1. Mohammed Jamal Mohammed[1], 2. Jameel Kadhim Abed[2], 3. Ali Jafer Mahdi[3*], 4. Basheer M. Hussein[4]

Branch of Physiology and Medical Physics, College of Medicine, University of Al-Ameed, Karbala 56001, Iraq (1),
Department of Medical Instrumentation Techniques Engineering, Middle Technical University, Baghdad 10011, Iraq (2),
Al-Zahraa University for Women, Karbala 56001, Iraq (3),
Department of Physics, College of Education for Pure Sciences, University of Kerbala, Karbala 56001, Iraq (4),

ORCID: 1. 0009-0000-1019-3123; 2. 0000-0001-9054-4009, 3. 0000-0002-0162-4064, 4. 0000-0002-3847-4936

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A Tuning of PID Power Controller using Particle Swarm Optimization for an Electro-Surgical Unit

***Abstract**. Electro surgical unit is a popular modern device. It has been used in operating rooms for cutting, fulguration and coagulation of human tissues. ESU generates high frequency alternating current to prevent the stimulation of nerves and muscles. The objective of this article was to improve the performance of an ESU by controlling its output power under the variation of tissue impedance using proportional integral derivative controller based on particle swarm optimization to achieve minimum overshoots and fast dynamic response. The controller was simulated in MATLAB/SIMULINK to demonstrate the superiority of the suggested method. A comparative analysis was presented with ESU utilizing manual tuning process. The results showed that the proposed controller offered best performance utilizing manual tuning method. Moreover, both of the tuning methods presented better results from open-loop controller as a result of which charring of tissues could be eliminated and clinical operations could be made more efficient.*

Streszczenie.** Aparat elektrochirurgiczny to popularne nowoczesne urządzenie. Stosowano go na salach operacyjnych do cięcia, nakłuwania i koagulacji tkanek ludzkich. ESU generuje prąd zmienny o wysokiej częstotliwości, aby zapobiec stymulacji nerwów i mięśni. Celem tego artykułu była poprawa wydajności ESU poprzez sterowanie jego mocą wyjściową przy zmianie impedancji tkanki przy użyciu proporcjonalnego całkowego regulatora pochodnego opartego na optymalizacji roju cząstek w celu uzyskania minimalnych przeregulowań i szybkiej odpowiedzi dynamicznej. W celu wykazania wyższości zaproponowanej metody przeprowadzono symulację sterownika w programie MATLAB/SIMULINK. Przedstawiono analizę porównawczą z ESU z wykorzystaniem procesu strojenia ręcznego. Wyniki pokazały, że proponowany regulator oferował najlepszą wydajność przy zastosowaniu metody strojenia ręcznego. Co więcej, obie metody strojenia dały lepsze wyniki w przypadku sterowania z otwartą pętlą, w wyniku czego można było wyeliminować zwęglanie tkanek i zwiększyć efektywność operacji klinicznych. (**Strojenie regulatora mocy PID za pomocą optymalizacji roju cząstek dla jednostki elektrochirurgicznej)

Keywords: PID Controller, Particle Swarm Optimization, Electro-Surgical Unit.
Słowa kluczowe: Kontroler PID, optymalizacja roju cząstek, jednostka elektrochirurgiczna.

