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_i 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.
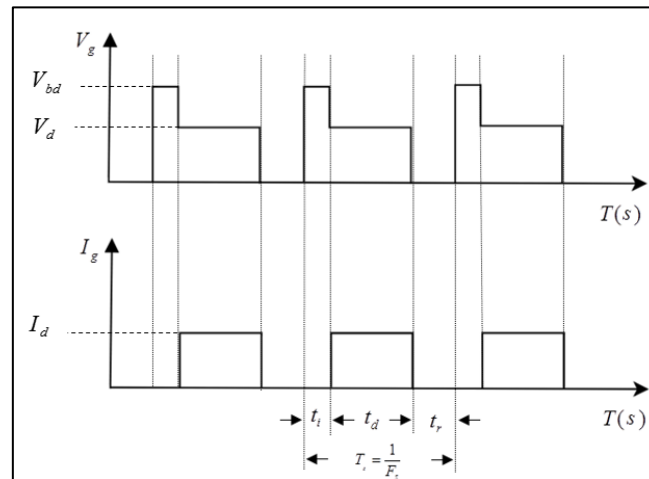

Figure 1. Profile of gap voltage and gap current during EDM process

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.
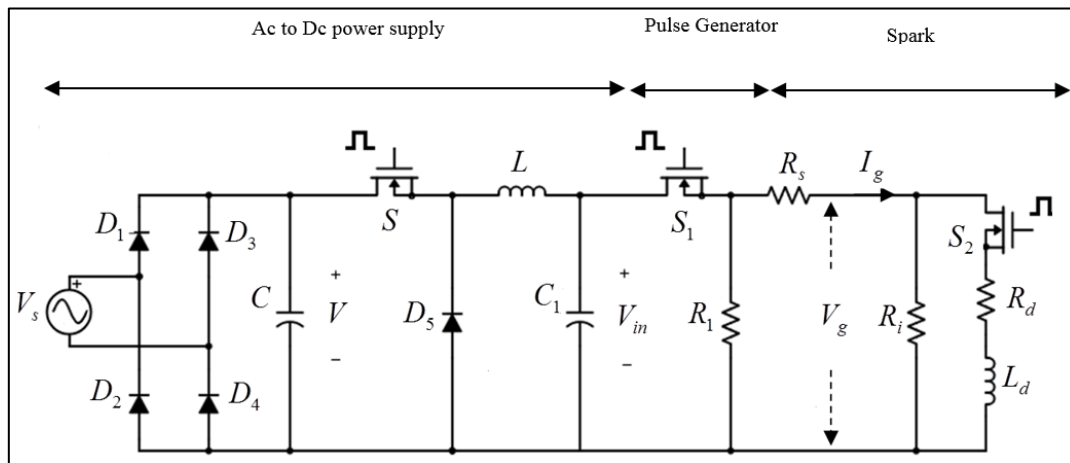
Figure 2. Equivalent model of the EDM spark pulse generator system

