Current waveform analysis for arc control in electrosurgical devices

Viktor Tomov, Ivo Iliev, Vessela Krasteva

Current trends in electrosurgery include digital algorithms and methods to control the effect of delivered energy to the patient. Process control of the delivered radio frequency power is used for various tissue treatments. A control unit in the form of digital signal processor (DSP) or field programmable gate array (FGPA) could be used to automatically supply the appropriate power. During a regular electrosurgical procedure i.e. cutting, coagulation or desiccation, electrical sparks are formed as part of the process. Electrosurgical sparks can create undesirable physiological effects like tissue carbonization and burns. This paper shows an experimental method for high-resolution monitoring of the output current waveform in the process of arcing. The recorded signals provide evidence that current waveform high-pass filtering and amplitude spectrum analysis are meaningful approaches for automatic discrimination between conditions of no arcing, low arcing and high arcing.

Keywords – Electrosurgery, Spark detection, Current waveform, Feedback, Digital control

Анализ на формата на изходния ток за контрол върху процеса на искрене в електрохирургически апарати (Виктор Томов, Иво Илиев, Весела Кръстева). *Съвременните тенденции в електрохирургията включват използването на цифрови алгоритми и методи за контрол на ефекта от приложената енергия върху пациента. Управлението на процеса за прилагане на радио-честотна мощност се използва при различни процедури за третиране на тъкани. Контролиращо устройство от типа на цифров сигнален процесор или чип с програмируема логика може да се използва за автоматично титриране на необходимата мощност. По време на обикновена електрохирургическа процедура, включваща рязане, коагулация и изсушаване, възникват електрически искри. Тези искри могат да причинят нежелани физиологични ефекти, като овъгляване и изгаряне. Това изследване представя експериментален метод за регистриране на изходния ток с висока резолюция по време на искрене. Записаните сигнали доказват, че високочестотна филтрация и анализ на амплитудния спектър на тока при електрохирургия са подходящи за автоматично разпознаване на различни условия на работа, в т.ч. без искрене, ниски и високи нива на искрене.*

Introduction

Basically, electrosurgery is the use of radio frequency (RF) alternating current (AC) to rise the intracellular temperature in order to achieve vaporization or the combination of vaporization with protein dehydration. These surgical effects are also known as cutting and coagulation of the tissue. There are at least two basic mechanisms whereby RF electricity increases cellular and tissue temperature [1]. The majority of heat is an electrical effect of the intracellular and extracellular ions (commonly include electrolytes Na+, Cl-, Ca++, Mg++, etc.) which act as a media for the high frequency current. Therefore, a resistance is encountered by ionic movement as ions collide with other molecules, resulting to heat generation. The other part of the heat is from net tissue resistance or conductive heat transfer [2], [3].

The central concept in electrosurgery is that any current passing through the tissue will dissipate energy as heat [4]. Joule's law commonly approximates the energy quantity in electrosurgical therapy: $Q = I^2 \times R \times t$, where Q is energy (joule, J), I is current (A), R is electrical resistance (Ω) and t is the time interval for current to flow. As the electrodes have relatively small amount of impedance compared to the tissue, the current passing through the closed circuit will dissipate the energy in the form of heat into the tissue resistance. When current carrying electrodes are brought into contact with the tissue, the current spreads out in the tissue volume.

In a monopolar system, the active electrode is relatively small, leading to high current density. On the other side, the dispersive electrode is large enough so that the contact electrode-tissue impedance is low, resulting in low current density and low heat dissipation. Assuming adiabatic conditions and no phase difference between the current and voltage (no reactive components), the temperature rise in the tissue volume can be approximated using the function [4]

$$(1) \qquad \Delta T = J^2 t / \sigma\rho c$$

where ΔT is the temperature rise, σ is the tissue electrical conductivity, *c* is specific heat capacity and ρ is the tissue density. Presuming an idealized model of a round electrode positioned in a medium, the power density is inversely proportional and falls off rapidly with the distance to the electrode

$$(2) \qquad W_v = \sigma V^2 a^2 / r^4$$

where V is the output voltage, a is the radius of the electrode and r is the distance from the electrode.

