Discharge analysis of EDM pulse generator

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Abstract. Electrical discharge machining (EDM) is a non-conventional manufacturing process used broadly in medical applications, aerospace industry and manufacturing in hard material fields. However, information about the process is still in an unfledged stage and it has been becoming a serious obstacle to its more improvements. In this paper, spark discharge condition is studied based on the simulated model of EDM spark pulse generator system equivalent form. Simulated model is verified by comparing with a series of experimental results. Frequency response is established through simplified model of EDM system. Influence of discharge time and stable discharge current on material removal rate (MRR) and stability of the system is analysed. This study is important to select the process parameters, and uses as a guidance to design the EDM spark pulse generator system.

Keywords: EDM, discharge, spark, MRR

1. Introduction

Electrical discharge machining (EDM) is one of the widely used machining methods, principally in medical applications, aerospace industry and manufacturing in hard material fields [1-3]. EDM uses spark discharge to remove material from high-toughness conductive workpieces. Non-contact machining character of EDM makes it feasible to process a variety of complex surfaces with high quality and machining accuracy [4-6]. Thus, EDM is an irreplaceable process in industries of medical, aerospace, nuclear, automotive, mold-die production, and many other fields [7-9]. However, research on theoretical basis and mechanism of EDM is still in an unfledged stage and it has been becoming a serious obstacle to its further improvements. Gap voltage, gap current, discharge duration and spark frequency are major parameters effect on the material removal rate as one of the significant aspects for machining process [10-14]. Presently, there is no unified comprehension about mechanism of EDM due to its complexity and particularity [15-18]. Experimental analysis is a time consuming and costly procedure, due to the highly stochastic and complex nature of the process. So, the influence of spark parameters on the machining operation should be studied through an equivalent model of EDM system.

As illustrated in figure 1, each spark cycle of EDM process, $T_s$, is divided into three phases. The ignition phase of the $t_l$ and is followed by the discharge phase of the $t_d$ and the next phase of the recovery of the $t_r$.

However, material removal takes place during discharge phase. So, research on spark characteristics in discharge phase is a guidance to reveal erosion performance of EDM and improve its machining quality and process efficiency. Transfer function and frequency analysis are most common techniques can be used to determine the behavior and quantify performance of EDM. So, research on the effect of
circuit parameters of spark discharge on machining function is very important to adjust the system parameters, maintain the stability of discharge and improve the process efficiency based on the EDM application.

![Figure 1. Profile of gap voltage and gap current during EDM process](image)

2. Equivalent model of EDM spark pulse generator system

2.1. Determination of circuit model parameters

In order to predict spark parameters and achieve desirable performance, an equivalent circuit-model for EDM spark pulse generator system is developed. As shown in figure 2, equivalent model is formed with ac to dc power supply, transistorized pulse generator and spark circuit. In most EDM applications, break down voltages needed to ignite a spark is less than the rectified utility supply voltage [19]. In this design, high switching frequency of buck converter is used as power supply to provide required break down voltage. Mosfet switch $S_1$ operates as pulse generator to control current from power supply along with resistor $R_1$. While Mosfet switch $S_2$ identifies discharge duration. Table 1 shows switching states of $S_1$ and $S_2$ in each machining phase during one spark cycle. EDM spark is modeled by the shunt resistor $R_s$ in series with two parallel branches of ignition resistor $R_i$ in one branch and discharge resistor $R_d$ in series with discharge inductor $L_d$ in another branch.

| Table 1. Switch states of $S_1$ and $S_2$ in one EDM spark cycle |
|---------------------------------------------------------------|
| phase            | $S_1$ | $S_2$ |
| Ignition         | ON    | OFF   |
| Discharge        | ON    | ON    |
| Recovery         | OFF   | OFF   |

The principles to determine the model parameters are as follows. First, buck converter components are calculated to provide input voltage $V_{in}$ close to the breakdown voltage $V_{bd}$. Based on the equivalent model, this selection lead to reach ideal value of gap current $I_g$ during ignition phase which is zero. Second, shunt resistor $R_s$ and ignition resistor $R_i$ are calculated according to gap voltage $V_g$ and gap current $I_g$ during ignition process. Then, discharge resistor $R_d$ is calculated according to the stable discharge voltage $V_d$ and stable discharge current $I_d$. Finally, discharge inductor $L_d$ is calculated based on the discharge duration $t_d$. 


MATLAB simulation of spark pulse generator system equivalent model is established according to conditions presented in table 2. Figure 3 illustrates simulated profiles of gap voltage and gap current for two different $I_d$ and $t_d$ as process (a) and (b). Comparison between figures 1 and 3 shows that there are some errors between desirable and simulation profiles, but simulation profiles are basically able to reflect variation of gap voltage and gap current. These errors are mainly attributed to the switching device losses, not related to the model.