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

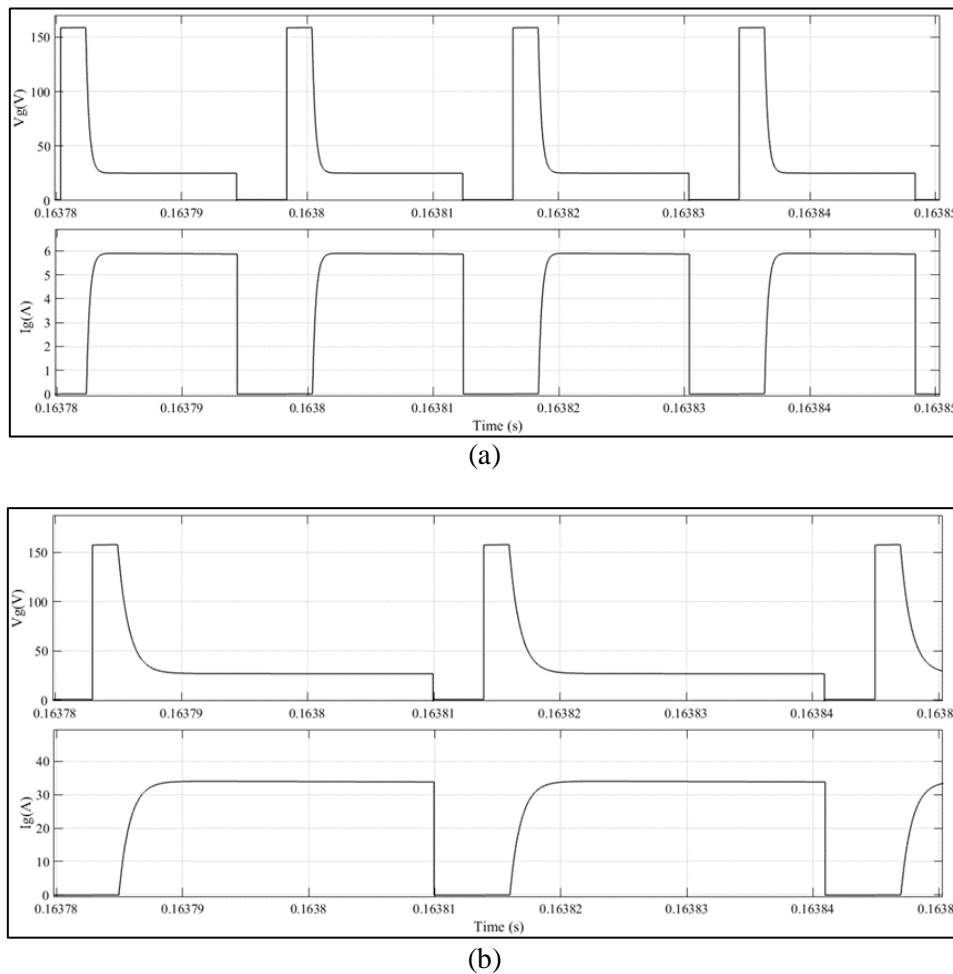| Parameter	Symbol	Value
utility supply voltage	V_s	$250V$
Filter capacitor	C	$1F$
Input voltage	V_{in}	160.1
Frequency of the utility supply	f_s	$50Hz$
Switching frequency of buck converter	f_{s_1}	$1MHz$
Breakdown voltage	V_{bd}	$160V$
Stable discharge voltage	V_d	$25V$
Discharge time	t_d	$4\mu s$
Ignition time	t_i	$2\mu s$

(a)

(b)

Figure 3. Simulated profile of V_g and I_g for (a) I_d=6A, t_d=6 μs , (b) I_d=36A, t_d=25 μs

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].

$$MRR = C\alpha V_d I_d t_d F_s \left[2.71\times10^{-7}\left(\frac{t_d}{t_i}\right)^3 - 9.66\times10^{-5}\left(\frac{t_d}{t_i}\right)^2 + 8.37\times10^{-3}\left(\frac{t_d}{t_i}\right) + 0.81 \right] \quad (1)$$

where C is the dimensionless constant and α is the material properties factor. For present calculation, constants C and α are assumed to be equal to the ones approximated by [20, 22] i.e., C=1.74 and $\alpha = 2\times10^{-12} m^3 J^{-1}$. equation (1) is valid for t_{on} up to 400 μs and t_d equal to 2 μs [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	$I_d(A)$	$t_d(\mu s)$	$T_{off}(\mu s)$	$F_s(KHz)$	MRR$^{(mm^3/min)}$		Error [%]
					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.
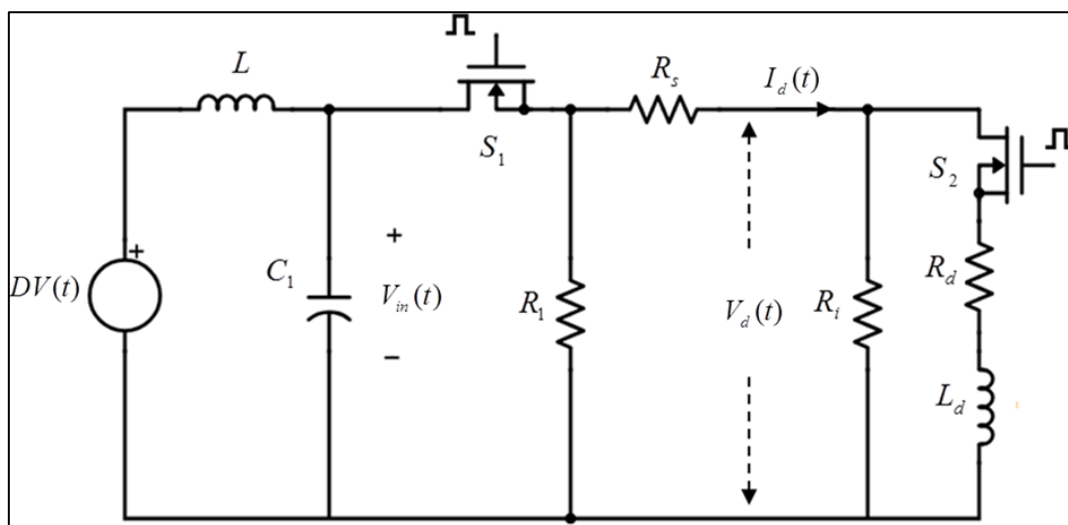
Figure 4. Simplified model of discharge circuit based on EDM spark pulse generator system equivalent form.

