

## EDM Process through Mathematical Model

Dana Dehghani<sup>1</sup>, Azli Yahya<sup>2</sup>, Nor Hisham Khamis<sup>3</sup>, Ali Idham Alzaidi<sup>4</sup>

<sup>1,3</sup> School of Electrical Engineering, Universiti Teknologi Malaysia, Malaysia

<sup>2,4</sup> School of Biomedical Engineering and Health Sciences, Universiti Teknologi Malaysia, Malaysia

---

### Article Info

#### Article history:

Received Aug 27, 2018

Revised Nov 19, 2018

Accepted Feb 25, 2019

---

#### Keywords:

EDM  
Spark profile  
MATLAB  
MRR

---

### ABSTRACT

EDM is a well-established hole machining option with various advantages due to non-contact characteristics of the process. However, knowledge about the process is not enough for its more improvements. Experimental studies are costly and time consuming because of the complex nature of process. Therefore, process modeling is a good alternative to reduce the experimental expense related to the technology. This paper studies EDM process through mathematical model, which includes the precise insight into the interactive behavior of EDM system. The ignition, discharge and recovery phases of the model have been developed through MATLABs time domain analysis. Simulation result shows good agreement with expected profile of EDM spark. To verify the model, simulated material removal rates (MRRs) from series of simulation are compared with the experimental ones reported by previous researcher. Ability of the model to predict the dynamic behavior profile of the EDM system is successfully confirmed by low average percentage error in predicting MRR.

*Copyright © 2019 Institute of Advanced Engineering and Science.  
All rights reserved.*

---

### Corresponding Author:

Dana Dehghani,  
School of Electrical Engineering,  
Faculty of Engineering, Universiti Teknologi Malaysia,  
81310 Johor Bahru, Johor, Malaysia.  
Email: danadehghani1@gmail.com

---

## 1. INTRODUCTION

EDM is a non-traditional machining process to remove material from the workpiece using a thread of electrical discharges between the electrode and the workpiece called gap [1]. non-contact characteristics of EDM makes it a valuable technique for variety of hole manufacturing approaches [2]. However, scientific knowledge about the process is still insufficient and it is the main obstacle for its more improvements. Experimental trials are challenging due to the highly stochastic and complex nature of the process caused by some process complications such as adhesion, short-circuiting and cavitations that increase the machining time and make the process become unstable [3].

Many EDM researchers have attempted innovative ideas such as ultrasonic vibrations and flushing effect with the purpose to solve the process complications and improve the system stability. Mahardika [4] found that using ultrasonic vibrations remove adhesion and short circuit during machining procedure. Shabgard [5] revealed that EDM of Ti-6Al-4V by using ultrasonic vibrations of copper electrode enhance MRR. He also claimed that crack density and tool wear ratio (TWR) reduce at finishing regimes while recast layer, cracks density, and TWR increase at roughing regimes. Although, ultrasonic vibrations help to promote productivity and feasibility in certain conditions, however there is still a long way to go for use in industry.

Flushing transfers dielectric fluid into the pipe electrode, so debris carries away and the insulating characteristics of the dielectric are preserved, it is an easy way to improve efficiency of EDM hole drilling [6]. Pressure and suction flushing techniques have the capability of eliminating the spark eroded particles, but they can only be used in particular applications. Ebisu [7] investigated the effect of jet flushing on the debris

stagnation during the cutting corner shape in 1st-cut wire EDM. He showed that applying jet flushing decreases debris stagnation in the gap only temporarily after the corner.

In order to overcome the difficulty aspects related to real machining environment and its effect on system stability, modeling and simulation is an alternative way to understand the mechanism underlying the EDM procedure. Although gap spark profiles play an important role in the analysis of the EDM process, but very few mathematical models have been developed to identify the profile of EDM spark during machining procedure. Minhat et al. [8] presented the mathematical model of EDM pulses based on the initial, ignition and discharge phases. However, the model failed to determine the EDM profiles correctly, Moreover, mathematical equation did not match the profiles in all phases.

