward
3. If *much* open-circuits move electrode forward

So far the fuzzy terms *„little“, „more“* and *„much“* were implemented using thresholds for tolerated open-circuits and short-circuits. With the possibilities of fuzzy-logic the control behavior can much finer be graded. Figure 11 shows the principle design of a fuzzy-controller. The measured input data must be „fuzzyfied“ before further processing. This is done inside the fuzzyfication component using membership functions. In the next step statement about the output are made inside the inference module using *if..then* clauses. At the end the ouput is converted into a format that can be sent to an actuator.

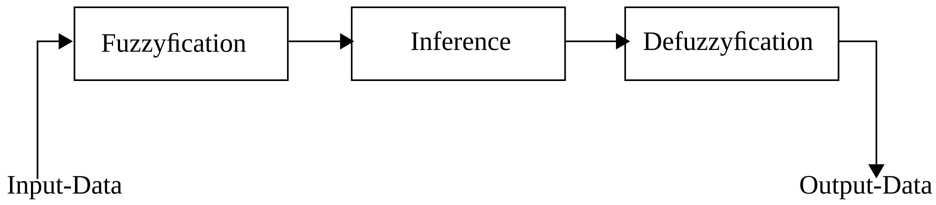


Figure 11: Principle design of a fuzzy control system [17]

The architecture of the gap-width controller is shown in figure 12. The membership functions used for fuzzyfication of the inputs are shown in figure 13 and figure 14. The membership functions of the output can be found in figure 15.

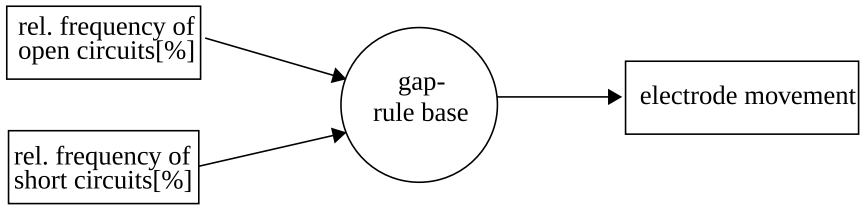


Figure 12: Fuzzy-architecture of the SC/OC-based gap-width controller

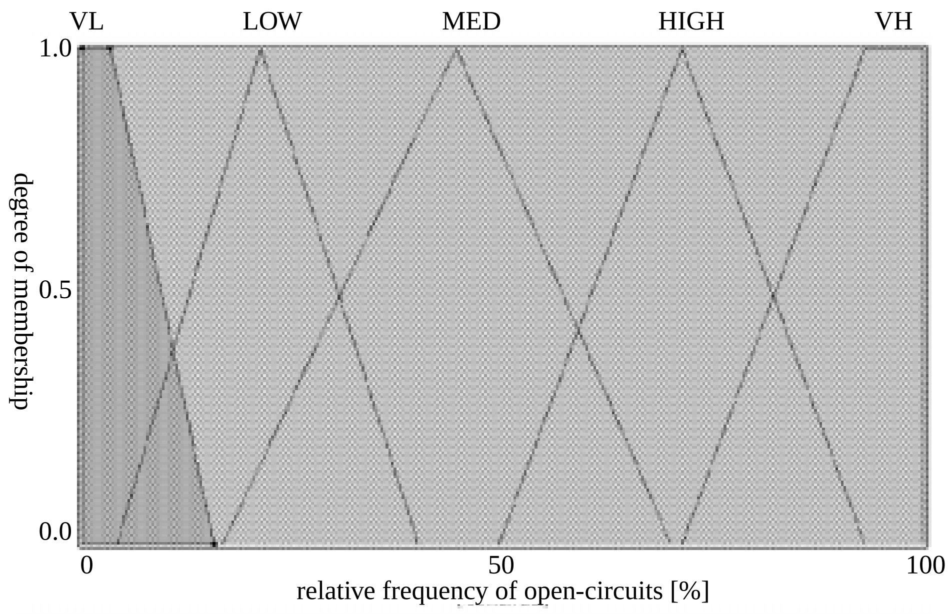


Figure 13: Membership-functions of the input „relative frequency of open-circuits“