Introduction

Electro Surgical Unit (ESU) is a popular modern device which have been used in most hospitals in operating rooms for desiccation, cutting, fulguration, and coagulation of biological tissues. The ESU was firstly discovered by Bovie in 1928, where it was commonly called Bovie unit. In 1920, it was improved by W. Bovie. It was the initial device that had ability to radio-frequency (RF) current surgery [1]. ESU generates a high-frequency (i.e.100-500 kHz) alternating current (AC) to ensure non stimulation occurring of other body organs [2]. A standard ESU depends on a resonant inverter to regulate the output frequency and wave shape [3].The current path starts from the active electrode (tip electrode) and enters the tissue, then it exits through passive electrode (nature electrode) [4]. ESU operates with two modes according to the path of entry and exit current through the patient's body. The two operation modes are mono-polar and bi-polar [5]. The basic ESU circuit has been composed of an ESU, two electrodes, connecting wires, and the patient. When a mono-polar mode has been utilized, one electrode has been known as an active electrode which is the mono-polar instrument itself. This electrode is similar with the shape of a spatula, hook, or pencil. The other electrode has been called a dispersive electrode and affixed to the patient's body. This electrode has been also called "nurture electrode". Each electrode has been linked by individual wire to ESU [6]. When the mono-polar mode has been activated, the current passes from ESU to the mono-polar electrode, through the patient's body, to the nurture electrode. Finally, it returns to ESU. This represents to a complete electric circuit [7]. In contrast, bi-polar mode contains two active electrodes within the tool itself, usually on each jaw of a bi-polar forceps. Only one wire has been linked with the bi-polar electrode to ESU. The current only passes into the tissue held by the grasp of the bi-polar forceps to make a complete electric circuit. This creates more targeted tactic to energy delivery, permitting for using a lower voltage and minimizing the spread of current to neighbouring tissues or inadvertent injury [8]. The standard form of ESU procedure with its operation modes has been shown in the Fig. 1 [4].

The mechanism work of ESU depends on joule's heat generated by transmission of the electric current through the tissues which enables to create the coagulation, cut, etc. [9]. From another side, tissue impedance converts the electrical current to thermal energy which increases the tissue's temperature and also permits to obtain the wanted effects. Various effect of the electrical current has been based on the temperature degree that the target tissues has been arrived [10]. The instability of the output power is due to the difference in the impedance of the tissue between its layers during the cutting and other operations. This leads to increase the temperatures of tissues above 200°C and the carbonization of the tissues has been occurred [11]. In a previous study, researchers proposed an ESU device that had the ability to control the output power by using Proportional Integral Derivative (PID) with sliding mode controller.

Researchers proposed an ESU with fast tracking ability using a two-rail multi-phase buck converter with GaN switches along with the use of digital controller applied on a Xilinx board. Task results were given by 4-phase ESU sample working from ±250 V at 2 MHz per-phase switching frequency and could provide up to 50 watts for an arc displayed as a 180 Ω to 3600 Ω load [3]. In a previous study, the suggested ESU had the ability to regulate the output power by using PID with Fuzzy logic controller and Ziegler Nichols strategy.

The purpose of this study is to prevent the latter condition and reduce thermal damage by preventing the increase in temperature during the surgical operation. Commercial ESU devices do not contain a controller to maintains the stability of the output power [12]. In this paper, ESU was proposed to have the capability to maintain output power stability, despite of changing tissue impedance, via Particle Swarm Optimization (PSO) technique for tuning the parameters of Proportional Integral Derivative (PID) controller. This proposal was designed to improve the ESU with PSO-PID controller that achieved a fast response, power regulation and overshoot reduction to obtain on reducing of the thermal damage.

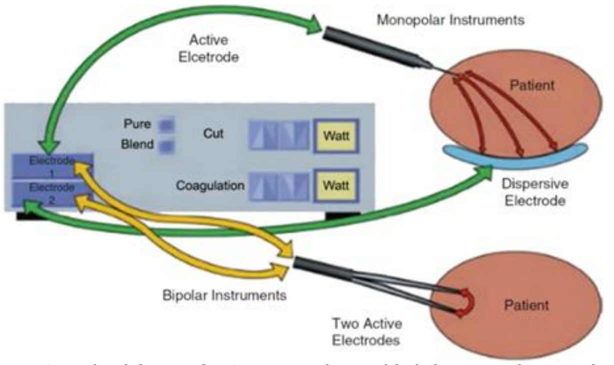


Fig.1. Standard form of ESU procedure with it is operation modes [4].