This paper proposes mathematical model to predict the dynamic behavior of the EDM spark, similar to the ideal one. The mathematical explanation of the model is located in section 2. Ignition, discharge and recovery phases have been considered properly. In section 3, MATLAB software is used to simulate machining procedure. Section 4 includes discussion about the validity of the simulated model using series of experimental data to calculate MRRs and compare with the experimental results from previous researcher. Finally, conclusion is given in Section 5.

## 2. MODEL DESCRIPTION

In this section, mathematical model during ignition, discharge and recovery phases is developed separately. The proposed model shown in Figure 1 consisted of pulse power generator and EDM spark. Pulse power generator, in turn, is made of an ac source, a transformer, rectifier and a capacitor as filter followed by a transistorized switching circuit as pulse generator. All components are supposed to be ideal in order to reach simple and clear insight into the model behavior.

Based on the model, AC source voltage  $v_s$  is applied to provide required value of DC input voltage  $V_{in}$  through the bridge diode and transformer with the turns ratio of  $n_1:n_2$  where  $n_1$  and  $n_2$  are the numbers of primary and secondary windings, respectively. Pulse generator comprised of a MOSFET switch  $S_1$  and a resistor  $R_1$ . Switch  $S_1$  is controlled by low power pulses of  $P_{w1}$  and used to control current from capacitor  $C$  to the gap. As can be seen in Figure 1, the EDM spark which is the gap model between electrode and workpiece consists of  $R_s$ ,  $R_{ig}$ ,  $R_{dis}$ ,  $L_{dis}$  and switch  $S_2$  driven by  $P_{w2}$ . Three defined phases of EDM pulses with related mathematical equations are explained in following.

### 2.1. Ignition phase

Based on the profile illustrated in Figure 2, ignition phase is occurred in the time interval from  $t_1$  to  $t_2$  which is called delay time  $t_d$ . Open gap voltage  $V_{oc}$  provided a severe electric field between electrode and workpiece. An ionization path created through the dielectric and flow of the current  $i_{gap}$  is interrupted. Gap voltage  $V_{gap}$  in this phase is equal to  $V_{oc}$ . Small delay time results larger spark time so more energy enters into the workpiece [9]. Equivalent model of EDM system in this phase is obtained from Figure 1 when switch  $S_1$  is close and switch  $S_2$  is open. Related equations of gap current  $i_{gap}$  and gap voltage  $V_{gap}$  obtained as following. As  $S_2$  is considered open so,

$$i_{gap} = i_{R_{ig}} \quad (1)$$

using Ohm's law,

$$i_{gap} = \frac{V_{gap}}{R_{ig}} \quad (2)$$

substituting (2) in (1),

$$R_{ig} = \frac{V_{gap}}{i_{gap}} \quad (3)$$

Switch  $S_1$  is on, thus applying voltage driver between resistors  $R_{ig}$  and  $R_s$  gives:

$$V_{gap} = V_{in} \left( \frac{R_{ig}}{R_{ig} + R_s} \right) \tag{4}$$

By substituting (3) in (4),

$$V_{gap} = V_{in} \left( \frac{V_{gap}}{V_{gap} + R_s i_{gap}} \right) \tag{5}$$

Simplifying both sides of (5) gives,

$$\frac{V_{in} - V_{gap}}{R_s} = i_{gap} \tag{6}$$

From (6) can be seen that small difference between  $V_{in}$  and  $V_{gap}$  makes the model more close to the ideal value of  $i_{gap}$  in this phase which is zero. So by applying (7), gap voltage reaches to its maximum value called open gap voltage  $V_{oc}$ .

$$V_{gap} \approx V_{in} \tag{7}$$

Then,

$$i_{gap} \approx 0 \tag{8}$$

Deficiency of this assumption in [8], led to a mismatch of its mathematical expression with the gap current profile in this phase.