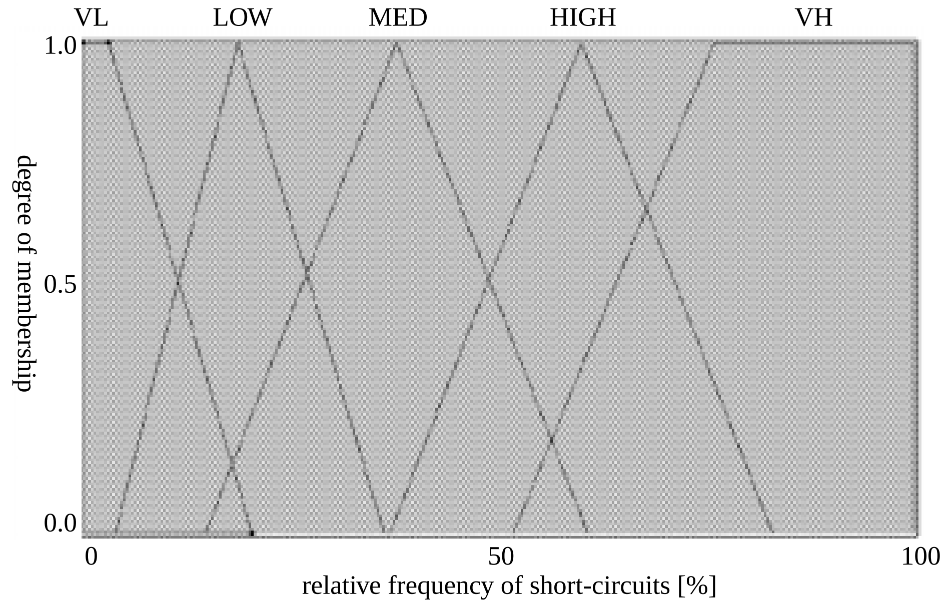


Figure 14: Membership-functions of the input „relative frequency of short-circuits“

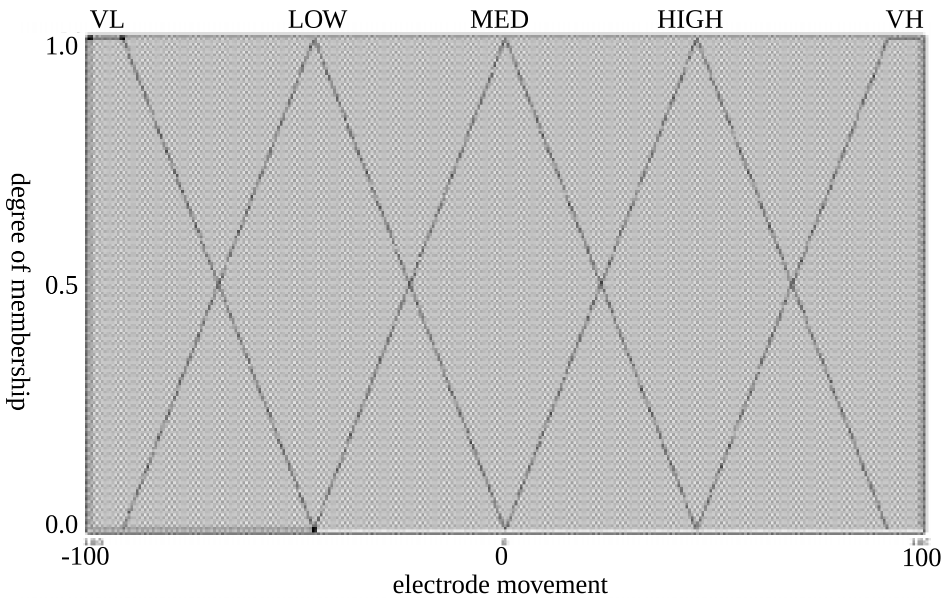


Figure 15: Membership-functions of the output „electrode movement“

Using „*If-then*“ clauses the controller output (electrode movement) is computed inside of the fuzzy rule-base. All these „*If-then*“ rules combine two linguistic values of the input variables by an AND operation. The Fuzzy-AND conjunction is implemented by the MIN[1] operation. The complete rule-set of the gap-width controller can be written as a table (Table 1).

Area I

AND		relative open-circuit frequency				
		VL				
relative short-circuit frequency	VL	MED	MED	MED	HIGH	VH
	LOW	MED	MED	MED	MED	HIGH
	MED	LOW	LOW	MED	MED	MED
	HIGH	LOW	LOW	LOW	MED	MED
	VH	VL	VL	VL	VL	VL

Area III

Table 1: Gap-Rulebase

Area II

The strategy of not moving the electrode in the situation of a high efficient process, if only a small number of open-circuits and short-circuits will be observed, is implemented in area I of the rule base (Table 1). Area II leads to an electrode backward movement because more short-circuits are detected. The forward movement of the electrode in case of a raising portion of open-circuits is implemented in area III.