Experimental Methods

Proposed ESU Block Diagram

The suggested control technique was illustrated as schematic diagram in the Fig. 2. This technique was consisted of several processing stages which were Alternative Current (AC) to Direct Current (DC) rectifier, DC chopper buck converter, DC to AC half bridge inverter and PID controller. The implementation of this controlling scheme led to regulate the output power from ESU inside the patient's body in order to minimize the thermal damage during surgical operation by controlling the voltage in spite of the variation of tissue impedance between skin layers.

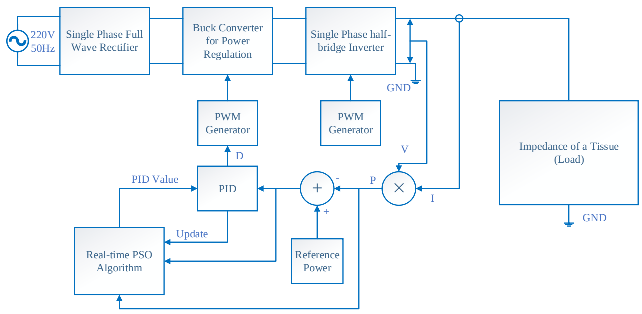


Fig.2. The **p**roposed ESU block diagram.

Single Phase Full Bridge Rectifier

The most common application for converting AC signal to DC signal is bridge rectifier. It has been comprised of four diodes which alters the AC input into the DC output. It has better properties compared with the rectifier included a 3-wire as inputs come out of a transformer with a centre-tapped secondary winding, where full-wave rectification has been produced by bridge rectifier [13]. Essentially, feature of the diode bridge is the polarity of the output which is the same regardless of the polarity of the input as shown in Fig. 3. When the input voltage rises from zero to a positive value, the D_1 and D_2 have been forward biased making a voltage drop of 0.7 V for each one. Through these diodes, the current has been flowed to the load generating a positive voltage across the load resistor. These diodes remain in ON-state until the source voltage drops below 1.4 V. D_3 and D_4 have been forward biased and the same voltage drop for D_1 and D_2 when the source voltage polarity has been flipped and gone to the negative value, but the negative half cycle has been flipped by D_3 and D_4 into positive half cycle across the resistive load. The D_3 and D_4 remain ON-state until source voltage drops below -1.4 V. At any polarity of the source voltage, a positive voltage has been supplied across the load via the two operations above [14].

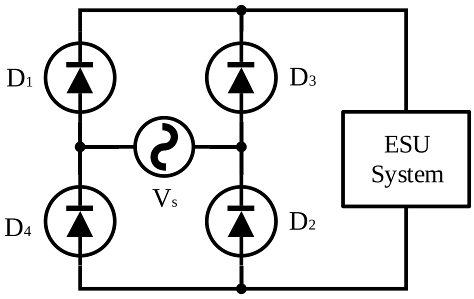


Fig.3. Single phase full wave bridge rectifier circuit.

The mathematical equations of full bridge rectifier have been clarified below [15]:

Average voltage across the load (V_o) has been determined by:

(1) $$V_o = \frac{1}{\pi}\int_0^{\pi} V_m \sin(wt)d(wt) = \frac{2V_m}{\pi}$$

Root mean square voltage (V_{RMS}) has been calculated via:

(2) $$V_{RMS} = \sqrt{\frac{2}{2\pi}\int_0^{\pi} (V_m \sin(wt))^2 d(wt)} = \frac{V_m}{\sqrt{2}}$$

The peak input voltage (V_m) has been determined by:

(3) $$V_m = \frac{V_s}{\sqrt{2}}$$

Single Phase Full Bridge Rectifier

The DC chopper has been used to obtain a regulated output variable DC voltage according to the type of application. It consists of two switches represented as MOSFET transistors controlled by a PWM signal, coil and capacitor [16]. The buck converter mathematical equations have been clarified below [17]:

(4) $$V_o = D * V_s$$

(5) $$D = \frac{T_{on}}{T} \backslash$$

(6) $$L_{\min} = \frac{R(1-D)T}{2}$$

(7) $$C_{\min} = \frac{(1-D)T^2}{8L(\frac{\Delta V_o}{V_o})}$$

where: T – total time, T_{on} – time interval, D – duty cycle of buck converter which has been utilized for regulating the output voltage. This permits the DC voltage to be regulated although variation in the load impedance. The inductance and capacitance minimize values of the dc buck converter that have been calculated from Eqs. 6 and 7 respectively.