One aspect in electrosurgery is to control the temperature and the time of the tissue exposure to this temperature. Applying exact amount of energy to achieve specific thermal effect is vital for patient recovery. Adverse thermal spread should be reduced to minimum. The mechanisms to control the tissue temperature exposure are closed loop systems using feedback parameters, such as temperature sensors, current and voltage waveform recognition, smart impedance sensing or combination between different methods.

The aim of this paper is to present the current trends for advance power control and spark detection. Experiments are performed to observe the process of arcing and its effect on the output current waveform.

Arcing and cutting effects on tissue

Due to the power dissipation, the tissue temperature increases, with highest temperatures right next to the active electrode. Some cytochemical processes occur in a tissue volume experiencing temperature increase up to 45°C. However, those processes are reversible and the tissue cells return to their normal state. In general, temperatures above 45°C cause breakdown in the living structure and degradation in the protein molecule. Depending on the applied time, temperatures between 45°C and 60°C solidify the proteins inside the cells during a process named coagulation. Up to 100°C slow boiling of the intracellular fluid occurs. As a result, several cells link up and form welding effect, which stops bleeding. Around 100°C vaporization of the tissue fluid within the cell membrane occurs, resulting in an explosion of the cells and forming a steam around the electrode. This process is termed electrotomy or cutting. Further increase of the temperature is causing carbonization of the tissue, leading to electrical impedance increase and lowering the current density [5].

During the cutting procedure, a desiccation close to scalpel electrode is formed. This desiccation pushes away the tissue front so that a gap between the active electrode and the tissue itself is formed. This gap is filled with various vapours during the electrotomy process (Fig.1). The steam channel makes good condition for sparks to break through between the electrode and the desiccated tissue. Due to the high current, whenever a spark is created on a local point, carbonization takes place in a small area around the electrode. Observations show that the degree of carbonization is increased with the increase of the light emissions around the active electrode. Furthermore, the intensity of arcing is highly dependent on the tissue type [6]. Carbonization effect is influenced mostly from the amount of sparks instead of the applied power. In order to minimize the unnecessary carbonization and tissue necrosis, it is assumed that the cut procedure mechanism should include feedback control not only based on the output power but also on the spark rate [6].

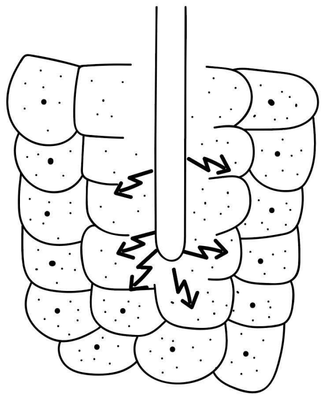

Fig.1. Sparks inside the steam channel while cutting.

Current waveform performance under arcing conditions

To generate a spark, electric field is developed reaching a high enough value for creating a medium for breakdown. Typically, a breakdown could be achieved at 3 MV/m for dry air [7].

Fig.2 shows the volt-ampere (V/A) characteristic of an electrosurgical process, which includes arcing conditions. The hysteresis is due to the intrinsic circuit reactance and the thermal misbalance between the particles [7]. The current is having small increment till 500 V, while significant positive increment is observed from 500 V to 1000 V. The latter represents conditions where arcing process is formed [7]. We can conclude that during spark formation a rapid current increase is observed overlayed with the sine wave output of the generator. Furthermore, sparks could be detected by the rapid peaks in the current-time waveform [6].