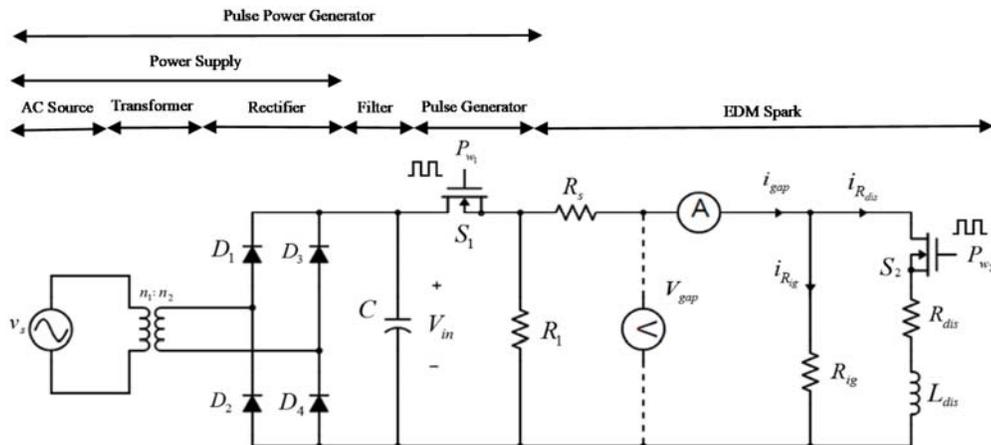


Figure 1. The EDM model in ignition phase

### 2.2. Discharge phase

The discharge phase is occurred in the time interval from  $t_2$  to  $t_3$  which is called  $t_{dis}$  as shown in Figure 2. During this phase, the isolating effect of the dielectric breaks down, current starts to flow while the voltage falls [10]. The spark is formed and machining continued to reach a peak gap current of  $I_g$  and a discharge voltage of  $V_{dis}$ . In this phase both switches of  $S_1$  and  $S_2$  from equivalent EDM model in Figure 1 are considered on.  $L_{dis}$  and  $R_{dis}$  are connected together in series which both are connected to resistance  $R_{ig}$  in parallel. Gap current  $i_{gap}$  and Gap voltage  $V_{gap}$  can be obtained as follows,

$$i_{gap} = i_{R_{dis}} + i_{R_{ig}} \tag{9}$$

$$V_{gap} = i_{R_{dis}} R_{dis} + L_{dis} \frac{di_{R_{dis}}}{dt} \quad (10)$$

modifying (10) gives,

$$\frac{dt}{L_{dis}} = \frac{di_{R_{dis}}}{V_{gap} - i_{R_{dis}} R_{dis}} \quad (11)$$

Integrating both sides of the (11),

$$\frac{t}{L_{dis}} \Big|_{t_2}^{t_3} = \int_0^{i_{R_{dis}}} \frac{di_{R_{dis}}}{V_{gap} - i_{R_{dis}} R_{dis}} \quad (12)$$

By applying assumption,

$$z = V_{gap} - i_{R_{dis}} R_{dis} \quad (13)$$

$$di_{R_{dis}} = -\frac{dz}{R_{dis}} \quad (14)$$

So,  $-\frac{R_{dis}t}{L_{dis}}$  can be explained as follows:

$$-\frac{R_{dis}t}{L_{dis}} \Big|_{t_2}^{t_3} = \int_0^{i_{R_{dis}}} \frac{dz}{z} \quad (15)$$

term (15) can be explained as follows,

$$-\frac{R_{dis}t}{L_{dis}} \Big|_{t_2}^{t_3} = \ln(V_{gap} - i_{R_{dis}} R_{dis}) \Big|_0^{i_{R_{dis}}} \quad (16)$$

using limits,

$$-\frac{R_{dis}(t_3 - t_2)}{L_{dis}} = \ln\left(\frac{V_{gap} - i_{R_{dis}} R_{dis}}{V_{gap}}\right) \quad (17)$$

taking antilog of both sides of equation (17),

$$V_{gap} e^{-\frac{R_{dis}(t_3 - t_2)}{L_{dis}}} = V_{gap} - i_{R_{dis}} R_{dis} \quad (18)$$

the current  $i_{R_{dis}}$  can be explained as follows:

$$i_{R_{dis}} = \frac{V_{gap}}{R_{dis}} \left(1 - e^{-\frac{R_{dis}}{L_{dis}}(t_3 - t_2)}\right) \quad (19)$$

also,

$$i_{R_{ig}} = \frac{V_{gap}}{R_{ig}} \quad (20)$$

By inserting equations (19) and (20) in equation (9), the current gap in this phase can be found as follows:

$$i_{gap} = V_{gap} \left[ \frac{1}{R_{dis}} \left(1 - e^{-\frac{R_{dis}}{L_{dis}}(t_3 - t_2)}\right) + \frac{1}{R_{ig}} \right] \quad (21)$$

applying the Kirchhoff law,

$$V_{in} = R_s i_{gap} + V_{gap} \quad (22)$$

substituting (21) in (22),

$$V_{in} = V_{gap} \left[ \frac{R_s}{R_{dis}} \left( 1 - e^{-\frac{R_{dis}(t_3-t_2)}{L_{dis}}} \right) + \frac{R_s}{R_{ig}} + 1 \right] \quad (23)$$

$V_{gap}$  is obtained as follow:

$$V_{gap} = \frac{R_{ig} R_{dis}}{R_{ig} R_s \left( 1 - e^{-\frac{R_{dis}(t_3-t_2)}{L_{dis}}} \right) + R_s R_{dis} + R_{ig} R_{dis}} V_{in} \quad (24)$$

From (21) and (24), it is clear that, final equation of gap current and gap voltage in this phase is quite different from that of presented in [8]. Expression of gap current and gap voltage in [8] can not describe the dynamic behavior of system accurately.

### 2.3. Recovery phase

The recovery phase is happened during the time interval from  $t_3$  to  $t_4$  which is called  $t_{rec}$  as shown in Figure 2. The flow of current is stopped and desired insulating electric properties of the dielectric fluid are recovered [11]. The schematic circuit of the EDM model in this phase is obtained from Figure 1 when switch  $S_1$  is off and no current goes through  $R_I$  and  $R_s$ . So  $V_{gap}$  and  $i_{gap}$  are equal to zero. This phase is totally missed in the model presented in [8].

Since the switch  $S_1$  is open, so:

$$\begin{aligned} V_{gap} &= 0 \\ i_{gap} &= 0 \end{aligned} \quad (25)$$

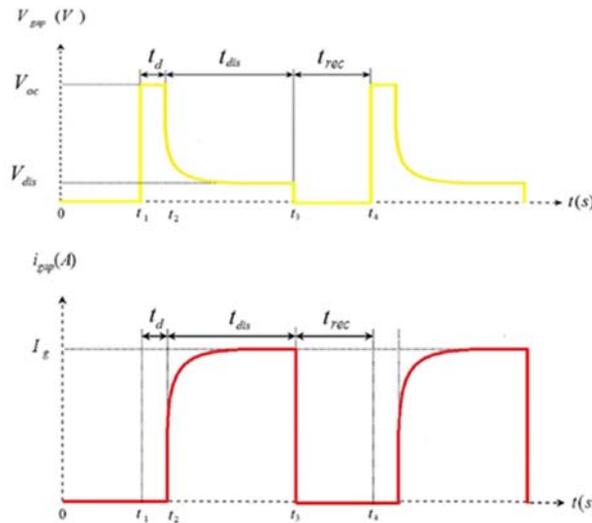


Figure 2. Profile of  $V_{gap}$  and  $i_{gap}$  during one spark cycle over time

### 3. SIMULATION

In this section, the diagram of the EDM system with ac to dc power supply and transistorized switching circuit as pulse generator designed in MATLAB and schematic diagram is shown in Figure 3. According to the estimation obtained in (7), transformer reduces the source voltage of 250V to the input voltage of  $V_{in}$  as near as open gap voltage  $V_{oc}$  of 160V. Figure 4 shows simulation results of gap voltage and gap current for a selected machining process. Simulated data are chosen from previous experimental tests presented by A. Yahya. [12]. In order to optimize discharge conditions and based on the experimental test

[12], delay time  $t_d$  is set to  $2\mu s$  which is insignificant compared with the discharge time  $t_{dis}$ . It is clearly seen in Figure 4 where simulation results are quite correlated with desirable profile of  $V_{gap}$  and  $i_{gap}$  in Figure 2.