These values have been increased to achieve continuous conduction mode operation of the buck converter and also to improve the reliability of ESU under the changing of tissue impedance.

Single Phase Half-Bridge Inverter

A single-phase Half-Bridge inverter (HBI) has been mainly used to convert DC voltage to HF AC voltage. The operation principle of the inverter's circuit is to feed the current into common ground. The two centre-tapped transformers work alternately by using two transistors (Q_1 and Q_2) that have been driven via a symmetrical square wave signal [18]. If the first transistor Q_1 has been switched with ON state for a time $T_o/2$, then the voltage across the secondary coil is nV_s. If the second transistor Q_2 has been switched with ON state for a time $T_o/2$, then the induced voltage in the secondary coil is equal to $-nV_s$. The V_s symbolizes the source voltage and n represents the turns ratio [19]. The output of the inverter has been connected with the active electrode of ESU via an HF transformer which reacts with the tissue during the surgical operation [12].

Impedance of a Tissue (The bio-load)

The normal body's temperature of the human is about 36.5 °C. If any person has a fever, it increases and can reaches at 40 °C. However, it does not find any thermal damage in these conditions. When the temperature reaches above 50 °C, the cells death has been occurred in some minutes because of the molecular changes in cell's membrane proteins [20]. The effect of the damaged cells has been obtained between 60 °C. to 100 °C. The two various processes have been occurred in the tissues. In the first process, loss of cellular water has been acquired by the thermal-induced destroying for the cell of the membrane leading to desiccate the collapses tissue. In the second process, breaking of the bonds among protein molecules has been taken place leading to denature and coagulate the extracellular collagen for building up a homogeneous gelatinous matter, this process is useful to achieve obstruction in blood vessels and stopped bleeding. When the tissue temperature degrees increase over 100 °C, boiling of intracellular water has been started. Also, vaporization of cells has been happened in cloud of steam, ions released, and organic matter blast [21]. At last, about 150-200 °C, the breaking down of live tissues has been occurred in the main carbon compounds and seemed the black carbonization. This effect is impractical for therapeutic purposes because it increases the impedance of the tissues and impedes the pass of current [22]. The Human tissue consists of three layers (skin, fat, and muscle) with different impedance [24]. As we go deep into the tissues, the value of impedance has been decreased gradually due to the presence of liquid materials that increase conductivity and reduce impedance. In this project a living tissue with equivalent circuit was designed. The bio impedance of the skin layer is 220 Ω, while the fat layer and muscle layer have impedance of 190 Ω and 160 Ω respectively [24]. The surgeon sets the output power of ESU on 50 W. The power is constant when the active electrode touches the first layer of tissue to be cut, while it reaches at the second layer, the impedance has been reduced with power increment according to Ohm's law clarified in the following equation [12]:

$$P = \frac{V^2}{|Z|} \tag{8}$$

where: *P* – output power of ESU, *V* – voltage of ESU, |Z| – impedance of tissue.

PID Controller

A technique for power regulation has been suggested and implemented to prevent the carbonization of tissue. This technique has been called PID controller. The main goal of the controller was to keep the output power constant despite of occurring changes in the impedance value between the tissue layers. It must control the voltage via pulse width modulation (PWM) using switch-mode converters (SMC) signal with constant HF, while the times of OFF and ON states has been changed to obtain the required closed-loop operation [25]. The PWM signal time period must be fixed but the D has been adjusted according to Eq. (9) to acquire the wanted voltage. In PWM1, the D has been altered and controlled to have an appropriate value of output voltage from the buck converter which has been attached directly to the single-phase inverter [26]. In PWM2, the D was constant at 50% in order to attain a symmetric square wave signal that activates the inverter [27]. Due to the changing on the impedance of tissue, the buck converter output voltage must be controlled by the PID controller to follow the voltage selected by the surgeon that has been produced from the power control loop. The PID controller equation in the time domain have been elucidated below [28]:

$$u(t) = k_p e(t) + k_i \int_{t_o}^{t} e(t)dt + k_d \frac{de(t)}{dt} \tag{9}$$

where u(t) is output signal, e(t) is error signal, k_p – proportional coefficient, k_i – integral coefficient, k_d – derivative coefficient. The PID controller Transfer Function (*TF*) has been presented as follow [29]:

$$TF = \frac{u(s)}{E(s)} = k_p + \frac{k_i}{s} + k_d s = \frac{k_d s^2 + k_p s + k_i}{s} \tag{10}$$

In this proposed article, the authors used two methods. The first one was Manual Tuning (MT) method and the second one was PSO for tuning the parameters k_p, k_i and k_d of PID controller.

Manual Tuning Method

MT is one of the traditional methods for tuning PID controller parameters. The method steps of MT set k_i and k_d terms to zero first can increase the k_p till the output of control loop wavers at a fix rate. The response of the system has been become faster due to the increment in k_p gain. This will not lead the system for unstable situation. When the k_p response is fast sufficient, integral term can be set for oscillations so it can be gradually minimized. Continue change in k_i magnitude has been accomplished until the steady state error has been minimized, but it may rise the overshoot. At k_p and k_i coefficients, which have been set to a wanted values with smallest steady state error, start to rise k_d gain till fast interaction has been implemented by the system to its set's point. Increasing of k_d term leads to decrease the overshoot of PID controller response [30].

Particle Swarm Optimization

Particle Swarm Optimization (PSO) algorithm was discovered by Ryenolds and Heppner and the algorithm was simulated by Eberhart & Kennedy in 1995 as demonstrated in the Fig. 4. The bird's swarm conventional conduct has been depended for this technique [30]. PSO has a strong technique for obtaining perfect results for non-linear systems where each particle is equal to an individual bird in a collection of birds [31]. A swarm composes from N particles transition over a dimensional search space. The technique of PSO has been reconstructed with a group of random particles and algorithms to search for perfect solutions by constantly updating the process. Particle swarm bird varies in moving according to their own, where it is previous better solutions at each iteration [32].

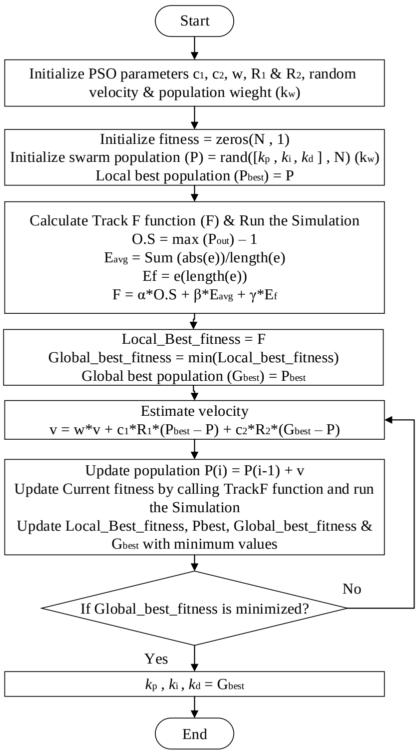


Fig.4. Implementation of PSO technique for the proposed ESU.