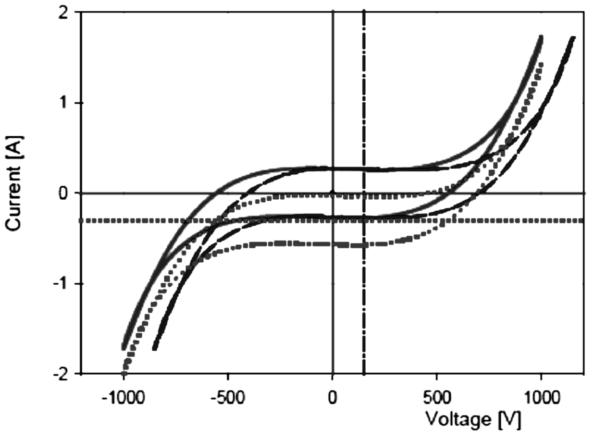

Fig.2. Electrical VA characteristic of the electrosurgical process [7].

Closed loop control and digital processing while arcing in electrosurgical system

Most of the electrosurgical generators on the market support operator-driven adjustment of the output power. Depending on the specific procedure, the proper power level could be manually selected. Some typical power values are listed in Table 1 [5].

Table 1

Typical surgical procedures using electrosurgical generators

Power Level	Procedures
Low power	
30 W cut	Neurosurgery
30 W coagulation	Dermatology, Plastic surgery
Medium power	
30 W - 150 W cut	General surgery
30 W - 70 W coagulation	Major vascular surgery
High power	
150 W cut	Transurethral resection
70 W coagulation	Ablative cancer surgery

In order to achieve the required performance, a digital power control unit could be implemented in the electrosurgical device. Computer-based systems are available for continuous monitoring of the current and voltage levels; therefore, an automatic power adjustment could be implemented to preserve the surgical effect while working on different types of tissues with various electrical impedances. The design of such system is presented in Fig.3. The output signals (V_{SENS}, I_{SENS}) are monitored and digitized by analog to digital converters (A/D). Furthermore, the computing unit implements a signal processing algorithm for calculation of the optimal power delivery. The result is used to take the decision for increment or decrement of the generator's output current in order to maintain the set power demand. Moreover, the digital signal processing of the current and voltage data streams could be used to further recognize distinguishable waveform characteristics under specific operating conditions, i.e. while arcing or drying out of tissue [8].

If we consider that the arcing process includes rapid current spikes or high frequency components, a high frequency filter could be implemented to detect this specific condition. A simplified digital high-pass filter in the form of first-difference differentiator of the successive samples *x(n), x(n-1)* (Eq.3) is appropriate [9]

(3) $$y(n) = x(n) - x(n-1) .$$

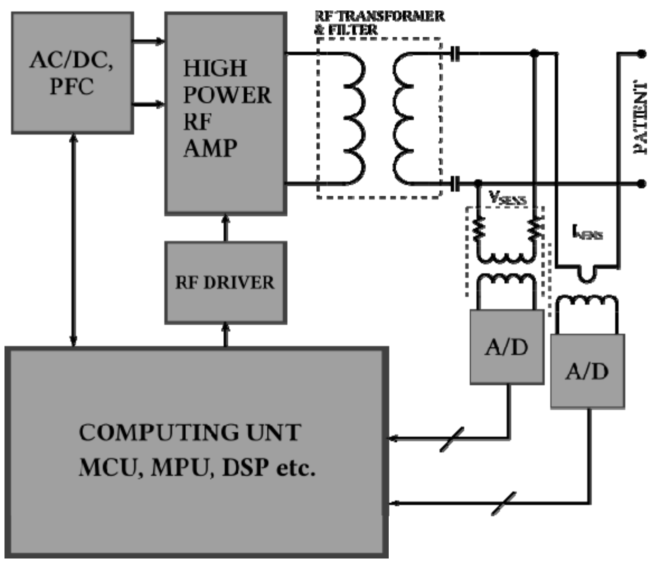

Fig.3. Simplified block diagram of a closed loop scheme.

