

Design of the Control Device for the Electrosurgical Generator

Zahra Suhail Alaq, Fatima Hayder Hussein, Zahraa Muhammed Rasool,
Noor AL-Huda Saad Abdulwahid, Ahmed Ayad Ali
Al-Mustaqbal University College, Biomedical Engineering Department

Received: 2024 19, Dec
Accepted: 2024 28, Jan
Published: 2025 04, Feb

Copyright © 2025 by author(s) and BioScience Academic Publishing. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).



Open Access

<http://creativecommons.org/licenses/by/4.0/>

Annotation: Electro surgery is a systematic process within different surgical procedures; The basic working idea was to heat the tissues in an area of focus using the radio-frequency high-power alternating current signals. As a result, several functionalities, including cutting, removal of tissues, and altering of blood flow across the damaged tissues, are achieved. In this work, sliding mode controller is used for regulation output power of the electrosurgical system to meet level which causes no effect on the patients. Sliding mode control one of the nonlinear controller which have many advantages such as Robustness against uncertainties and disturbances, simplicity of implementation, insensitivity to model inaccuracies, effective control of nonlinear systems, and strong stability guarantees. In this work, one case of the tissue impedance was assumed for the controller of the electrosurgical unit i.e. constant impedance. Sliding mode controller give well behavior for the power regulation. Matlab file is the software used for the simulation process.

Keywords: simplicity of implementation, insensitivity to model inaccuracies, disturbances, electrosurgical.

Introduction

Power electronics converters are widely used in medical and bioscience applications, as examples for these applications are X-ray machines, magnetic resonance imaging (MRI) and electrosurgical units (ESU) [1] [2], where these converters have high practical efficiency [3]. In this study, ESUs are selected as a case study for medical applications that use high-frequency and power electronic converters in their design, the ESU is studied and designed with improved practical properties. Before addressing the basic concepts of ESU, a summary will be given of the developmental stages that energy-dependent surgical units have gone through in their work, up to the ESU that are currently used. In the past centuries, heat (hot cautery) was the standard method used for medical purposes or to stop bleeding, and this method continued to be used for a long time. After the discovery of electricity, most surgeons resorted to the so called electrocautery method, which is a method that was invented using direct current (DC) and it is still used nowadays. In 1920 William. T. Bovie (Figure 1.1), a physicist from Harvard University and in collaboration with pioneering neurosurgeon Harvey Cushing presented the first surgical unit operating on alternating current (AC) and radiofrequency (RF) it called the Bovie unit (Figure 1.2 a), and it is the surgical unit that is currently used for clinical procedures with some improved practical developments for it (Figure 1.2 b) [4] [5]



Figure 1-1 Dr. William. T. Bovie inventor of the ESU [4].



(a)



(b)

Figure 1-2 The Bovie unit (a) in 1950 and (b) in 2010 [4].

The term the electrosurgery can be defined as the use of AC current and radiofrequency to cut the target tissues and/or dry them through the coagulation process, this approach is used to achieve clinical outcomes with less blood loss and less working time than traditional surgeries [7] [8]. are the procedure by the ESU, this procedure benefits both the patient and the medical team by speeding up cutting tissues, stop the bleeding as soon as possible and the speed of recovery of the patient after surgery as well as reducing medical team effort [10]. In general, the

electric circuit of the electrosurgical units consists of four components, which are: electrosurgical generator (ESG), an active electrode, return (dispersive) electrode and the target vital tissues which represent the load for the circuit. The basic principle of electrosurgery work is summarized as in the following, the ESG sends the RF electric current to the target tissues via the active electrode to heat the tissue in order to achieve the operation of the cut or/and coagulation, and then these current returns to the generator through the return electrode to complete the path of the electrical circuit [11]. In electrosurgery, high-frequency electric currents must be used to avoid

The muscle and nerve stimulation that occur when using low frequency electric currents, causing harmful effects to patients such as pain or heart failure, etc. [12]. The ESG's load (vital tissues) is varied due to the tissue's structure and qualities, which are presented as an impedance. The tissue resistance variation causes functional problems in the generator output parameters that include variation in the output power, current and voltage, which does not match the power parameters specified by the specialist medical team to achieve the desired clinical effects. This change in power causes health damages to the patient, such as burns, resulting in to damage the tissues or other organs, in addition to adverse effects caused to the medical team [13] [14]. this study suggested a number of solutions that it finds suitable to reduce or eliminate the defects faced by the ESU that are not proposed previously. The proposed inverter circuits can thus improve the practical performance of the ESG and reduce the health damage caused to the generator. The number of loads is used to test the performance of the ESG proposed to obtain more accurate and correct results because we are dealing with variable and different loads according to age and gender, not fixed loads, and this difference affects the generator's performance. Therefore, these constant loads are proposed in age and gender in order to make sure that the proposed solutions are appropriate with all the loads that the ESG uses. ESU provide a number of advantages over traditional surgical methods. These units have limitations that produce negative effects on patients or medical staff [15]. Burn (carbonation) injuries, heat injuries, and surgical smoke [16] are examples of these effects that produce minor or severe injuries. It is estimated that 2-5 per 1000 patients per year are injured by the ESU [9] [17]. As a result of the ESU's burn injuries, which cause tissue damage, 550-600 [18] or 40000 [19] are anticipated to occur annually. Additionally, heat injuries (heat dispersion) to the target tissues or nearby organs such as the bladder, ureters, and intestines might occur by ESU [20]. According to the studies' statistics, 70% of the injuries mentioned are not detected during the surgical procedure but rather at a later stage, resulting in late diagnosis and an increase in morbidity and mortality [17]. Research has revealed that approximately 500000 operating room workers, including surgeons, anesthesiologists, nurses, and technicians, are exposed to surgical smoke on a daily basis. This smoke contains harmful chemicals that can cause cancer or the transmission of bacteria and viruses to those exposed despite wearing protective masks [21] [22]. Economically, medical institutes incur large sums of money in statutory financial compensation for unintended injuries caused by ESU [19]. The main objective of the proposed study is to propose an economic ESU with an additional feature of output power regulation and design of controller system for the power regulation purpose in electrosurgical system by variation voltage and current using a non-linear control method called a Slide Mode Control (SMC) tuned controller. Unlike the previous studies, the proposed controller is designed in a fully closed-loop control fashion to regulate the output power of the ESU to a fixed value under the consideration of highly dynamic tissue impedance. The performance of the proposed method is tested in the MATLAB/SIMULINK environment. In order to validate the superiority of the proposed method, a comparative analysis with a simple (SMC) controller based ESU is presented. This study aims to Design a non-ideal synchronous buck converter circuit, which is a component of the ESG's electrical power circuits, in order to construct a circuit that is realistic, less expensive, and more efficient. Design a robust and efficient closed loop control system for the ESG that maintains the output power at a constant value specified by the surgeon, despite changes in the tissue's bio impedance. Design advanced multilevel inverter rather than a traditional inverter, which is one of the energy

converter circuits used in the design of the ESG to limit the quantity of heat energy that causes heat dissipation in the tissues.

2.1 Overview

Implementation of a closed-loop system for the ESG unit is proposed in this work. To regulate the output power of the ESG unit. After presenting the detailed analysis of all controllers that used, it was concluded that SMC-based ESG is more robust and efficient compared with other method. The results clearly show that the open-loop system is not a reliable option for ESG in terms of human safety. A closed-loop system is presented, which ensures that the ESG maintains the desired power in normal condition as well as during variation in human tissue impedance

2.2 The ESU component

1. The generator :

Electrosurgical generators can produce a variety of electrical waveforms. As these waveforms change, so do the corresponding tissue effects.