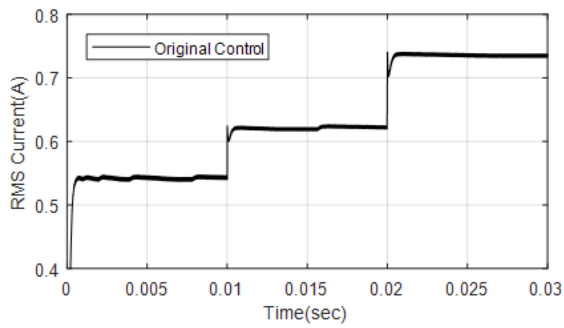
The expressions of the PSO technique can be illustrated in the following paragraph [33]:

The i^{th} particle swarm is P(i), the better former solution of i^{th} particle swarm is local best_population (i); the velocity of particle swarm depends on position change rate is v(i); the better achieved solution by total swarm (G_{best}) is global_best_population (i). The flowchart in Figure 4 above illustrated the implementation of PSO in PID tuning for the ESU power regulator. The symbols of k_p, k_i, and k_d are multiplying coefficients used to optimize the k_p, k_i, and k_d PID parameters; N particles for each variable; k_w main limit C_1, R_1, C_2, and R_2 are constants; α, β and γ are positive constants.

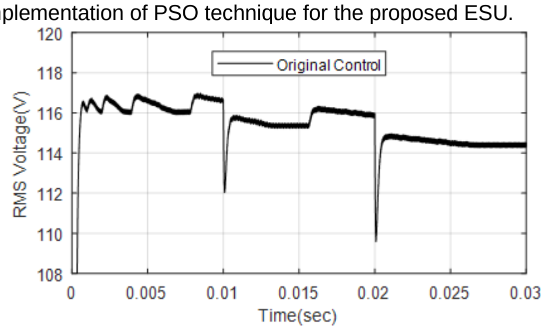
Result and Discussion

The suggested system was implemented in MATLAB/SIMULINK using Sim-scape Library. To validate the proposed PID controller, simulation results were demonstrated in Fig. 5-7. It was agreed that power conservation must be compensated by current and voltage. A comparison was implemented between the results of the Open Loop (original controller) and the Close Loop PID-(MT,PSO) to show the superiority of the proposed controller PID-PSO in its ability for regulating the output power.

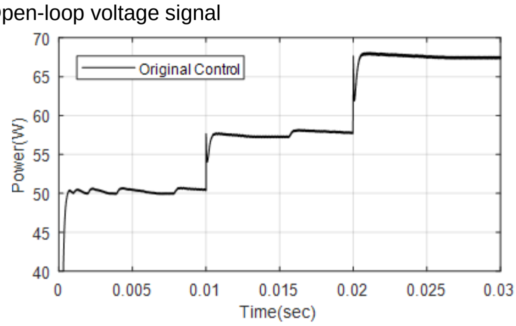
Figures 5-6 depicted current, voltage and output power graphs for the commercial ESU (original controller) and the proposed ESU with PSO-PID controller compare with PID-MT controller respectively. When the active electrode contacted with the tissue and the cutting process started, the impedance of the first layer of the tissue equal to 220 Ω was begun to decrease due to the presence of liquid materials. Deeply to the second layer, the current increased in the original controller up to 0.625 A. In the proposed controller, it reached to 0.57 A. Unlike commercial devices, the voltage of the proposed ESU gradually decreased with reducing in the impedance of the tissues to keep the output power value constant. It has been noticed that the output energy of the commercial device has constant value at the first layer of the tissue but it begins to increase in the second and third layers leading to the charring of the tissues, while the output power of the proposed ESU with PSO-PID controller remained constant despite of the change in the impedance of the tissues between its layers with the reduction of the overshoot and the steady state error. This led to prevent the tissues from thermal damage. The number of iterations particle swarm was 50, and the chaotic particles was 8. Figure 7(a) showed fitness curve and the optimization curves of k_p, k_i and k_d were clarified in the Figures 7(b), 7(c) and 7(d) respectively according to the optimization process parameter of PID controller using PSO.



a) Implementation of PSO technique for the proposed ESU.



b) Open-loop voltage signal



c) Open-loop power signal

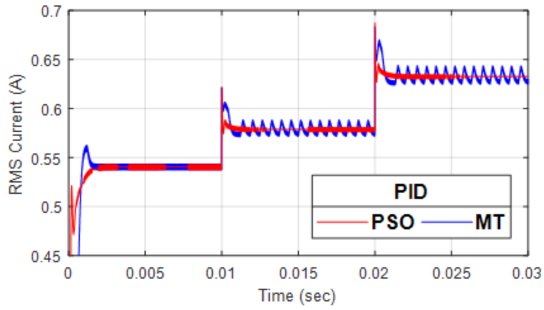
Fig.5. ESU with original controllers.