**Table 2. Simulated circuit parameters**

| Parameter               | Symbol | Value  |
|-------------------------|--------|--------|
| utility supply voltage  | $V_s$  | 250V   |
| Filter capacitor        | $C$    | 1F     |
| Input voltage           | $V_{in}$| 160.1  |
| Frequency of the utility supply | $f_s$ | 50Hz   |
| Switching frequency of buck converter | $f_{ss}$ | 1MHZ   |
| Breakdown voltage       | $V_{bd}$| 160V  |
| Stable discharge voltage| $V_d$  | 25V    |
| Discharge time          | $t_d$  | 4μs    |
| Ignition time           | $t_i$  | 2μs    |
2.2. Comparative analysis of simulated and experimental results

To verify the simulated model of EDM spark pulse generator system, predicted MRR from series of simulations are compared with series of experimental MRRs carried out by A. Yahya. [20]. Predicted MRR is obtained through following equation (1) which is came by former researcher [21].

\[
MRR = C \alpha V_d I_d t_d F_s \left[ 2.71 \times 10^{-7} \left( \frac{I_d}{I_i} \right)^3 - 9.66 \times 10^{-5} \left( \frac{I_d}{I_i} \right)^2 + 8.37 \times 10^{-3} \left( \frac{t_d}{t_i} \right) + 0.81 \right]
\]  

(1)

where \(C\) is the dimensionless constant and \(\alpha\) is the material properties factor. For present calculation, constants \(C\) and \(\alpha\) are assumed to be equal to the ones approximated by [20, 22] i.e., \(C = 1.74\) and \(\alpha = 2 \times 10^{-12} m^3 J^{-1}\). equation (1) is valid for \(t_{on}\) up to 400 \(\mu s\) and \(t_d\) equal to 2 \(\mu s\) [21]. All data in current research conform to this range of validations.

Table 3 presents the simulated (Predicted) MRR and the experimental (Actual) MRR during several stable discharge currents \(I_d\), discharge times \(t_d\) and sparking frequencies \(F_s\). The last column of this table shows predicted error which is a comparison between the experimental and the simulated MRR under identical conditions. The average simulated error is below of 7.74\%. It seen that the simulated model has ability to predict the MRR with acceptable error.
As shown in this table, increasing in simulated MRR with the increase in stable discharge current $I_d$ or discharge time $t_d$ is confirmed by the corresponding value of experimental MRR in each process. This increase can be attributed to reason that during discharge, current is allowed to flow. Material removal is directly proportionate to the amount of energy used in discharge time. This energy is controlled by gap current and discharge time [23].

**Table 3. Comparison between experimental (Actual) and simulated (Predicted) MRR**

| Process | $I_d$ (A) | $t_s$ ($\mu$s) | $T_{on}$ ($\mu$s) | $F_s$ (KHz) | MRR ($\text{mm}^3/\text{min}$) | Error [%] |
|---------|-----------|----------------|-------------------|--------------|-------------------------------|-----------|
|         | Actual    | Predicted      |                   | Actual       | Predicted                     |           |
| 1       | 6         | 6              | 4                 | 83.33        | 12                            | 12.49     | 4.08 |
| 2       | 6         | 12             | 4                 | 55.55        | 19                            | 17.36     | 8.63 |
| 3       | 6         | 25             | 4                 | 32.25        | 23                            | 22.72     | 1.22 |
| 4       | 8.5       | 6              | 4                 | 83.33        | 21                            | 17.8      | 15.24 |
| 5       | 8.5       | 12             | 4                 | 55.55        | 23                            | 25.02     | 8.78 |
| 6       | 8.5       | 25             | 4                 | 32.25        | 31                            | 32.03     | 3.32 |
| 7       | 18        | 6              | 4                 | 83.33        | 42                            | 37.56     | 10.57 |
| 8       | 18        | 12             | 4                 | 55.55        | 54                            | 49.72     | 7.93 |
| 9       | 18        | 25             | 4                 | 32.25        | 68                            | 67.43     | 0.84 |
| 10      | 36        | 6              | 4                 | 83.33        | 72                            | 67.32     | 6.5  |
| 11      | 36        | 12             | 4                 | 55.55        | 111                           | 97.31     | 12.33 |
| 12      | 36        | 25             | 4                 | 32.25        | 137                           | 118.70    | 13.36 |

2.3. *Frequency analysis of spark discharge EDM system*

Figure 4 is the simplified model of discharge circuit based on EDM spark pulse generator system equivalent form. In Figure 3, $DV(t)$ is equivalent input supply which is the voltage given by the rectified utility supply voltage of $V(t)$ for the buck converter duty cycle of $D$ [24]. The rest implementation of the model is similar to that of figure 2.
Figure 4. Simplified model of discharge circuit based on EDM spark pulse generator system equivalent form.