2. The electrodes :

Which have two types:

- ✓ monopolar : consist of the active electrode which placed at the surgical site.
- ✓ bipolar: consist of the active electrode and the return electrode like as figure (2-2).[23]

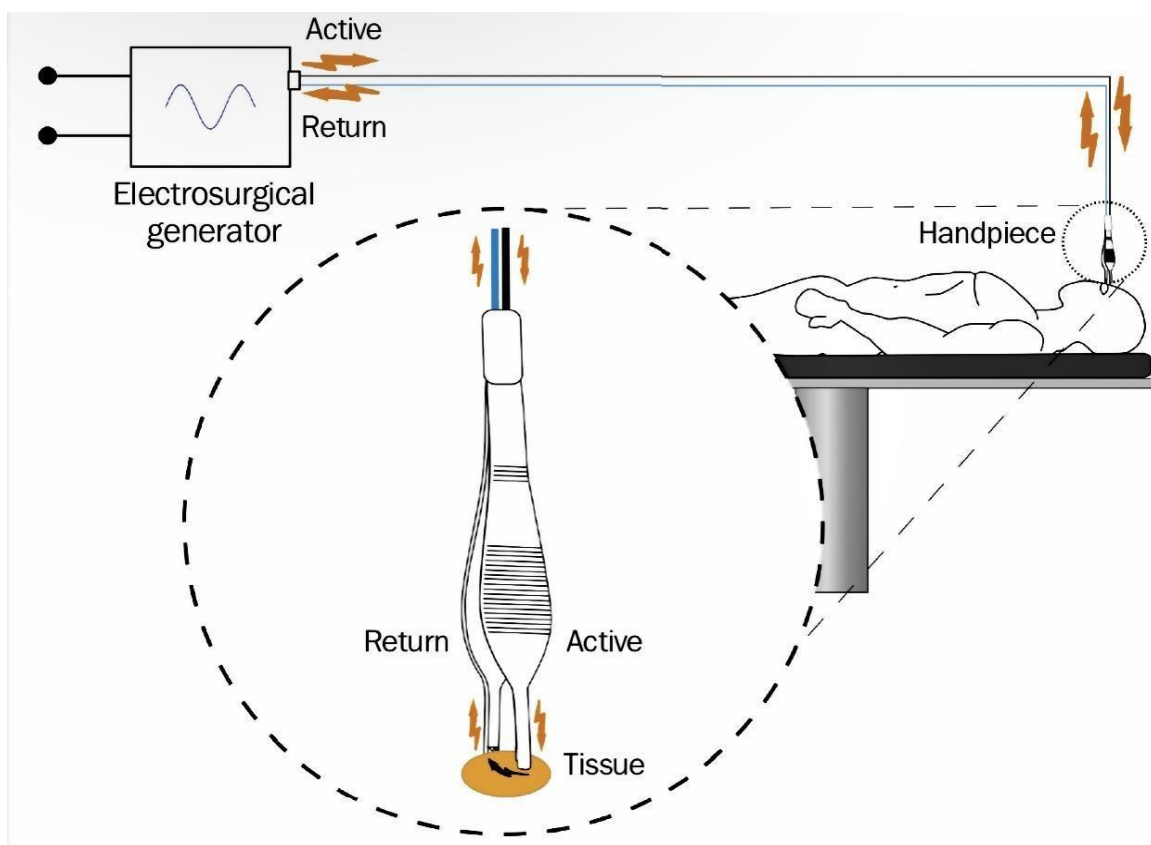


Figure 2-2 (bipolar)

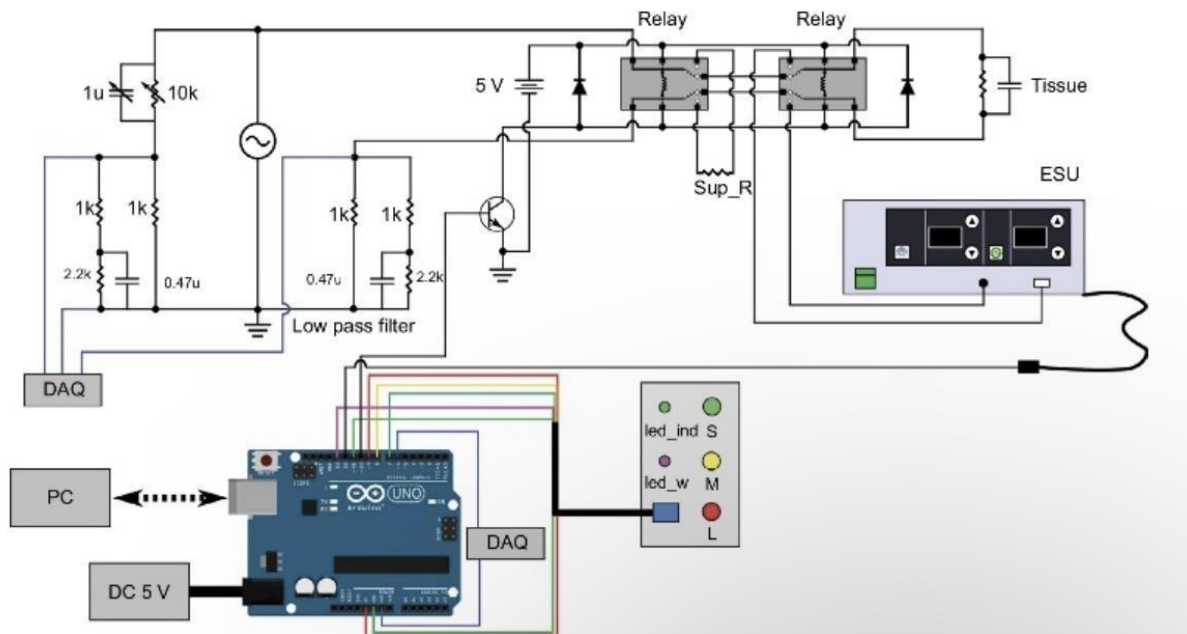


Figure 2-3 Circuit diagram of bipolar

- 3. Foot switch:** Foot switches or foot pedals are safety switches that are operated with the foot. Footswitches are used in industry and machine construction to switch parts on or off, whereby manual operation is not practical or possible. Foot switches are available with or without safety function.

ESU ACCESSORIES

Accessories for an ESU include the generator, the active electrode with tip(s), dispersive electrode, foot switch with cord (if applicable), adapters, and connectors. An accessory could contribute to an injury if it is damaged or personnel use it incorrectly. [25]

- 4. Adapters** -Since there is a difference in the years of manufacture, there is a difference in the outlets between the old and the new, so you will have to use adapters

- 5. Connectors** It is about wires connected to an electrical source and the device with tools

2.3 Types of Electrosurgery

There are two types of electrosurgery:

The first type is Monopolar electrosurgery that contains two separate electrodes, one is the active electrode and the other is the patient return electrode. The active electrode is at the surgical site and the patient return electrode is placed in another part of the patient's body. The current passes from the active electrode through the tissues to the patient return electrode and then continues electrosurgical circuit back to the electrosurgical unit. Methods of monopolar electrosurgery include cutting, mixing, drying and slicing [26].