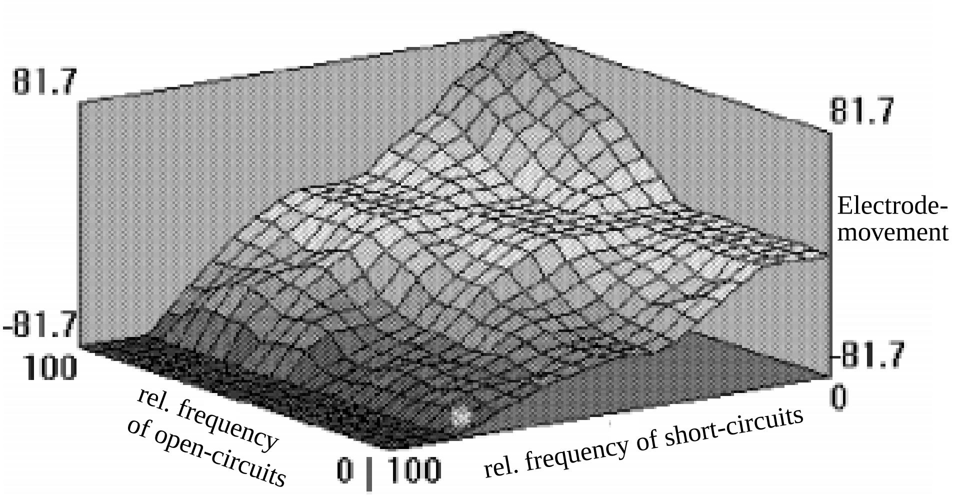


Figure 16: Illustration of gap-width controller function in 3-D

1. The operation MIN(a,b) return the smallest value of the two arguments a,b

Output of the fuzzy gap-width controller is the electrode movement ranging from -100 to 100. To compute a new target value for the spindle drive, a multiplication with a scaling factor is necessary. It is possible to use different scaling factors for forward (S_V) and backward (S_R) movement. Both scaling factors can be adapted by an optimization system.

The described fuzzy gap-width controller was tested using the EDM-application described in figure 5 for roughing as well as finishing. The resulting removal rates and electrode wear in comparison to former tested gap-width controllers can be seen in figure 17.