More complex method to analyze the voltage and current data streams is to perform discrete Fourier transform (DFT). The DFT of a sample vector *X(j)* with length *n* is defined as follows:

(4) $$Y\left(\frac{k-1}{nT}\right) = \sum_{j=1}^{n} X(j) e^{\frac{(-2\pi i)(j-1)(k-1)}{n}} ,$$

where k follows the sequence 1 to n, j is the sample from the time domain vector and T is the sampling period [10].

We suggest that the design of an algorithm that analyzes the power spectrum Y could be a powerful solution for the reliable detection of spark conditions.

Experimental setup

A commercial electrosurgical generator is selected for the purpose of this experiment (Bovie's IDS-310 model). Fig.4 shows simplified block diagram of the measurement setup.

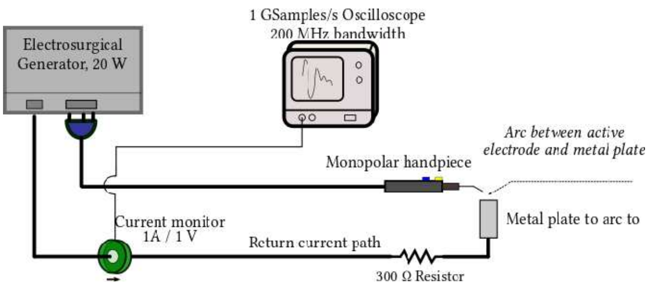

Fig.4. Experimental setup to investigate the current waveform in spark conditions.

The experiment is performed on a simulated patient tissue in the form of non-inductive resistance. To achieve consistent measurements, a 300 Ω resistor is connected between the neutral and the active electrode of the generator. The current waveform is recorded using high speed oscilloscope at various test scenarios described below. The sampling rate of the oscilloscope is 25 MS/s (the period between the samples is 40 ns).

Results

The experiments are performed while the electrosurgical generator is set to output power (20 W), cut mode (492 kHz sinewave), output load (300 Ω). The waveform is recorded in the following conditions:

- *No arcing* – both active and neutral electrodes are firmly connected to the non-inductive load. The snapshot of the waveform is shown in Fig.5.
- *Low arcing* – a metal plate is connected at one end of the load. Using the monopolar pencil with disposable electrode, the hand-piece is approached to the metal plate. The active electrode is moved and kept at distance from the metal plate, such that small arcing film is created. At this moment a snapshot of the waveform is recorded (Fig.6).
- *High arcing* – the same setup as in low arcing is used, but the distance between the active electrode and the metal plate is increased. Furthermore, more aggressive bursts of arcs are created. Snapshot of the waveform is recorded (Fig.7).

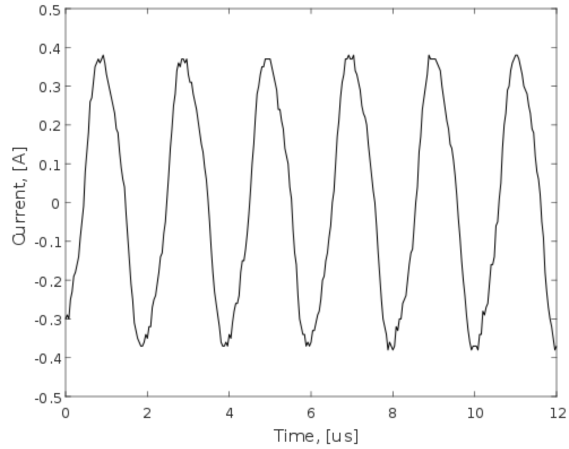

Fig.5. Current waveform, no arcing, 20 W power setting, 300 Ω output load.