Accurate positioning of the patient return electrode is important in monopolar electrosurgery. It should be placed over a muscular area rather than a bone area because incorrect positioning of the patient return electrode leads to burns for the patient [27]. It is preferable to use this type of surgery because of its versatility and effectiveness in large areas.[28]

The second type is Bipolar electrosurgery that contains one double electrode consisting of the active electrode and the patient return electrode, meaning that both electrodes are in the surgical site only. The current passes only in the area held between the teeth of the forceps. The electrosurgical unit is usually activated by (foot pedal). High frequency current passes through only one side of the forceps through the tissue and then back to the other side of the forceps. This

type of electrosurgery uses a low voltage, so less energy will be released as a result. The electrodes will not be used in large areas. It is best used when the tissue can be easily gripped on both sides, making This type of electrosurgery is more widely used, thus preventing damage to the surrounding tissues [3]. This type can be used for patients who have devices implanted in the body.[28]

2.4 The principle of Electro surgery

Electrosurgery harnesses electricity with the intention of creating various thermal effects to achieve resection, incision, hemostasis, and devitalization of target tissues. The therapeutic basis of all electrosurgery is the production of thermal energy at the cellular level, typically as a result of a high-frequency alternating current created by an electrosurgery generator or unit. Heat generated by this process is the result of resistance or impedance to the flow of electricity within the tissue. The electrical current must alternate (i.e., change direction between positive and negative) at a frequency of more than 100,000 times per second (100,000 Hz) to avoid the neuromuscular responses and shocks that occur with Radiofrequency electrosurgery technology differs from the commonly used cautery devices. The cautery devices utilize the direct current (DC), while the ESU utilizes the AC power for heating of the tissues. The ESU units are utilized for cutting or to stop bleeding by causing coagulation (hemostasis). The target area of the tissues receives thermal energy from the tip of the electrode due to which drying up, vaporization, and scorching of the tissues is achieved. .[29]

2.5 Working and design specifications of electrosurgical unit

The output of the high-frequency and high-power inverter forms an arc between the output probe of ESG unit and the patient; thus, it introduces joule heating effect. As shown in figure (2-5), the current flows from the output of the inverter through the probe in other words the probe conducts electrons to the patient. For the return current, the grounding pad placed below the back of the patient before beginning the procedure to complete the circuit back to the ESU , If the circuit is broken, no current will flow at any point within the system . The patient acts as a resistive element as a result of flow of electrons at high frequency within the tissue this process generate heating effect across it. The surgical procedures are carried out by passing the charges through the tissues in controlled manner. The electrical power of ESU unit is representation of the amount of work the circuit will do at the point of contact. Generally, the ESU unit consists of three stages. Figure (2-6) The first stage is the rectification stage, which is used to convert the (AC to DC) power. In the second stage, a buck converter is used to step down the magnitude of the DC-rectified voltage signal. The third stage used the push pull inverter to convert the DC signal to high



Figure 2-5 Working diagram of electrosurgical unit.

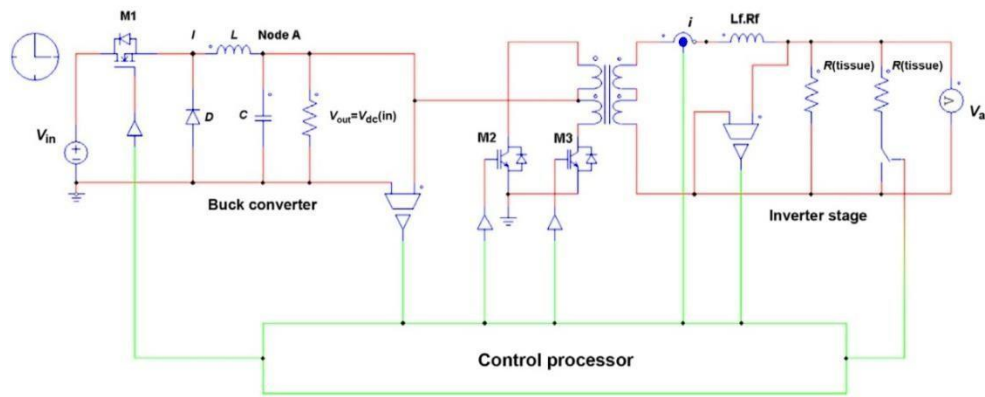


Figure 2-6 Power stages of electro-surgical unit.

power and high-frequency AC power signal. A high frequency transformer is used to connect the output of the inverter with the probe through a high frequency transformer. A different sensors such as output voltage and current sensors are used for measuring the output quantities of the inverter unit. The output voltage and current measurement used to calculate the device power. To calculate the RMS power of the ESU unit, sensors require outputting RMS values of the quantities measured. Depending on the mode of operation, either of three measured signals is used as feedback to the controller board for operation of the unit in closed loop manner. The feedback signals from both the buck converter and the inverter circuit is being used the main controlled and based on it controls output power of the inverter. The AC source which is the input voltage source of the ESU ,step down to 24 V and rectified to 24-V DC. The 24-V DC is input to the buck converter, while the output voltage and current of the buck converter are regulated at levels of 11.11 V and 11 A, respectively. **Figure (2-7)** shows the ideal output characteristics of the electro-surgical unit. This graph represent a function of the output voltage and current of the inverter unit. The device is operated in three modes, including constant current, constant voltage, and constant power modes. Constant voltage mode imposes restriction on the maximum output voltage of the inverter unit, which in turns limits the arc length, which is usually formed between the ESU unit and the patient due to the interaction of high impedance tissues at high powers.

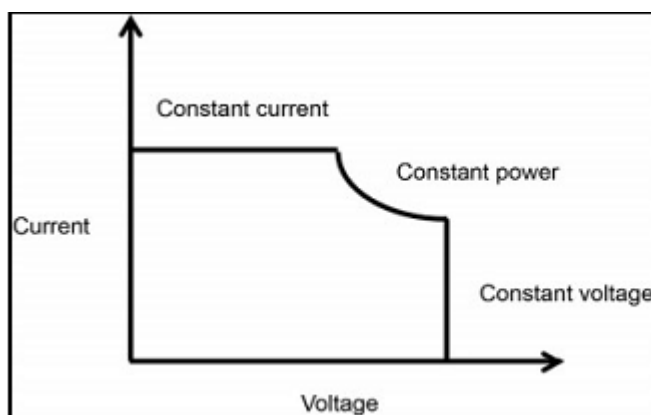


Figure 2-7 Output characteristics of electro-surgical unit

Similarly, the constant current mode limits the maximum output current of the inverter unit, while in the constant power mode; the current and voltage of the unit are changing such that the product of the two quantities is always constant within the upper limits. The ESU unit must be intelligently programmed so that the device can switch automatically between all the three regions based on the patient tissue measurement to ensure safe surgical procedures. The constant voltage mode is used when the device senses high impedance tissues of the patient. When the tissue impedance is smaller constant current mode is used and the region of it represents the low

impedance range. Constant voltage mode represents the high impedance range and for constant power range, the tissue impedance is medium. [30]

2.6 The risks of Electrosurgery

There two types of risks in ESU

The first one deals with medical staff:

- a. ESU malfunction may result in failure to generate any current, current in the specified mode, and/or current at the desired power output. Complications directly related to ESUs are rare and are more often related to faulty connections and operator error than to malfunction of the generator it self.[31],One of the contents of the electrosurgical generators is the contact quality monitoring system, the function of which is to monitor the interface of the electrode returning from the patient. The contact quality control system disables the general surgery generators when a pad failure occurs [31]
- b. The use of monopolar current, to prevent skin burns because the surface area is large for the return electrode, which disperses the intensity of the current. [31]
- c. When the use is finished, the handpiece is placed in the non-conductive holster,[33]
- d. The fewest generators that will achieve the surgical effect are used, and when higher voltages are applied than required, the chances of bending increase.
- e. Clean the electrode tip frequently. The electrical impedance may increase when scarring (dead tissue as a result of burning) accumulates and may cause (a spark, flaming of the eschar or ignition...) When cleaning the electrode using a sponge rather pads because these pads will scratch the grooves at the electrode tip ,which leads to an increase in the eschar build-up [33]
- f. In some of the risks present in the general surgery device, the connection wires are not safe, they are exposed to rupture, and the doctor and medical staff may be in danger.