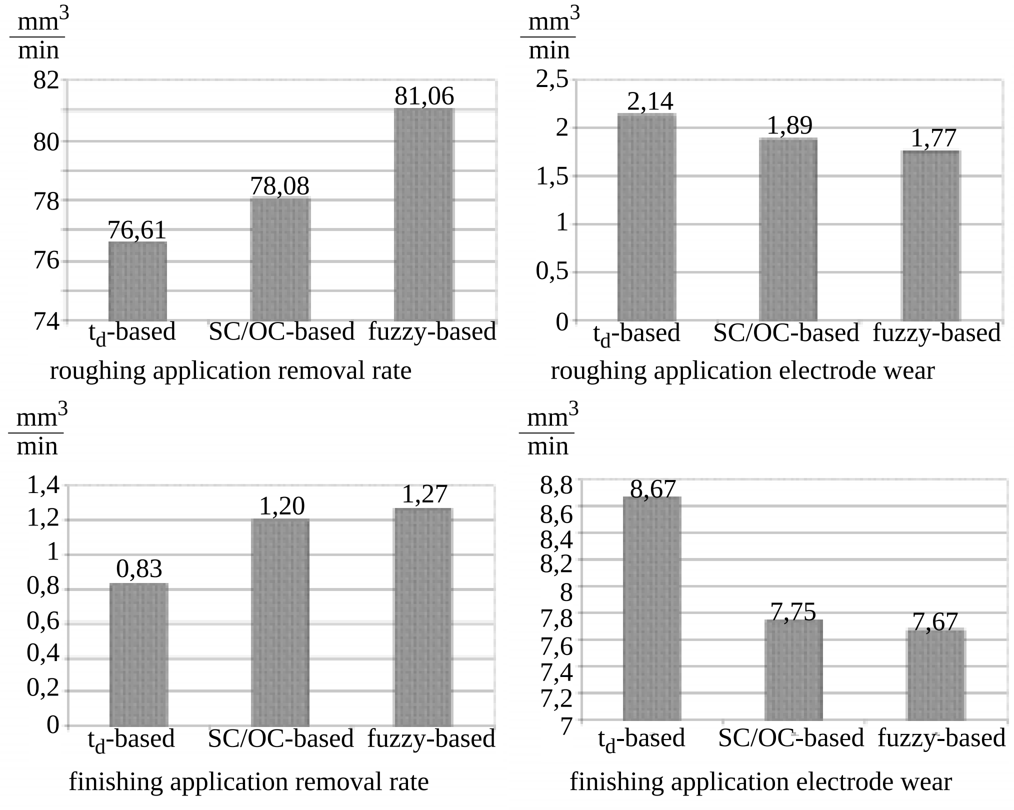


Figure 17: Experimental results using the SC/OC-based Fuzzy-controller

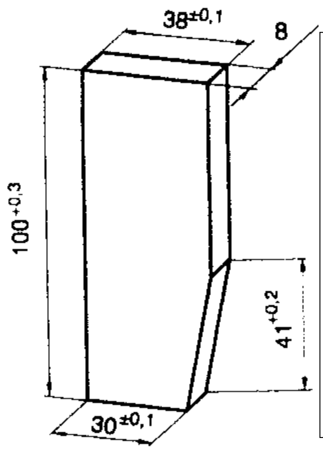
4. Relation towards the evolution of gap-width controllers

Since now many research work has been spent to develop adaptive control strategies for EDM [4], [5], [7], [10], [15], [19], [21], [22], [23]. In the beginning of ED-technology gap-width controllers were based on the classification of pulses into open-circuits, short-circuits and normal ignitions [18] similar to the controller introduced in this work. These early gap-width-controllers were implemented using simple logic- and counter-circuits due to a lack of powerful computer systems. Because of a more precise process estimation analog controllers based on the mean gap voltage $\bar{u}$ displaced these kind of controllers in industrial application. Nowadays most modern ED-machines use controllers based on the ignition delay time t_d with the disadvantages already pointed out.

On the level of control-optimization there are many methods adapting the target value of the gap-width controller (e.g $t_{d\text{-target}}$) on the basis of an impulse classification as it is used in this work. As an example the work of Dauw [20] can be mentioned. Here the ED-process is evaluated by classifying each pulse into one of 15 classes. This classification is used to adapt the target-value of a t_d-based gap-width controller. In contrast to this procedure the work presented here is not an adaption. It is a pure gap-width controller based on the former method of controlling the gap-width by classifying pulses into open-circuits, short-circuits and normal ignitions. The concept of this work is a renaissance of the early gap-width controlling techniques but in combination with an effective arc detection and prevention strategy together with fuzzy computation and improved generator control.

5. Summary and experimental results

The considerable variance of t_d-values leads to a flutter movement of the electrode during ED-processing when using t_d as an input for gap-width-control. This movement can cause short-circuits and arcing especially when running a finishing application. With modern generator technology, working as a current source, predominantly small t_d-values can be observed, because the hard rise of gap voltage at pulse beginning. By limiting the range of t_d-values to a small region, the random variation of t_d has more negative effect. To avoid this effect the relative frequency of open circuits and short circuits has been used as controller input values. The developed fuzzy gap-width controller achieves better results than a t_d-based controller. By using the relative open-circuits and short-circuit frequency the process runs in a condition with increased open-circuits and only a very few short-circuits or arcs. The electrode movement can be characterized as a slow forward movement. Fast electrode motions are only necessary for flushing. The improvement of this kind of controller can be seen more clearly by looking at the application shown in figure 18



Machining parameters:
I_e: 27A
U_0: 180V
t_e: 250 µs
t_0: 20 µs
Number of Arcs for flushing: 200
Electrode: E-Cu (+)
Workpiece: 56NiCrMoV7
Deepness: 30 mm

Results using t_d-based controller:
Duration: 106,5 min
V_w: 78,9695 mm^3/ min
V_E: 1,10405 mm^3/ min
ϑ1,398%

Results using SC/OC-based Fuzzy-controller:
Duration: 116 min
V_w: 72,9443 mm^3/ min
V_E: 0,58887 mm^3/ min
ϑ: 0,807%

Figure 18: EDM-sinking of a wedge shaped electrode

By looking at results shown in figure 18 one can see the big difference in electrode wear (V_E). The t_d-based controller has an electrode wear that is 50% bigger compared to the SC/OC-based controller. This higher wear is visible on the final shape of the electrode and the workpiece. The increased electrode wear can be explained by the frequent pulse switch-off due to arcing.

These arcs were caused by the flutter electrode movement. The SC/OC-based controller was not so often in the danger of arcing because of an increased number of open-circuits during processing. On the other hand this increased number of open circuits is responsible for the slightly reduced removal rate (V_W).