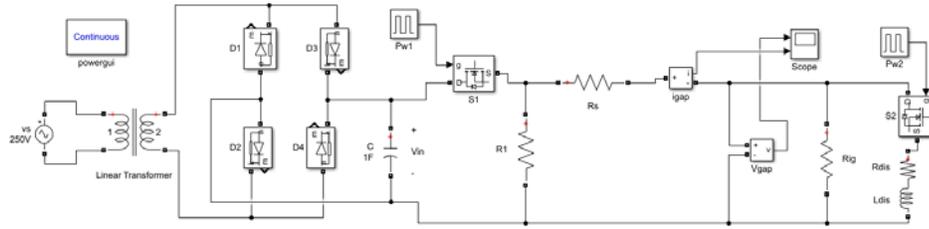


Figure 3. Simulation diagram of EDM system

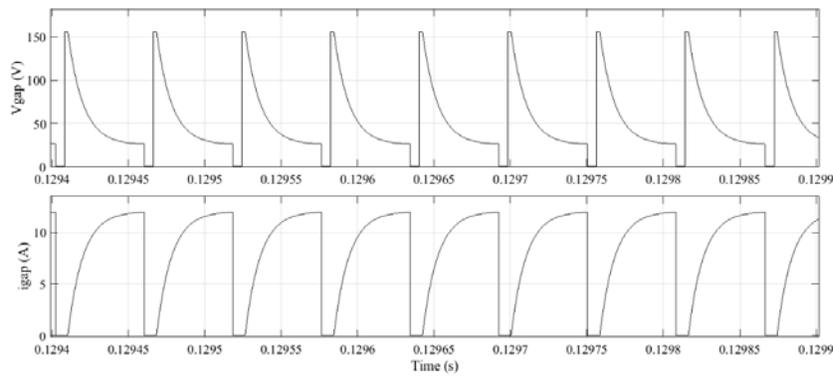


Figure 4. Spark profiles for  $I_g = 12.5 A$  and  $F_s = 17.24 KHZ$

#### 4. RESULT AND DISCUSSION

As shown in Figure 2, the profile of EDM spark during one cycle consists of the initial phase occurred during the time interval between  $t_1$  and  $t_2$ , followed by the discharge phase from  $t_2$  to  $t_3$  and the last phase which is recovery from  $t_3$  to  $t_4$ . Conforming to the equation (7), small difference between input voltage and gap voltage is selected to get the model close to the ideal profile through ignition phase. Noteworthy point to mention is that to better evaluate the procedure, proposed model did not considered noise during EDM process which results from the stochastic nature of the EDM spark. MATLAB software is used to develop the complete model of EDM system. Simulation results in Figure 4, as gap voltage and gap current, are absolutely similar to the modeling profile from Figure 2.

To verify the simulated model, predicted MRRs from series of simulations are compared with series of experimental MRRs carried out by A. Yahya [12] using steel workpiece and copper electrode. Predicted MRR is determined by inserting simulated data into equation (26) obtained by the same researcher in [13].

$$MRR = \alpha V_{dis} I_g t_{dis} F_s \left[ 3.52 \times 10^{-7} \left( \frac{t_{dis}}{t_d} \right)^3 - 1.33 \times 10^{-4} \left( \frac{t_{dis}}{t_d} \right)^2 + 1.25 \times 10^{-2} \left( \frac{t_{dis}}{t_d} \right) + 1.53 \right] \quad (26)$$

where  $\alpha$  is material properties factor. For the present study,  $\alpha$  considered to be equal to the one selected by [14] i.e.,  $\alpha = 2 \times 10^{12} m^3 J^{-1}$ . Equation (26) is valid for  $t_{dis}$  up to  $400 \mu s$  and  $t_d$  equal to  $2 \mu s$ . All data in current research conform to this range of validations.