The second deals with patient:

- a. Avoid placing the electrodes on areas prone to cushion failure, such as areas with moisture (sweat, creams, ...) or other effects that reduce the conduction of electrical current (such as hair scars, artificial joints, ...) and avoid placing electrodes Returns to the sites of skin creases. Ensure that no parts of the patient's body is in contact with the bed rails. [30]
- b. The monoterminial mode in electrosurgery is limited, especially when a high power is used on the patient on an unconscious or a person suffering from neuropathy who cannot feel pain when burns. And correct use of return electrode increases from the force and the safety of the electrosurgical device.[31]
- c. If the tissues is over heated as a result of long application time , the carbonization effect of the tissue occurs with the possibility of perforation. Avoiding this by modulating currents is crucial to reduce tissue injury while providing the necessary cutting and coagulation effect. The harmful effects are excessive spark and carbonization . The modification allows the device to produce high peak currents with calculated intervals. This prevents excessive carbonization and uncontrolled effects (such as rapid cutting when in use) and also reduces the risk of perforation. [32]
- d. If the surgeon uses a higher voltage than required, this will indicate that the of the skin /dispersive pad interface compromised [32]
- e. Transmission of infection: Certainly using the device for more than one person or the same person in more than one place exposes you to the risk of transmission of infection, such as skin diseases

2.7 Literature

This chapter deals with historical perspective of the ESU Unit :

Ali R, proposed an economic ESU with an additional features. They achieved by using Fuzzy PID controller.

Daniel A. et al. they improved output power efficiency as well as reducing complexity and number of parts by using a new dual-mode current controller that produces fast, accurate, constant-power high-frequency AC output. They achieved this by near-deadbeat control. They achieved the regulation of output power control and fast shifts in a simpler and more precise way. It led to better surgical results.[35] [2012]

Scott J. et.al. performed fast tracking ESG capable of shaping the output AC waveform over a range of frequencies, they provided improved flexibility and control in electrosurgery applications. They proposed fast tracking ESG is based on a two-rail multi-phase buck topology using GaN switches, They concluded Using zero-voltage switched GaN devices, the converter is capable of high-frequency switching with wide-bandwidth control loops supporting output current and power shaping across a range of output frequencies and across varying loads associated with the arc.

[36][2015]

The results are shown for both open-loop and closed-loop operation. Open-loop results demonstrate the flexibility in output current shape and frequency, providing a platform for the exploration of new clinical results. Closed loop results are described for a 100 kHz constant ac reference current. The magnitude of the reference current is such that the power is quickly adjusted according to changes in the output load. The closed-loop results are shown for resistive loads, as well as for actual tissue cuts, with load resistance values representative for the range of resistances seen during electrosurgery. The sample tissue cuts demonstrate that a current driven ESG has favorable arcing characteristics. The arc is established quickly, with the load becoming a nearly constant output resistance.[37][2015]

Vlad Bluvshstein et al. performed on electrosurgical generator control methods that can improve cutting performance. They achieved theoretical and experimental methods to determine the impacts of electrode speed combined with generator control methods. They concluded that there are three factors affects the cutting performance i.e., voltage control, power factor and speed compensation.[40][2019]

NasimUllaha .et al performe to The interaction of the radiofrequency high-power currents with the human tissues changes its impedance . so , the ESU unit must be designed in such a way as to incorporate the uncertainty of the tissue impedance and be able to deliver power in specified limit. So to perform this study the device is tested in constant power region with both fixed and variable tissue impedance. Fractional-order robust control scheme has been derived for voltage and current loop control of the buck converter and inverter unit, respectively. The controllers have been tested in the simulation environment and from the numerical simulation results, it is concluded that in comparison to the integer-order controllers, the ESU unit offers superior performance with fractional-order controllers[41][2020]

Hussban Abood Saber.etalThe electrosurgical generator (ESG) unit must be adapted to satisfy tissue impedance unpredictability while supplying powe, integer-order PID (IO-PID) and fractional order PID (FO-PID) controllers are designed for controlling the output power and voltage. The particle swarm optimization (PSO) method is used to optimize IO-PID and FO-PID controllers' gainsr. The achived by Comparative Analysis of Integer and Fractional PID. it can be concluded that the ESG equipped with a type FO-PID control unit is more powerful and more efficient when compared with an ESG equipped with a type control unit IO-PID.[37][2021]

The results of the simulated experiment show that the design is able to meet the desired design targets while at the same time maintain a high level of efficiency. The next step in the research is to design and develop a new generator for RFG and ESU power supply in which the efficiency of both DC to DC and RF stages are improved. The simulation of the converter will be implemented and built using actual hardware. The performance of the generator and the converter is expected to be improved by the implementation of circuits as well as the usage of switching modules. The developed ESG will be used for experimental analysis by machining. The experimental procedure will also be performed in order to identify the RF stage pattern for higher survival rate of

ESG.[39][2021]

Nimitha G. et al. designed and implemented a converter and controller topology for regulated power. they achieved by keeping their value within the required energy characteristics ,They used blocks from Sim Power Systems tool box in MATLAB/SIMULINK. They found the possibility of making the system's output power constant regardless of the load using a two-level output waveform.[34]

Scott Jensen.etal describes fast tracking ESG capable of shaping the output ac waveform over a range of frequencies, thus providing improved flexibility and control in electrosurgery applications to eliciting a clinical response in tissue (e.g., cutting or cauterization). The proposed fast tracking ESG is based on a tworail multi-phase buck topology using GaN switches.

Ali Idham et al. Used high frequency generator for bipolar electrosurgical unit, The new designed system has a capacity to produce high efficient output power with high resonance, this improves the performance of the surgery operation.

3. Materials and Methods

Mathematical modelling

3.1 Overview

In this work, a closed-loop control system is designed and tested for ESG to improve its performance in the nonlinear constant power region. A quantitative study of a buck converter and boost inverter is presented along with the closed-loop response for the ESG unit. Results represented confirm that the presented closed-loop system can highly improve the performance of the ESG system and SMC is found to be a more suitable choice.

3.2 Mathematical modeling of electro surgical unit

In this section, a detailed mathematical model of the ESU unit is derived. The derived mathematical model is later on utilized for the derivation of the robust control system, the basic ESU device consists of two units. The first unit represents a buck converter and the second unit consists of a DC-AC converter. Referring to Fig 3-1, the switch M1 of the buck converter unit can be operated either in closed or open stage. When the switch M1 is closed, the diode D is reverse biased, and the inductor L and capacitor C will store energy in their respective fields, and it will form a series loop.