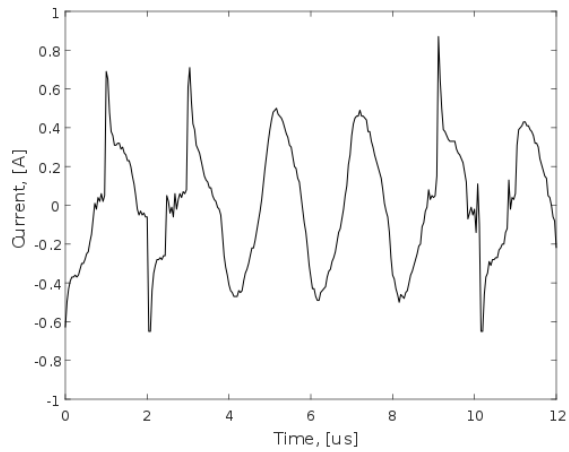

Fig.6. Current waveform, low arcing, 20 W power setting, 300 Ω output load.

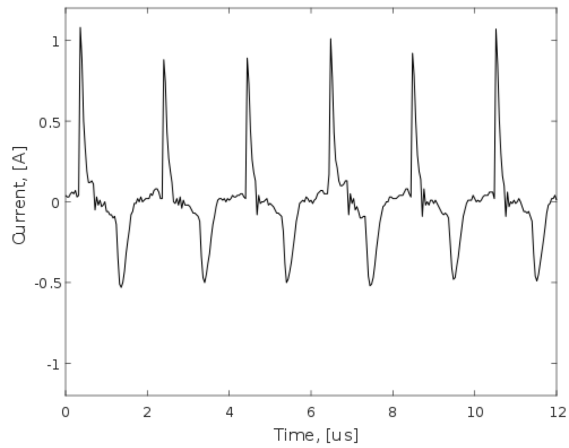

Fig.7. Current waveform, high arcing, 20 W power setting, 300 Ω output load.

All recorded current signals in Fig.5-Fig.7 are further passed through the first-difference filter (Eq.3), and the resulting high-pass components are illustrated in Fig.8-Fog.10, respectively.

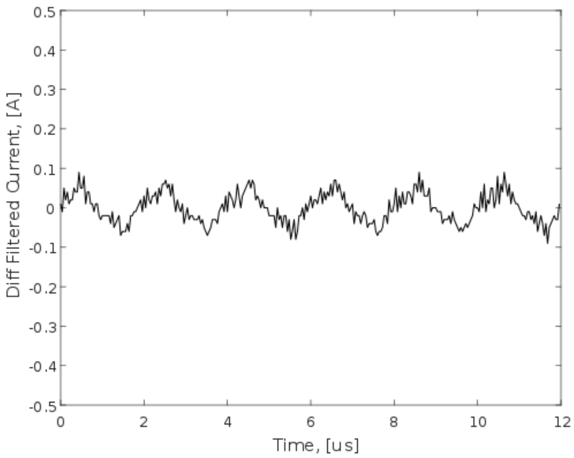

Fig.8. High-pass components of the current waveform in Fig.5, no arcing, 20 W power setting, 300 Ω output load.

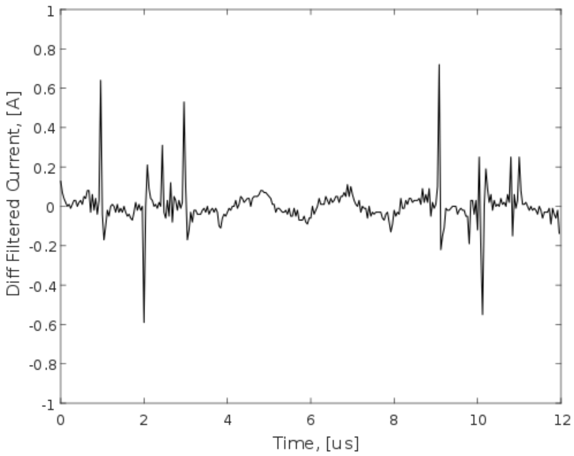

Fig.9. High-pass components of the current waveform in Fig.6, low arcing, 20 W power setting, 300 Ω output load.