The percentage of overshoot (OS%), rise time (t_r), peak time (t_p), and error of the output power were summarized in Table

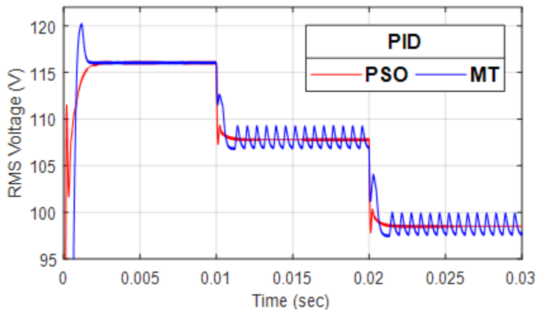
Table 1. The summary of results.

No.	Tuning method	OS% [s]	t_r[s]	t_p[s]	Error
1	MT	7.2	0.79×10^{-3}	1.19×10^{-3}	1.92×10^{-2}
2	PSO	0	0.64×10^{-3}	2.38×10^{-3}	0

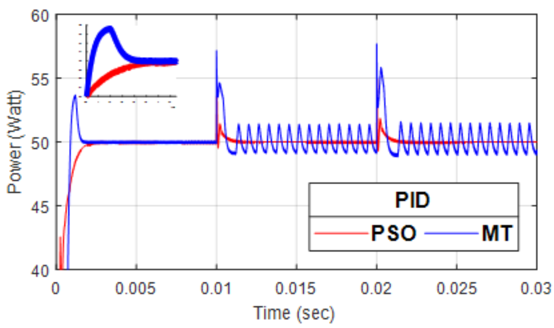
The drawback of the open-loop (original controller) was the unregulated rise in the output power after the first layer of the tissue. This was the riskiest method among all other ESU control techniques. The advantage of PID-MT controller was succeeded to regulate the output power along the three tissue layers. However, the drawback of this method has higher overshoot than the original controller which has been considered one of the traditional methods of tuning PID parameters. The advantage of the proposed PSO-PID controller was succeeded to achieve a fixed value of output power whatever the tissue impedance changes. Also, reducing the overshoot and the steady-state error to zero as illustrated in Table 1. It was perfectly cleared from the analysis above that the ESU with closed-loop PSO-PID controller offered the best performance in order to prevent the thermal damage of the tissue. The specifications of the proposed ESU simulation are shown in Table 2.