In order to derive the dynamics of the converter with the switch M1 is closed, apply Kirchhoff's voltage law (KVL) and current law (KCL) to the series loop and node A, respectively. The resultant expressions are derived as following.

$$V_{in} = LI + V_{out} \quad (3-1) \quad CV_{out}$$

$$= I - V_{out} \quad (3-2)$$

RL

L: inductance

C: capacitance

V: voltage

I: current

Referring to Fig. 2, Eqs. (3-1), (3-2), V_{in} and V_{out} represent the input DC voltage of the buck converter, L and C represent the inductance and capacitance of the power stage elements, I represents the inductor current, and R_L is the load resistance. When the switch M1 is opened, the primary source of voltage E is disconnected from the circuit and the current flowing due to stored energy in the capacitor is circulated in the loop to make diode D as forward biased. The system's dynamics with switch M1 open state are expressed as

$$LI' = -V_{out} \quad (3-4) \quad CV'_{out}$$

$$= I - V_{out} \quad (3-5) \quad R$$

All the parameters of Eqs. (3-4), (3-5) have already been defined in Eqs. (3-1), (3-2). By combining Eqs. (3-1) to (3-5), the Average model of the buck converter is derived as following.

$$LI' = u E - V_{out} \quad (3-6) \quad C V'_{out}$$

$$= I - V_{out} \quad (3-7) \quad R$$

In Eq. (3-7),

u represents the switching function and it can have two states, i.e., one or zero. The two-state variables are represented

As x_1 and x_2 .

Hence,

$$x_1 = I \quad (3-8)$$

$$\dot{x}_1 = I' \quad (3-9)$$

$$x_2 = V_{out} \quad (3-10)$$

$$\dot{x}_1 = u B - A_1 x_2 \quad (3-11)$$

$$\dot{x}_2 = A_2 x_1 - A_3 x_2 \quad (3-12)$$

$$E \quad 1 \quad 1 \quad 1$$

Where $B = \frac{E}{L}$. $A_1 = \frac{V_{out}}{L}$. $A_2 = \frac{1}{C}$. $A_3 = \frac{1}{CR}$

L

Table 3-1 parameters of the buck converter of the electrosurgical system

| Parameter | |
|---------------------------------|------------|
| Input voltage | 11.11 V |
| Output voltage | 100 V |
| Efficiency | 90 % |
| Switching frequency of inverter | 500 KHZ |
| Output power | 110 W |
| Input DC current | 11 A |
| Input power | 122 W |
| R_{min} | 40 Ω 200 Ω |
| R_{max} | 50 W |
| Reference command | |

3.3 Slide Mode Control (SMC)

Slide Mode Control (SMC) is a non-linear control method, belonging to the Variable Structure Control (VSC) framework, which considered as one of the most efficient methods for designing robust control for high-order nonlinear dynamical systems. SMC methodology allows models to be inaccurate, as inaccuracies arise from structured (or parametric) and / or unstructured uncertainty (such as unmodeled dynamics) in the presence of disturbance inputs. The SMC performs models in accurate way by using the methodology of the sliding surface and equivalent control. Equivalent control replaces the discontinuous control on the intersection of switching surface by continuous control the low sensitivity to the variations of the system parameters and disturbances considers as the main advantage of the SMC design which eliminates the necessity of the exact mathematical modelling. The design of the SMC consists of two step: the first one is the designing of the sliding surface, on which the state trajectory of the system is forced to the sliding surface. In the second step, the control law designed such that the system remains on the sliding surface. Therefore the sliding mode control design includes the performing of the sliding surface as well as control design law [40]. The state trajectory behavior for a typical second order system using sliding mode control is depicted in Figure 3.1.

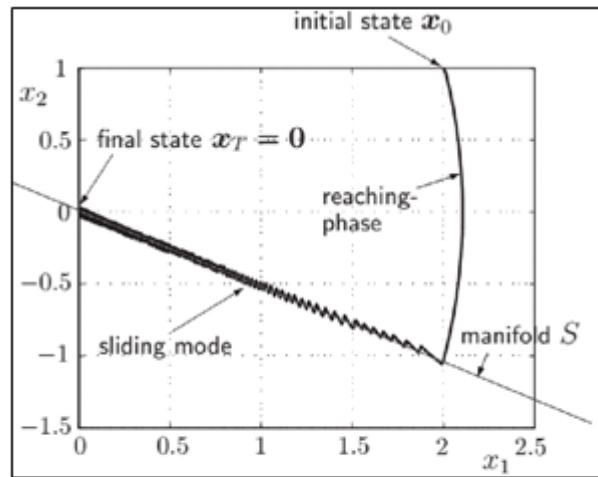


Figure 3-1 sliding surface [19]

Sliding mode was performed in the dynamic system governed by ordinary differential Equation s with discontinuous parts in the right hand side [41].

Consider a system modeled by a set of first order differential Equation s as:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (3-13)$$

Where, $x(t) \in R^n$ is a state vector, $u(t) \in R^m$ is a control vector, and **A**, **B** are known non zero constants. Take a sliding variable $s(x) = Gx$, then a sliding manifold is described by $s(x) = Gx = 0$, where $G \in R^{m \times n}$. In addition, when the system trajectories are located on the manifold, the system behavior satisfies a specified control objective. Then, suppose that the control signal is designed so that it is capable of forcing the system trajectories from any initial state to reach the manifold in finite time and it slides on it. Mathematical details and application of such an approach are named sliding mode control

Since the sliding mode control relates with state feedback control which employs switching control actions, the control input $u(t)$ is selected as a discontinuous function of the system state;

$$u^+ \text{ if } s(x) > 0$$

$$u^- \text{ if } s(x) < 0 \quad (3-14)$$

Where, the sliding variable $(x): R^n \rightarrow R^m$ is a continuously differentiable function. The feedback signal (t) exhibits a point of discontinuity at $s(x) = 0$. The SMC is designed as a discontinuous function of the system states such that each component undergoes discontinuities in some surface in the system state space of dimension $(n - m)$ [42].

In SMC, the system path begins from an first point in state space at time instant $t = 0$, then the sliding mode controller must force the path to reach the sliding surface $(x) = 0$ after fixed time interval and remain on it. Moreover, for all $t \geq 0$, the velocity vectors of the state trajectory are always directed toward the sliding surface. This can be derived using the Lyapunov method of stability, which requires finding a suitable Lyapunov function (x) . To perform the stability, positive definite multiply by its derivative $V(x)$ should be negative definite [42]. The candidate Lyapunov function (x) can be taken as:

$$V(x) = |s|$$

Differentiating (x) yields (3-15)

$$V(x) = \text{sig}(s) \dot{s} \quad \forall s \neq 0 \quad (3-16)$$

In order to $V(x) < 0$, the following inequality must be held:

$$\text{sign}(s) * \dot{s} < 0 \quad (3-17)$$

The inequality in Equation (4.5) is named as the sliding condition. Alternatively, equivalent control approach analyzes the motion during sliding mode. In which the discontinuous control (which brings sliding modes to $(x) = 0$ is replaced by an equivalent control which be continuous. The equivalent control is obtained by setting $\dot{s}(x) = 0$ for the nominal system. During sliding motion, sliding implies $(x) = 0$ for $t > ts$, therefore, $\dot{s}(x) = 0$ which may be used to describe the state paths during sliding mode. The rapid switching control u is a problem for using conventional sliding mode control methods, so it disregards the control discontinuities and calculates the vector u , such that the time derivative of vector s on the state trajectories is equal to zero. For the system in Equation (4.1), the equivalent control is [54]

$$u_{eq} = -(GB)^{-1} GA x(t) \quad (3-18)$$

The motion in sliding mode was considered as an ideal motion. It was assumed that the change in control occurs at high, theoretically infinite, frequency, such that the velocity vector state is oriented exactly on the intersection of discontinuity surfaces. However, in reality, many defects put the state oscillate in some region near the intersection, and control components are transformed at finite frequency alternatively taking the values $u^+(x)$ and $u^-(x)$. These oscillations have high frequency and slow components. The oscillations with high frequency was filtered system under control process, in the same context, the motion of the system in sliding mode is performed by component of slow frequency. Conversely, the Equations of SMC were determined by replacement of equivalent control for the real control.