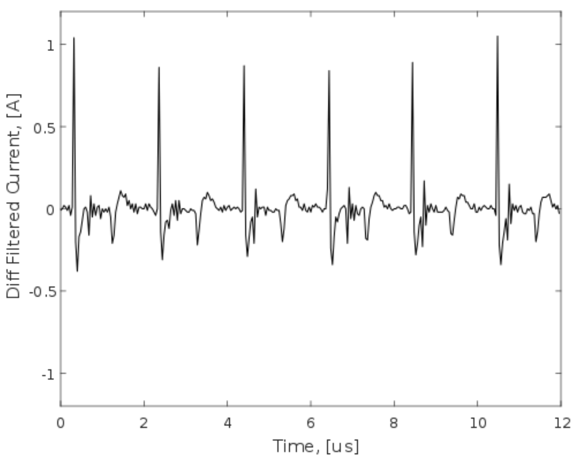

Fig.10. High-pass components of the current waveform in Fig.7, high arcing, 20 W power setting, 300 Ω output load.

At the next step, the DFT spectrum of all recorded current signals in Fig.5-7 is calculated and illustrated in Fig.11-13, respectively. The amplitude spectrum is represented up to the Nyquist frequency, equal to 12.5 MHz (half of the sampling rate).

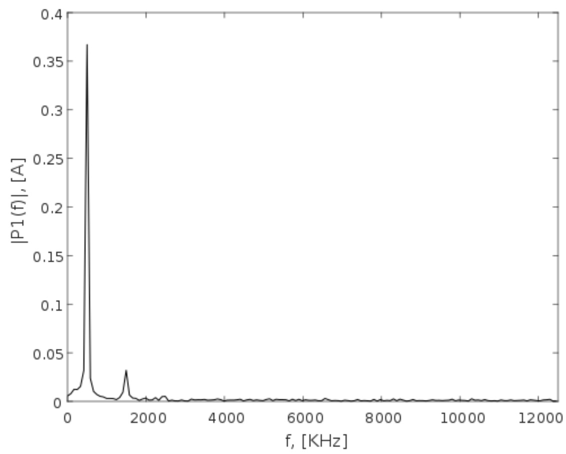

Fig.11. Amplitude spectrum of the current waveform in Fig.5.

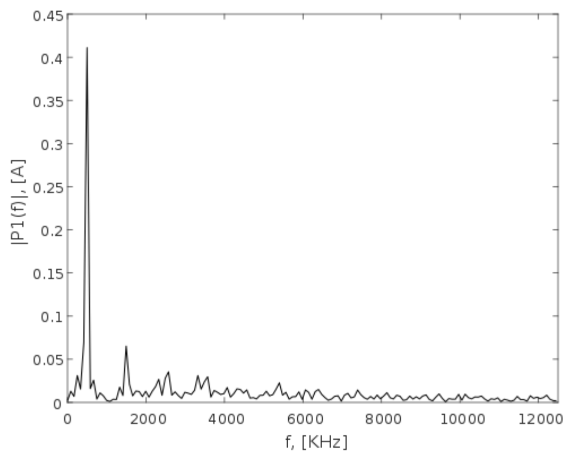

Fig.12. Amplitude spectrum of the current waveform in Fig.6.

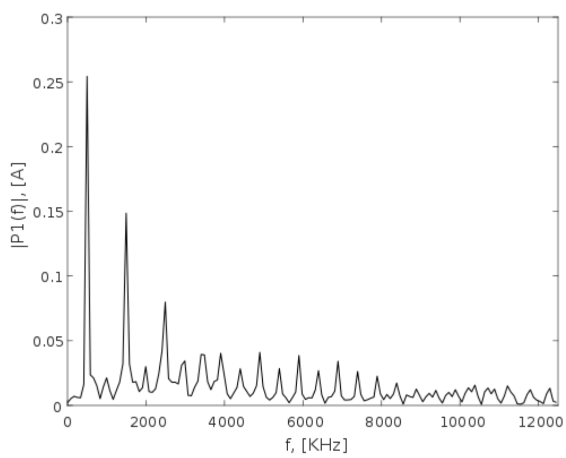

Fig.13. Amplitude spectrum of the current waveform in Fig.7.