Based on the simplified model in figure 4, the general form of transfer functions for the stable spark discharge current-to-rectified input voltage $H_i(s)$ can be expressed as equation (2).

$$H_i(s) = \frac{I_d(s)}{V(s)} = \frac{a_1 s + a_0}{b_3 s^3 + b_2 s^2 + b_1 s + b_0}$$

(2)

where

$$a_0 = DR_1 (R_d + R_i)$$

$$a_1 = DL_d R_i$$

$$b_0 = R_i R_d R_d + R_i (R_1 R_d + R_1 R_i)$$

$$b_1 = (L_d + L) R_i R_i + L (R_i R_d + R_d R_i + R_d R_i + R_i R_i) + L_d R_i R_i$$

$$b_2 = LL_d (R_i + R_i + R_i) + LC_i R_i (R_d R_i + R_d R_i + R_i R_i)$$

$$b_3 = C_1 LL_d R_i (R_i + R_i)$$

For all processes in table 3, theoretical calculation of the frequency response about the simplified discharge model are obtained by substituting the above expressions result into $H_i(s)$. Table IV presents the gain and phase margins corresponding to each process. As shown in these tables, increasing the discharge time at constant stable discharge current led to the sensible decrease of GM. Furthermore, PM decreases with increasing the stable discharge current at constant discharge time. Based on these observations, it can conclude that discharge time and stable discharge current affect the system stability. So that, increase in stable discharge current or pulse on-time can reduce the stability of the system.

Table 4. Gm and Pm for different discharge current and discharge time

| Process | $I_d$ (A) | $T_d$ (μs) | Gm     | Pm    |
|---------|----------|------------|--------|-------|
| 1       | 6        | 6          | 597.03 | 34.35 |
| 2       | 6        | 12         | 464.38 | 34.33 |
| 3       | 6        | 25         | 417.95 | 34.33 |
| 4       | 8.5      | 6          | 683.92 | 27.12 |
| 5       | 8.5      | 12         | 341.90 | 27.09 |
| 6       | 8.5      | 25         | 205.16 | 27.04 |
| 7       | 18       | 6          | 149.56 | 17.10 |
| 8       | 18       | 12         | 89.74  | 17.02 |
| 9       | 18       | 25         | 44.87  | 16.84 |
Comparison between frequency responses of stable discharge current-to-rectified utility supply voltage for two different discharge times $t_d$ and stable discharge currents $I_d$ are depicted in figure 5. It is found that transfer characteristics of the theoretical results tally well agreement with the simulation results.

\begin{table}[h]
\begin{tabular}{cccccc}
10 & 36 & 6 & 111.18 & 11.61 \\
11 & 36 & 12 & 55.59  & 11.51 \\
12 & 36 & 25 & 27.80  & 11.30 \\
\end{tabular}
\end{table}

**Figure 5.** Comparison between frequency response of stable discharge current-to-rectified utility supply voltage through transfer function and simulation for (a) $I_d=6A$, $t_d=6\mu s$, (b) $I_d=36A$, $t_d=25\mu s$.

3. Conclusion
In this paper, spark discharge is established through simulated model of EDM spark pulse generator system equivalent form and the discharge process is replaced by simplified model of discharge circuit. Simulated model of EDM system is verified by comparing with the former researcher’s experimental results. Then, the simplified model of discharge circuit is reformulated into a transfer function from the rectified voltage of utility supply to stable discharge current. Frequency analysis of spark discharge model is carried out during several discharge time and stable discharge current. It is found that increasing discharge time and stable discharge current increase the MRR but reduce the stability of
system. This provides guidance for optimal selection of process parameters based on the EDM application.