Controller of ESG unit

Let us the state error is:

$$e_2 = x_{2r} + x_2 \quad (3-19) \quad e_2 = \dot{x}_{2r} + \dot{x}_2 \quad (3-20)$$

Assume the sliding surface is

$$s = \dot{e} + c \quad (3-21)$$

By combining (3-11), (3-12), (3-19), (3-20)

$$\dot{s} = \ddot{e} + C \dot{e}$$

$$= C(\dot{x}_{2r} - \dot{x}_2) + \ddot{e}$$

$$= C(\dot{x}_{2r} - A_2 x_1 + A_3 x_2) + \ddot{e} \quad (3-22)$$

The virtual control , which express the current of the buck converter

Since the condition of sliding control $ss' = 0$

$$s [C(\dot{x}_{2r} - \dot{x}_2) + \ddot{e}] = 0 \quad (3-23)$$

$$(C [\dot{x}_{2r} - A_2x_{1r} + A_3x_2] + \ddot{e}) \div C$$

$$\dot{x}_{2r} - A_2x_{1r} + A_3x_2 + \ddot{e} = 0$$

C

1

$$x_{1r} = [\dot{x}_{2r} + A_3x_2] + \ddot{e} \quad (3-24)$$

$A_2 \quad C$

Now drive the actual control law ,the second state error is defined as in equation below :

$$e_1 = x_{1r} - x_1 \quad (3-25)$$

$$\dot{e}_1 = \dot{x}_{1r} - \dot{x}_1 \quad (3-26)$$

$$s = \dot{e}_1 + Ce_1 \quad (3-27)$$

$$s' = \ddot{e}_1 + C\dot{e}_1 \quad (3-28)$$

$$= C[\dot{x}_{1r} - \dot{x}_1] + \ddot{e}$$

$$= C[\dot{x}_{1r} - uB - A_1x_2] + \ddot{e} \quad (3-29)$$

Applying the condition of sliding mode control $ss' = 0$

$s [C[\dot{x}_{1r} - uB - A_1x_2] + \ddot{e}] = 0$ Therefore, the actual controller u:

$$u = \frac{1}{B} (\dot{x}_{1r} - A_1x_2) + \ddot{e} \quad (3-30)$$

$B \quad C$

Next is the inverter stage to which the power is fed by the buck converter. For the corresponding tissue impedance, the output voltage and current at the output of the buck converter will vary subject to the condition that the product (power) is constant. Now, the inverter unit cannot be made an open loop. So, the reference voltage generated at the output of the power controller x_{2r} is made as a reference for the boost inverter unit and the measured RMS voltage forms the output of the inverter which served as feedback. Thus, an additional voltage loop is regulating the output voltage of the inverter for a specified tissue impedance and constant power.

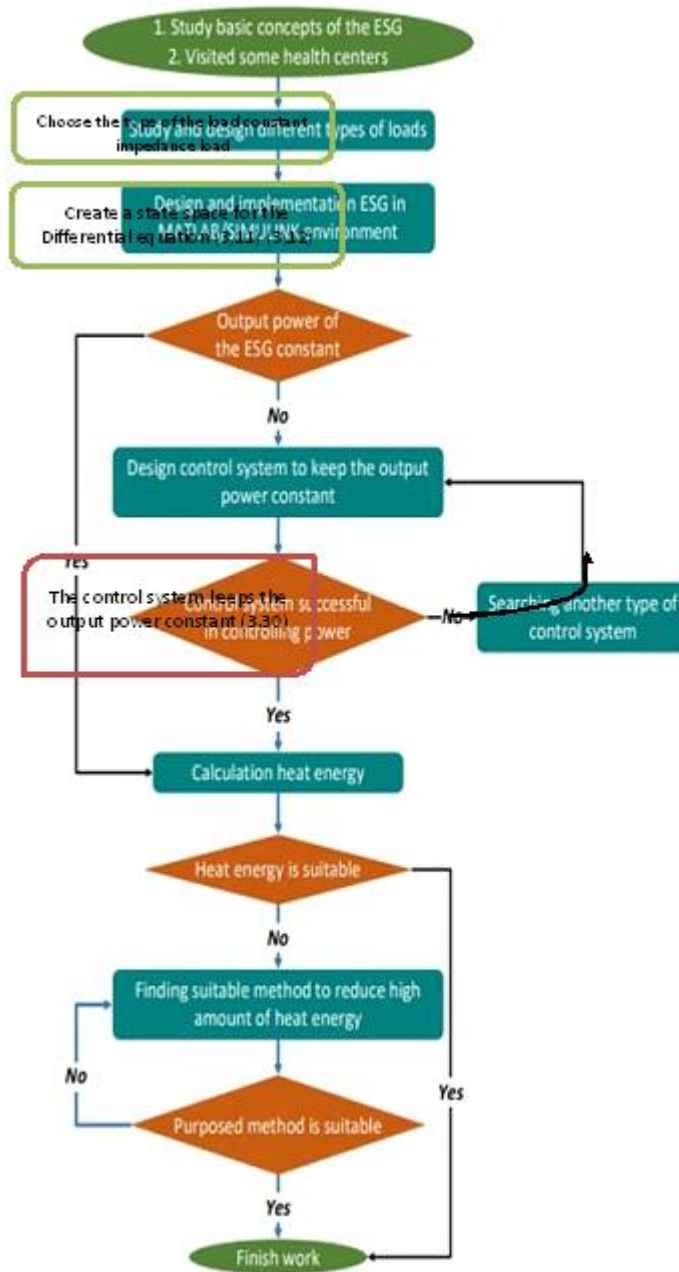


Figure 3.2 Flow chart of the controller design.

4. RESULTS AND DISCUSSION

4.1 Overview

The result obtained by apply SMC equation by using matlab to perform the coding of the state space and controllers

4.2 Results and Discussion

The current chapter is devoted to presenting the results and their discussion for controller system of the electrosurgical system. In this chapter, only one case of tissue impedance was assumed i.e. fixed load impedance.

Firstly, the open loop of voltage and power are calculated under fixed load, figure (4-1) and (4-2) respectively. In an open loop, the voltage is very high and achieves its steady-state condition at almost 100 V after a transient of almost 0.002 s.