Discussion and Conclusions

This work shows that sparks generate significant complexity of the current waveform. In particular, the arcing process adds high frequency components to the waveform. As shown in Fig.8-10, a simple first-difference filter could be used to enhance the high frequency components, where rapid current bursts during sparking conditions are recognized. Comparing Fig.9 (low sparks) to Fig.10 (high sparks), we see evidence that the more the arcing process is, the higher peaks in the high-pass filter output appear. For reference, we do not notice any peak bursts in the high-frequency current components without arcing.

Considering the DFT of the current waveforms (Fig.11-13), we can confirm that the higher sparks induce more high frequency components. In the first case of no arcing (Fig.11), the spectrum is formed mostly of the base harmonic (492 kHz) together with small amount of third harmonic (1476 kHz), which represents the output characteristic of the generator. In case of low arcing (Fig.12), additional high frequency components >2 MHz are observed. In the case of high arcing (Fig.13), the spectrum includes more frequency harmonics together with lower amplitude of the base frequency compared to low arcing in Fig.12.

To control the amount of arcing, current waveform analysis could be implemented in the form of:

- High frequency filter together with peak detection to measure the rate and periodicity of peak events.
- Crest factor (CF) measurement - CF is equal to the ratio of the peak value to the root mean square (RMS) value. Typically, the crest factor of a sinewave is 1.41. Rapid bursts in the sinewave current will lead to increase of the CF value.
- The increase of the current during a spark is introducing high frequency components. Low frequency moving average filter after a high-pass one could be implemented to detect the amount of arcing. Additionally, DFT could be introduced to detect the high order harmonics.

Advanced electrosurgical devices (Fig.3) include mechanism and sensors to measure the current waveform in a real-time process. A computing unit in the form of DSP or FPGA is appropriate to implement the above stated methods for spark control.

Further developments could include time and frequency domain signal processing of the measured waveforms for the design of loop algorithms for spark control. Moreover, the voltage and current waveforms could be synchronously proccessed and advanced measurements could be implemented in the spark detection algorithm, such as complex impedance monitoring and measurements on VA characteristics.

REFERENCES

[1] Feldman, L.S. et al. eds. The SAGES manual on the fundamental use of surgical energy (FUSE). Springer Science+Business Media, LLC 2012.

[2] Vilos, G., C. Rajakumar. Electrosurgical generators and monopolar and bipolar electrosurgery. J Minim Invasive Gynecol, 2013;20(3):279–287.

[3] Pfiedler Enterprises. Electrosurgery. An online continuing education activity, Denver, 2016.

[4] Frich, L. Radiofrequency ablation of liver tumors, an experimental and clinical study. University of Oslo, Faculty of Medicine, 2007.

[5] Eggleston, J.L., W.W. Von Maltzahn. Electrosurgical devices. CRC Press LLC, 2000.

[6] Wurzer, H., R. Maeckel, J. Lademann, H. Audring, D. Liess. A spark counter as a control unit of a radio frequency surgery device. IEEE Transactions on Biomedical Engineering, Vol. 44, 1997, pp. 831 – 838.

[7] Schneider, B., E. Dias, P.J. Abatti. How can electrosurgical sparks generate undesirable effects?. First IEEE Latin American Symposium on Circuits and Systems (LASCAS), 2010.

[8] Tomov. V. Modern Advances in energy based electrosurgical devices. Electronica, 2017, pp. 81–84.

[9] Lyons, R. A differentiator with a difference. Blog, November 3, 2007,
https://www.dsprelated.com/ showarticle/35.php

[10] Matlab documentation, Fast Fourier transform function (fft)
https://www.mathworks.com/help/matlab/ref/fft.html.

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