Table 1 presents the simulated (Predicted) MRR and the experimental (Actual) MRR during several peak gap currents  $I_g$ , discharge times  $t_{dis}$ , recovery time  $t_{rec}$  and spark 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 5.14 %. It seen that the simulated model has ability to predict the MRR with acceptable error.

Table 1. Comparison between experimental (Actual) and simulated (Predicted) MRR

Process	$I_g (A)$	$t_{dis} (\mu s)$	$t_{rec} (\mu s)$	$F_s (kHz)$	MRR ( $mm^3 / min$ )		Error (%)
					Actual	Predicted	
1	4	2	4	125	4	4.48	12.00
2	4	3	4	111.1	6	6.05	0.83
3	4	4	4	100	8	7.36	8.00
4	4	6	4	83.33	10	9.34	6.60
5	4	12	4	55.55	13	12.62	2.92
6	4	25	4	32.25	15	15.56	3.73
7	4	50	6	17.24	17	18.14	6.71
8	4	100	12	8.77	19	19.52	2.74
9	4	200	25	4.41	13	14.00	7.69
10	4	400	50	2.21	12	11.77	1.92
11	6	2	4	125	7	6.87	1.86
12	6	3	4	111.1	9	9.01	0.11
13	6	4	4	100	11	11.07	0.64
14	6	6	4	83.33	12	13.94	16.17
15	6	12	4	55.55	19	18.97	0.16
16	6	25	4	32.25	23	23.49	2.13
17	6	50	6	17.24	26	26.44	1.69
18	6	100	12	8.77	21	21.97	4.62
19	6	200	25	4.41	23	21.44	6.78
20	6	400	50	2.21	19	18.07	4.89
21	8.5	3	4	111.1	11	11.83	7.55
22	8.5	4	4	100	16	15.44	3.50
23	8.5	6	4	83.33	21	19.39	7.67
24	8.5	12	4	55.55	23	24.36	5.91
25	8.5	25	4	32.25	31	30.87	0.42
26	8.5	50	6	17.24	36	37.58	4.39
27	8.5	100	12	8.77	38	40.46	6.47
28	8.5	200	25	4.41	33	36.61	10.94
29	12.5	3	4	111.1	16	14.54	9.13
30	12.5	4	4	100	20	21.17	5.85

## 5. CONCLUSION

In this paper, a time domain mathematical model of EDM system has been developed. The whole model is simulated in accordance to the EDM conditions including ignition, discharge and recovery phases. . MATLAB simulation result is quite correlated with desirable spark profiles. Validity of the simulated model is carried out by comparing MRR from the previous researcher's experimental results. It is found that, well-designed model for EDM system can easily provide the possibility to predict dynamic behavior of pulse profiles by eliminating complications related to the stochastic nature of EDM process in experimental trial.

## ACKNOWLEDGEMENTS (10 PT)

Authors are thankful for financial supporting from Research Management Center (RMC) of Universiti Teknologi Malaysia through Q.J130000.2545.15H69.

## REFERENCES

- [1] Y. Zhu, *et al.*, "Precision machining of high aspect-ratio rotational part with wire electro discharge machining," *Journal of Mechanical Science and Technology*, vol. 31, pp. 1391-1399, 2017.
- [2] N. Mahmud, *et al.*, "Electrical Discharge Machining Flyback Converter using UC3842 Current Mode PWM Controller," *Proceeding of the Electrical Engineering Computer Science and Informatics*, vol. 1, pp. 311-314, 2014.
- [3] C Li, *et al.* "An EDM pulse power generator and its feasible experiments for drilling film cooling holes". *The International Journal of Advanced Manufacturing Technology*. vol/issue: 87(5-8), pp. 1813-21, 2016.
- [4] M. Mahardika, *et al.*, "The parameters evaluation and optimization of polycrystalline diamond micro-electrodischarge machining assisted by electrode tool vibration," *The International Journal of Advanced Manufacturing Technology*, vol. 60, pp. 985-993, 2012.
- [5] M. Shabgard and H. Alenabi, "Ultrasonic assisted electrical discharge machining of Ti-6Al-4V alloy," *Materials and Manufacturing Processes*, vol. 30, pp. 991-1000, 2015.