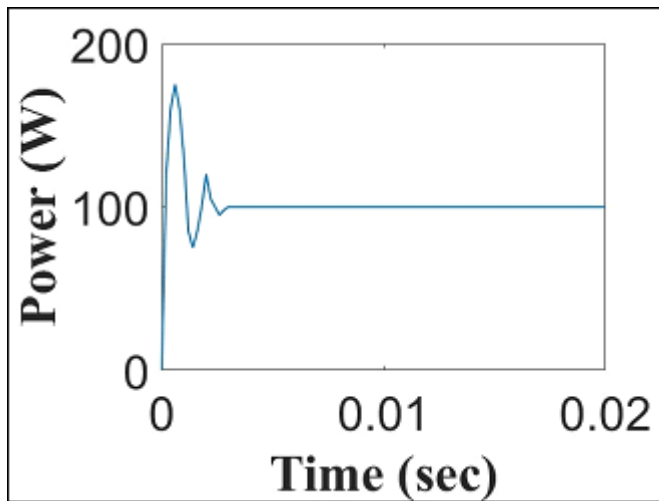


Figure 4-1 open loop power response under fixed load

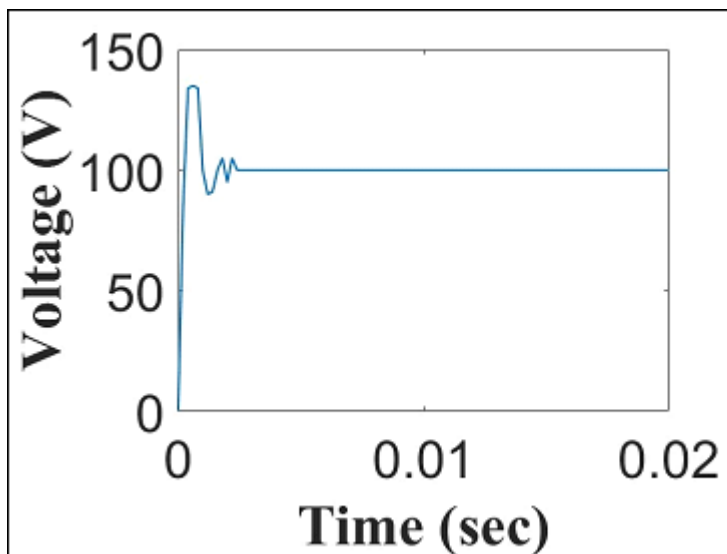


Figure 4-2 open loop voltage response under fixed load

Likewise, the power in the open loop is recorded to be approximately 100 W during a steady state. This disadvantage of the open-loop system is that at the desired power cannot be achieved as no reference following loop is considered. For this issue, a closed-loop system is required to keep the power fixed according to the desired application. The same fixed load case of 100Ω is tested under closed-loop controllers with a reference power of 50 W. Results of voltage and power responses of the ESG unit with closed-loop control and fixed tissue impedance are shown in figure (4-3) and (4-4) respectively.

For a fixed load, the voltage and power are reduced to roughly 74.2 V and 48 W, respectively, for both closed-loop controllers. The transient time lasts for almost 0.005 s, it lasts only for 0.0005 s. It is evident from the basic laws of electronics engineering that the

higher voltage and power can inflict severe or at least unwanted penetration during the time of application especially when it is the case of human tissues. This reduction and regulation in voltage and power is the obvious evidence that the closed loop system is better in terms of a precaution for human safety.

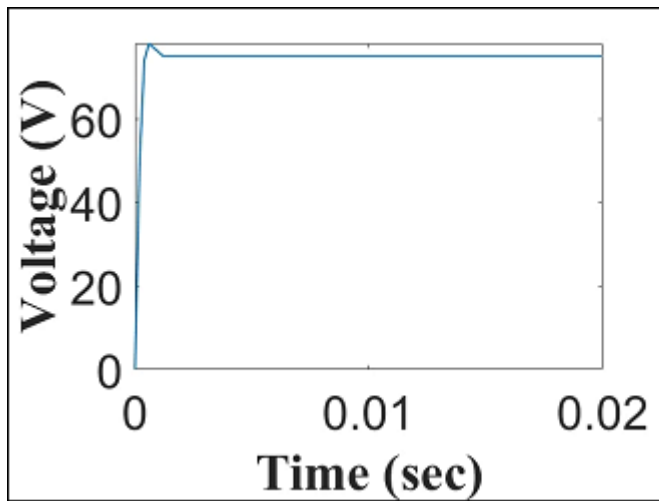


Figure 4-3 closed loop voltage response under fixed load

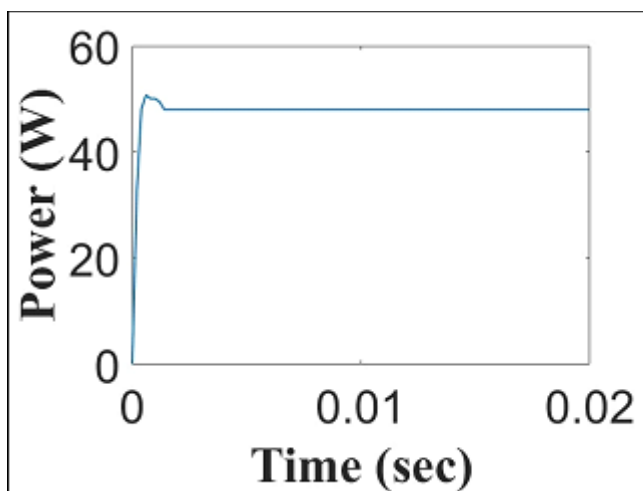


Figure 4-4 closed loop power response under fixed load

5.1 Conclusion

This paper presents an inverter topology and control algorithm which combines current- and voltage-mode control to realize the desired output characteristic of an electrosurgical generator in a markedly simpler and more accurate fashion. By directing which of the two conversion stages is to be current mode controlled, constant power, constant current, and constant voltage outputs can be achieved with excellent regulation and fast transitions. Effective regulation of an ESG's output is critically important to achieving the desired clinical effects. If output power is allowed to exceed the desired value, excessive thermal spread will occur, unnecessarily damaging and scarring tissue and impeding healing. If maximum output voltage exceeds the limiting value, charring of tissue will occur, which is frequently undesirable as it may unnecessarily damage tissue and obscure the surgical field. Use of our dual current-mode control scheme in an ESG can provide near-deadbeat regulation of output power, ensuring that thermal spread is minimized by accurately supplying the specified power in each individual cycle. In addition, fast and accurate regulation provided by the constant voltage mode minimizes unintentional tissue charring. Thus, reduced thermal spread and charring should result in better surgical outcomes by reducing scarring and decreasing healing times.

5.2 Recommendations

- ✓ Use another controller method for the regulation process
- ✓ Use variable bio impedance tissues in the modeling of the electrosurgical system