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References
[1] Wei W, Zhidong L, Wentai S, Yueqin Z and Zongjun T 2016 Surface burning of high-speed reciprocating wire electrical discharge machining under large cutting energy The International Journal of Advanced Manufacturing Technology 87(9-12) 2713-20
[2] Ayesta I, Izquierdo B, Sanchez J, Ramos J, Plaza S, Pombo I and Ortega N 2016 Optimum electrode path generation for edm manufacturing of aerospace components Robotics and Computer-Integrated Manufacturing 37 273-81
[3] Lassandy M, Budiono H, Supriadi S, Qosim N and Whulanza Y 2018 Retracted: Calculation of the cnc edm complexity process for biomedical implants Journal of Fundamental and Applied Sciences 10(5S)
[4] Zhang Z, Peng H and Yan J 2013 Micro-cutting characteristics of edm fabricated high-precision polycrystalline diamond tools International Journal of Machine Tools and Manufacture 65 99-106
[5] Tiwary A, Pradhan B and Bhattacharyya B 2015 Study on the influence of micro-edm process parameters during machining of 6al-4v superalloy The International Journal of Advanced Manufacturing Technology 76(1-4) 151-60
[6] Li C, Li Y, Tong H, Zhao L, Kong Q and Wang Z 2016 An edm pulse power generator and its feasible experiments for drilling film cooling holes The International Journal of Advanced Manufacturing Technology 87(5-8) 1813-21
[7] Shen Y, Liu Y, Dong H, Zhang K, Lv L, Zhang X, Wu X, Zheng C and Ji R 2017 Surface integrity of inconel 718 in high-speed electrical discharge machining milling using air dielectric The International Journal of Advanced Manufacturing Technology 90(1-4) 691-8
[8] Abbas NM, Yusoff N and Mahmod R 2012 Electrical discharge machining (edm): Practices in malaysian industries and possible change towards green manufacturing Procedia Engineering 41 1684-8
[9] Srivastava V and Pandey PM 2012 Performance evaluation of electrical discharge machining (edm) process using cryogenically cooled electrode Materials and Manufacturing Processes 27(6) 683-8
[10] Singh B, Kumar J and Kumar S 2015 Influences of process parameters on mrr improvement in simple and powder-mixed edm of aa6061/10% sic composite Materials and Manufacturing Processes 30(3) 303-12
[11] Gopalakannan S, Senthivelan T and Ranganathan S 2013 Statistical optimization of edm parameters on machining of aluminium hybrid metal matrix composite by applying taguchi based grey analysis Journal of Science and Industrial Research 72 358-65
[12] Apuzzo A, Barretta R, Luciano R, de Sciarra FM and Penna R 2017 Free vibrations of bernoulli-euler nano-beams by the stress-driven nonlocal integral model Composites Part B: Engineering 123 105-11
[13] Manivannan R and Pradeep Kumar M 2018 Improving the machining performance characteristics of the µedm drilling process by the online cryogenic cooling approach Materials and Manufacturing Processes 33(4) 390-6
[14] Tseng K-H, Chiu J-L, Lee H-L, Kao Y-S and Tien D-C 2016 Spark parameter monitoring feedback system for preparation of nanosilver colloid in edm Materials and Manufacturing Processes 31(2) 186-93
[15] Renjie J, Yonghong L, Baogui W, Xiaopeng L, Baoping C and Zhao J 2015 Development of experimental platform for electrical discharge status detection based on labview *Experimental Technology and Management* (2) 20

[16] Schumacher BM 2004 After 60 years of edm the discharge process remains still disputed *Journal of Materials Processing Technology* **149(1-3)** 376-81

[17] Fan Y, Bai J, Li Q, Li C, Cao Y and Li Z 2016 Research on maintaining voltage of spark discharge in edm *Procedia CIRP* **42** 28-33

[18] Li C, Bai J, Ding J and Fan Y 2015 Gap current voltage characteristics of energy-saving pulse power generator for wire edm *The International Journal of Advanced Manufacturing Technology* **77(5-8)** 1525-31

[19] Looser A, Linares L, Zwyssig C, Kolar JW 2010 Novel power supply topology for large working gap dry edm *Proc The International Power Electronics Conference (ECCE) - ASIA* (Zurich/IEEE) pp 306-10

[20] Yahya A 2005 Digital control of an electro discharge machining (edm) system (London/Loughbrough University) *Doctoral dissertation*

[21] Yahya A, Trias A, Erawan MA, Nor Hisham K, Khalil K and Rahim MAA 2012 Comparison studies of electrical discharge machining (edm) process model for low gap current *Advanced Materials Research* Trans Tech Publ

[22] DiBitonto DD, Eubank PT, Patel MR and Barrufet MA 1989 Theoretical models of the electrical discharge machining process. I. A simple cathode erosion model *Journal of applied physics* **66(9)** 4095-103

[23] Kiyak M, Aldemir BE and Altan E 2015 Effects of discharge energy density on wear rate and surface roughness in edm *The International Journal of Advanced Manufacturing Technology* **79(1-4)** 513-8

[24] Vitale G 2015 Analysis of dc/dc converters by mean node voltage method *Renewable Energy and Power Quality Journal (RE&PQJ)* **1(13)**