- [6] Q. Gao, "Impact of electrode length on EDM inclined hole drilling process," *The International Journal of Advanced Manufacturing Technology*, vol. 94, pp. 1171-1175, 2018.
- [7] T. Ebisu, *et al.*, "Influence of Jet Flushing on Corner Shape Accuracy in Wire EDM," *Procedia CIRP*, vol. 68, pp. 104-108, 2018.
- [8] A. E. B. Minhat, *et al.*, "Model of Pulsed Electrical Discharge Machining (EDM) using RL Circuit," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 5, pp. 252-260, 2014.
- [9] O. Flaño, *et al.*, "Improvement of EDM performance in high-aspect ratio slot machining using multi-holed electrodes," *Precision Engineering*, vol. 51, pp. 223-231, 2018.
- [10] M. Raja, *et al.*, "Investigation of Cryogenic Cooling of Micro EDM Drilling Process on AISI 304 Stainless Steel," in *International Mechanical Engineering Congress and Exposition*, 2016. ASME 2016. American Society of Mechanical Engineers, pp. V002T02A009-V002T02A015.
- [11] W.-H. Hsu and W.-T. Chien, "Effect of Electrical Discharge Machining on Stress Concentration in Titanium Alloy Holes," *Materials*, vol. 9, p. 957, 2016.
- [12] A. Yahya, "Digital control of an electro discharge machining (EDM) system," doctoral dissertation, Loughborough University, 2005.
- [13] A. Yahya and C. Manning, "Determination of material removal rate of an electro-discharge machine using dimensional analysis," *Journal of Physics D: Applied Physics*, vol. 37, p. 1467, 2004.
- [14] D. D. DiBitonto, *et al.*, "Theoretical models of the electrical discharge machining process. I. A simple cathode erosion model," *Journal of applied physics*, vol. 66, pp. 4095-4103, 1989.

## BIOGRAPHIES OF AUTHORS



Dana Dehghani received her M.Sc. degree in Electrical-Mechatronics and Automatic Control by course work and dissertation, from Universiti Teknologi Malaysia, Skudai, Johor in 2014. She is currently with the School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia. Her research interests include Electrical Discharge Machining System, MATLAB, Switch Mode Power Supply, Electric and Hybrid Electric Vehicle.



Azli Yahya received his B.Eng (Hons) degree in Electro-Mechanical Power System and M.Sc. degree in Electronic Production from University of Glamorgan, Wales-UK. In 2006, he obtained his PhD degree in Electronic/Electrical Engineering from University of Loughborough, UK. He is currently an Associate Professor at School of Biomedical Engineering and Health Sciences, Faculty of Engineering, Universiti Teknologi Malaysia. His research areas cover Electrical Discharge Machining System, Analog /Digital Circuit, Microcontroller, PSPICE, MATLAB, Switch Mode Power Supply, Biomedical instrumentation.



Nor Hisham Khamis received his B.Eng degree in Science from the University of Evansville, Indiana, USA in 1988 . The M.S. degree in Electrical Engineering from the University of New South Wales, Sydney, Australia, in 1992, and the Ph.D. degree in Electrical Engineering Universiti Teknologi Malaysia, Johor, Malaysia, in 2005. He is currently an Associate Professor at School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia. His research interests include Sonar, Radar, and Wireless Communication.



Ali Idham Alzaidi received his B.Eng degree in Biomedical Engineering from North Technical University of Mosul, Iraq, in 2000 and MSc in Biomedical Engineering from University of Bridgeport, USA, in 2011. He is currently with the Department of Biomedical Engineering, Universiti Teknologi Malaysia. His research interests include Electrosurgical System, MATLAB, Switch Mode Power Supply, and Thermal Control.