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).

$$H_i(s) = \frac{I_d(s)}{V(s)} = \frac{a_1 S + a_0}{b_3 S^3 + b_2 S^2 + b_1 S^1 + b_0} \tag{2}$$

where

$$a_0 = DR_1(R_d + R_i)$$
$$a_1 = DL_d R_1$$
$$b_0 = R_1 R_i R_d + R_s(R_1 R_d + R_1 R_i)$$
$$b_1 = (L_d + L)R_1 R_i + L(R_1 R_d + R_d R_i + R_d R_s + R_i R_s) + L_d R_1 R_s$$
$$b_2 = LL_d(R_1 + R_i + R_s) + LC_1 R_1(R_d R_i + R_d R_s + R_i R_s)$$
$$b_3 = C_1 LL_d R_1(R_i + R_s)$$

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	$I_d(A)$	$T_d(\mu s)$	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

10	36	6	111.18	11.61
11	36	12	55.59	11.51
12	36	25	27.80	11.30

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.
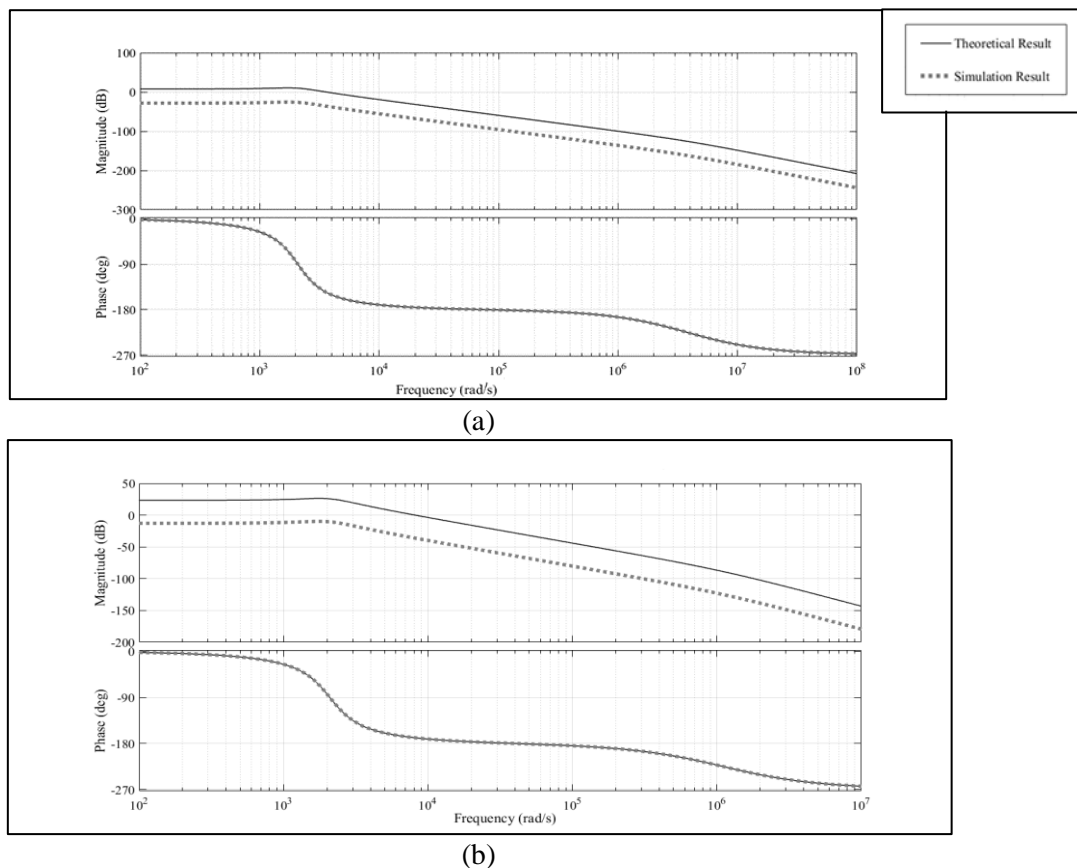

(a)

(b)

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 μs , (b) I_d =36A, t_d =25 μs .

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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