(a) Closed-loop current signal

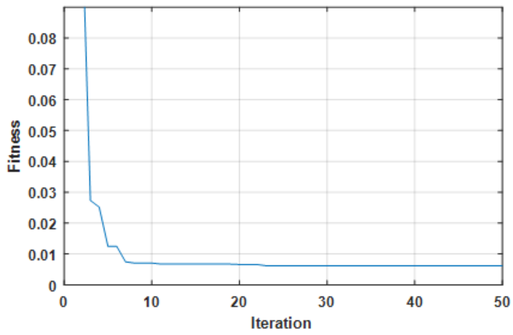


b) Close-loop voltage signal

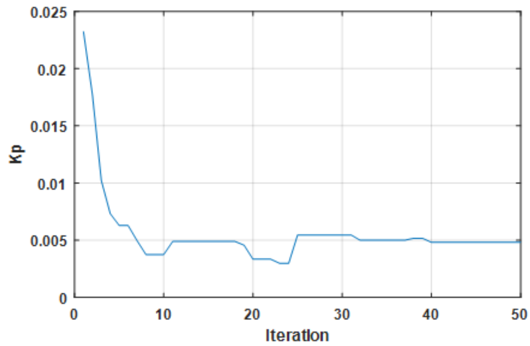


(c) Close-loop power signal

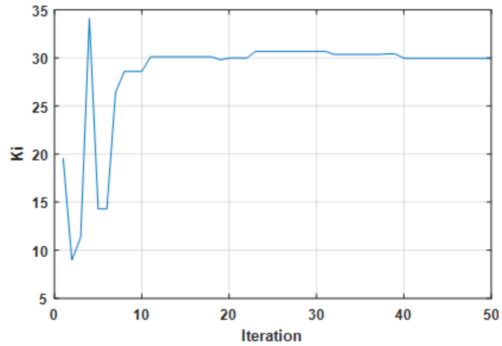
Fig. 6. ESU with proposed controllers.



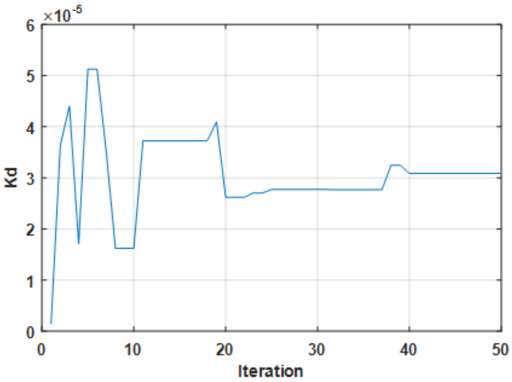
a) Fitness curve



b) k_p coefficient curve



(c) k_i coefficient curve



(d) k_d coefficient curve

Fig. 7. The process of optimizing PID controller parameters using PSO algorithm

Conclusion

The aim of this study was to achieve the stability of the given power during the operation despite of the sudden change in the impedance of the tissues between its layers. The proposed controller (PID-PSO) was improved by increasing in power for uncertainty in the original controller from 36.2% to 9.86% in the proposed ESU. Also, the standard deviation (STD) of power for the original controller was 36.4% while PSO-PID was reduced to 5.00%. Finally, the PSO-PID controller was concluded to be the best controller because it has the ability to maintain the stability of the output power given to the patient during the surgery, regardless of the change in the impedance of the tissues, thus reducing thermal damage on the patient body.

Table 2. The specifications of the proposed ESU simulation.

Description		Symbol	Value
Source Reference		V_s	220 V
		P_{ref}	50 W
Buck Converter		L	33 µH
		C	220 µF
		Switching frequency	500 kHz
Tissue Impedance		1st layer, Z_1	90 Ω
		2nd layer, Z_2	60 Ω
		3rd layer, Z_3	30 Ω
		Z_{min}	130 Ω
PID Tuning Method	MT	k_p,	0.01
		k_i	10
		k_d	0
	PSO	k_{pnew}	0.0048
		k_{inew}	29.9685
		k_{dnew}	3.085e-5
Transformer		L_1	40 µH
		L_2	0.10 µH
		L_3	0.10 µH
Rectifier		L	10 mH
		C	2200 µF

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***Authors**: Prof. dr. Ali Jafer Mahdi, Al-Zahraa University for Women, Karbala 56001, Iraq, E-mail: ali.j.mahdi@alzahraa.edu.iq, A. L. Mohammed Jamal Mohammed, Branch of Physiology and Medical Physics, College of Medicine, University of Al-Ameed, Karbala 56001, Iraq, E-mail: eng.mohammed.j@alameed.edu.iq, prof. dr. Jameel Kadhim Abed, Department of Medical Instrumentation Techniques Engineering, Middle Technical University, Baghdad 10011, Iraq, E-mail: drjameel57@gmail.com, A. L. Basheer M. Hussein, Department of Physics, College of Education for Pure Sciences, University of Kerbala, Karbala 56001, Iraq, E-mail: basheer.m@uokerbala.edu.iq*

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