BIBLIOGRAPHY

[1] Patentanmeldung, Deutsches Patentamt DE 195 12 291 A1
„*Verfahren und Schaltung zur Überwachung und Vorhersage eines Funkenerodierprozesses in einer Funkenerodiermaschine*"
Inventor: A. Behrens, M.P. Witzak, F.-L. Bruhns; April 1995

[2] B. M. Schumacher, D. Weckerle: „*Funkenerosion - richtig verstehen und anwenden*", Velbert 1989

[3] B. Bommeli: „*Ètude de l'influence de la contamination sur l'amorcage des décharges dans les diélectriques liquides*", Dissertation, Universität Genf, 1979

[4] M. P. Witzak: „*Verbesserung der Prozeßführungssysteme für funkenerosive Senkanlagen unter Einbeziehung von Fuzzy-Technologien*", Dissertation, Universität der Bundeswehr Hamburg, 1997

[5] R. P. Raabe: „*Prozeßoptimierung für das funkenerosive Senken mit Neuro-Fuzzy-Control*", Dissertation, RWTH Aachen, 1999

[6] M. Boccadoro, D. Dauw: „*About the Application of Fuzzy Controllers in High-Performance Die-Sinking EDM Machines*", Proc. ISEM XI, Lausanne, pp. 333 - 341, 1995

[7] H. Peuler: „*Identifizierung des Entladungsprozesses bei der funkenerosiven Senkbearbeitung und Auslegung von Regelungseinrichtungen*", Dissertation, RWTH Aachen, 1981

[8] M. Slomka: „*Funkenerosives Senken - adaptive Vorschubregelung und Planetärbewegung*", Dissertation, RWTH Aachen, 1989

[9] P. Odensass: „*Ein Verfahren zur Prozeßsteuerung und digitalen adaptiven Vorschubregelung funkenerosiver Senkanlagen*", Dissertation, Universität der Bundeswehr Hamburg, 1995

[10] J. M. Dehmer: „*Prozeßführung beim funkenerosiven Senken durch adaptive Spaltweitenregelung und Steuerung der Erodierimpulse*", Dissertation, RWTH Aachen, 1992

[11] A. Behrens, J. Ginzel: „*Neuartige Konzepte für Prozeßführungssysteme funkenerosiver Senkanlagen*", Proc. Fachtagung Leistungselektronik und intelligente Bewegungssteuerungen, Magdeburg, pp. 198 - 203, 1999

[12] A. Behrens, M. P. Witzak: „*An Hierarchical Process Control System for Highly Efficient Electro-Discharge Machining*“, Proc. ISEM XII, Aachen, pp. 173 - 183, 1998

[13] E. H. Mamdani, N. Baaklini: „*Prescriptive Methods for Deriving Control Policy in a Fuzzy Logic Controller*“, Electronic Letters 11, pp. 625-626, 1975

[14] S. Murakami, F. Takemoto: „ *Weld-Line Tracking Control of Arc Welding Robot using Fuzzy-Logic-Controller*“, Fuzzy Sets and Systems 32, pp. 221-237, 1989

[15] A. Morita: „*Fuzzy Controller for EDM*“, Proc. ISEM IX, Nagoya, pp. 236-239, 1989

[16] A. Behrens, M. P. Witzak: „Integrating Fuzzy Technology in EDM Process Control“, Proc. ISEM XI, Lausanne, pp. 287- 295, 1995

[17] L. A. Zadeh: „*The Concept of a Linguistic Variable and its Application to Approximate Reasoning*“, Information Sciences 8/9, pp. 199-249, 1975

[18] V. Lüders: „*Probleme bei der Vorschubregelung von Funkenerosionsmaschinen*“, Technische Mitteilungen Krupp, Band 33 Heft 1, 1975

[19] D.F. Dauw: „*On-line Identification and Optimization of Electro-Discharge Machining*“, Dissertation, Kath. Universität Leuven, 1985

[20] D.F. Dauw, R. Snoeys: „*EDM Tool Wear Control and Workpiece Removal Rate Optimization By Adaptive Control Optimization*“, Proc. ISEM VIII, Moskau, pp. 46-55, 1986

[21] P. Kruth: „*Adaptive Control Optimization of Electro-Discharge Machining*“, Dissertation, Kath. Universität Leuven, 1979

[22] M. Kunert: „*Meßwerterfassung und - verarbeitung bei der mikrorechnergestützten on-line Optimierung des funkenerosiven Senkens*“, Dissertation, TH Magdeburg, 1984

[23] K. P. Rajurkar, W. M. Wang: „*A New Model Reference Adaptive Control of EDM*“, Annals of the CIRP Vol38/1/1989, S. 183-186