- ✓ Performing experimental simple model for the electrosurgical system

References

1. A. I. Alzaidi, A. Yahya, T. T. Swee, and N. Idris, "Development of high frequency generator for bipolar electrosurgical unit," *International Journal of Engineering and Technology (UAE)*, vol. 7, no. 2, pp. 20–23, 2018.
2. H. Sarnago, O. Lucia, Senior, and J.M. Burdio, "High frequency and power density gallium nitride based inverter for magneto fluid hyperthermia." *IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society*, pp. 5222-5225. IEEE, 2016.
3. B. Grzesik and M. Stepień, "Power electronics in biomedical applications-An overview." *2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC)*.
4. Ariana Eginli,, Wasim Haidari, Michael Farhangian,, Phillip M. Williford, "Electrosurgery in dermatology." *Clinics in dermatology*, vol. 39, no. 4, pp. 573-579, 2021.
5. Christopher Sutton and Jason Abbott, "History of power sources in endoscopic surgery." *Journal of Minimally Invasive Gynecology*, vol. 20, no. 3, pp. 271-278, 2013
6. Arash Taheri, Parisa Mansoori, Laura F. Sandoval, Steven R. Feldman, Daniel Pearce and Phillip M. Williford, "Electrosurgery: part I. Basics and principles." *Journal of the American Academy of Dermatology*, vol. 70, no. 4, pp. 591-e1., 2014.
7. K. Charoenkwan, Z. Iheozor-Ejiofor, K. Rerkasem and E. Matovinovic "Scalpel versus electrosurgery for major abdominal incisions." *Cochrane Database of*
8. Prashant Babaji, Vikram Singh, Viswajit Rampratap Chawrasia and Manisha R Jawale, "Electro surgery in dentistry: Report of cases." *J Pediatr Dent [Internet]*, vol. 1, no. 2, 2014.
9. Taras V. Nechay, Svetlana M. Titkova, Mikhail V. Anurov, Elena V. Mikhalechik , Kirill Y. Melnikov-Makarchyk , Ekaterina A. Ivanova , Alexander E. Tyagunov , Abe Fingerhut and Alexander V. Sazhin , "Thermal effects of monopolar electrosurgery detected by realtime infrared thermography: an experimental appendectomy study." *BMC surgery*, vol. 20, no. 1, pp. 1-12., 2020.
10. mitry V. Belik, Aleksander V. Shekalov, Nikolay A. Dmitriyev, Sergey A. Bogayev and Konstantine Dornhopf, "Development of RadioFrequency Electrosurgical Unit EHVCh1.76." *2018 XIV International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE)*, pp. 349-351. IEEE, 2018.
11. Petros C. Benias and David L. Carr-Locke, "Principles of electrosurgery." *Ercp. Elsevier*, pp. 86-92, 2019.
12. Irina A. Vladimirov Yuri N. Lankin, Igor B. Philyppov, Lyudmyla F. Sushiy, and Yaroslav M. Shuba, "Frequency dependence of excitation– contraction of multicellular smooth muscle preparations: the relevance to bipolar electrosurgery." *Journal of Surgical Research*, vol.186, no. 1, pp. 119-125, 2014.
13. Wang and A.P. Advincula, "'Current thoughts" in electrosurgery." *International Journal of Gynecology & Obstetrics*, vol. 97, no. 3, pp. 245-250, 2007.
14. C. Randle Voyles, "The art and science of monopolar electrosurgery." *The SAGES manual on the fundamental use of surgical energy (FUSE)*. Springer, New York, NY, pp. 81-91, 2012.
15. Elton Dias Jr, Bertoldo Schneider Jr and Evaldo Ribeiro, "On the origin of skin burns and neuromuscular electrical stimulation as a consequence of electrosurgical procedures." *Research on Biomedical Engineering*, vol. 35, no. 2, pp. 111-122., 2019.

16. Manjunath Siddaiah-Subramanya, Kor Woi Tiang and Masimba Nyandowe, "Complications, implications, and prevention of electrosurgical injuries: corner stone of diathermy use for junior surgical trainees." *The Surgery Journal*, vol. 3, no. 04, pp. e148e153, 2017.
17. Mohsen El-Sayed, Sahar Mohamed and Ertan Saridogan, "Safe use of electrosurgery in gynaecological laparoscopic surgery." *The Obstetrician & Gynaecologist*, vol. 22, no. 1,
18. Asad J. Choudhry, Nadeem N. Haddad, Mohammad A. Khasawneh, Daniel C. Cullinane, Martin D. Zielinski, "Surgical fires and operative burns: lessons learned from a 33-year review of medical litigation." *The American Journal of Surgery*, vol. 213, no. 3, pp. 558564., 2016.
19. Frédérique C. Meeuwsen, Annetje C. P. Guédon, Ewout A. Arkenbout, Maarten van der Elst, Jenny Dankelman and John J. van den Dobbelen, "The art of electrosurgery: trainees and experts." *Surgical innovation*, vol. 24, no. 4, pp. 373-378, 2017.
20. Ümit Özdemir, Ahmet Karayiğit, İhsan Burak Karakaya , Dursun Burak Özdemir, Hayrettin Dizen , İltar Özer , Bülent Ünal, "Is electrosurgery a revolution? Mechanism, benefits, complications, precautions." *Journal of Pharmaceutical Technology*, vol. 1, no. 3, pp. 60-64, 2021.
21. Kevin Bree, Spencer Barnhill Spencer Barnhill, and William Rundell William Rundell, "The dangers of electrosurgical smoke to operating room personnel: a review." *Workplace health & safety*, vol. 65, no. 11, pp. 517-526, 2017.
22. Ayesha J. Dalal and Andrew S. McLennan, "Surgical smoke evacuation: a modification to improve efficiency and minimise potential health risk." *The British journal of oral & maxillofacial surgery*, vol. 55, no. 1, pp. 90-91, 2016.
23. Guideline for electrosurgical safety Denver AORN V114 N1 P65 2021
24. Electrosurgical generators Ismael Cordero Community Eye Health V 28 (89) P(6-16) 2015
25. Electrosurgery with cellular precision Palanker DV, and others *IEEE Trans Biomed Eng* 55:838–841. 2008.
26. Electrosurgery Kieran Gallagher; and others 29(2), 70-72 2011.
27. Exploring difference between Bipolar and Monopolar modes on electrosurgical units Becky Crossley *AAMI ARRAY* 53(2):152-153 2019.
28. Petros C. Benias, David L. Carr-Locke, *Principles of Electrosurgery ERCP (Third Edition)*, charter11 Elsevier Pages 86-92 2019.
29. Ahmad Taher Aza "Control Applications for Biomedical Engineering Systems" Elsevier Pages 151-153 2020.
30. Electrosurgical generators Jeffrey L. Tokar, MD, et al. Elsevier | VOLUME 78, ISSUE 2, P197-208, 2013.
31. Electrosurgical generators Adam Slivka, MD, PhD Elsevier VOLUME 58, ISSUE 5, P656-660, 2003.
32. Electrosurgery Part II. Technology, applications, and safety of electrosurgical devices Taheri, Arash and Mansoori ,et al. Elsevier volume={70}, 2014.
33. Ali Mohammed Ridha, Ali Jafer Mahdi, Jameel Kadhim Abed , Shah Fahad.
34. Nimitha Gopinath Praveen Kumar *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE vol.13,pp52-60)* .

-
35. Daniel A. Friedrichs, Student Member, IEEE, Robert W. Erickson, Fellow, IEEE, and James Gilbert, Member, IEEE IEEE TRANSACTIONS ON BIOMEDICAL CIRCUITS AND SYSTEMS, VOL. 6, NO. 1, FEBRUARY 2012.
 36. Scott Jensen, Dragan Maksimovic Colorado Power Electronics Center ECEE Department, University of Colorado, Boulder, Daniel Friedrichs, James Gilbert Covidien Surgical Solutions 978-1-4799-6735-3-15-2015 IEEE.
 37. Hussban Abood Saber, 29 October 2021; Revised: 12 December 2021; Accepted: 14 December 2021.
 38. Scott Jensen, * Fast Tracking Electrosurgical Generator Using Two-Rail Multi-Phase Buck Converter with GaN Switches 2015 IEEE.
 39. Ali Idham alzaidi , *Development of high frequency generator for bipolar electrosurgical unit, Accepted: 14 December 2021.
 40. Vlad Bluvshstein, Member, IEEE, Lori Lucke, Member, IEEE, Matt Widule , 2019
 41. NasimUllaha , Muhammad Mohsin Rafiqb , M. Ishfaqc , Mumtaz Alid , Asier Ibease , Jorge Herreraf a Department of Electrical Engineering, College of Engineering, Taif University, Taif, Kingdom of Saudi Arabia, 2020
 42. W. L. J. J. E. Slotine, Applied Nonlinear Control. Englewood Cliffs, New Jersey: Prent