

Efficiency Performance Evaluation of A Second Stage GaN Based High Frequency Inverter for Electrosurgery

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Abstract

Electrosurgery is a medical device that provides a thermal effect using high frequency current. When the tissue load changes over a broad scale during surgery, it should maintain a constant output power, that mean the broad output and high frequency voltage must be supplied by electrosurgery. In this study, class D resonant inverter design based on GaN is presented for electrosurgery. Due to its resonant nature, the inverter is convenient for broad scale voltage regulation and inverter switches provide ZVS (Zero Voltage Switching) operation. The technical analysis and simulation result of the proposed class D resonant inverter for different cutting modes are given. As a result, it is aimed to design an electrosurgery with high efficiency and high frequency.

1. Introduction

The widespread use of electrosurgery is usually attributed to William T. Bovie. He discovered that alternate current at 250-2000 kHz frequency range could be used to cut coagulated tissue and achieve hemostasis and developed the first commercially available electrosurgical device [1]. Electrosurgery has great importance in surgery operations. Before the surgical procedure, the energy manually adjusted by the doctor is transmitted to the tissue from the device. The energy delivered is adjusted according to the type of tissue and clinical effects [2]. The cutting and coagulation processes are carried out using high frequency alternate current. A power generator that support high frequency alternate current provide the necessary effect for electrosurgery [3].

An electrosurgery produces alternate signals at fundamental frequency higher than 200 kHz and lower than 5 MHz to achieve clinical requirements such as cutting, coagulation, etc. [4]. Depending on the purpose and place of use, these devices can produce 15-400 Watts of energy [5]. The muscle stimulation is not occurred when the alternate current at 200 kHz and higher frequencies is applied to the tissues. [6]. Therefore, electrosurgical devices are generally designed at frequencies above 200 kHz to prevent muscle stimulation. As mention in Massarweh et al.'s 2006 study [7], different frequency applications and electrosurgery frequency range can be represented in the Fig. 1.

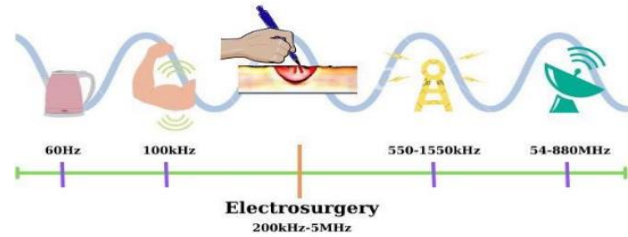


Fig. 1. Applications of different frequencies.

There are several modes of electrosurgery. The main modes are pure cutting, blend and coagulation modes. When these modes are examined, the pure cutting mode requires a continuous sine output voltage. In the blend mode, the aim is to heat and cool the tissue, that is, to perform both cutting and coagulation processes. So, the output must be in a modulated waveform. The third mode, coagulation mode, a sudden sine output is needed to ensure coagulation [8].

Studies on electrosurgery have been increased recently. These studies are generally on high efficiency and better operation performance [4, 9, 10].

GaN elements have been developed recently and are in great demand due to their high performance and power density [11]. In addition, since it is a semiconductor with a broad band gap, it has been used quite frequently [12]. In 2017, Sarnago et al. proposed a boost converter topology incorporating GaN elements to provide a high frequency and versatile electrosurgery generator. The rated output power is 50 W and the switching frequency is chosen as 1 MHz. The proposed study provides a high degree of versatility in waveform generation, opening a field of perspective to advanced surgical procedures [13].

In electrosurgery operation, the output power needs to remain constant as tissue load varies widely during surgery; this means that a broad scale output and high frequency voltage must be supplied by electrosurgery. In [9], a two-stage power conversion including resonance SEPIC (Single Ended Primary Inductor Converter) for the first stage and then class DE resonant inverter for the second stage is proposed to provide wide range output voltage regulation. The reason for using a resonant inverter is that it ensures ZVS operation for all semiconductors and is also suitable for large-scale voltage regulation. Large-scale voltage regulation expands the scope of electrosurgery. However, only the pure cutting mode is studied and the performance of other modes has not been evaluated in this work.

In the study of Bao and Mazumder in 2021, it was suggested the necessity of a VHFI (Very High Frequency AC Inverter) to power the electrosurgery and proposed a phase shifted full bridge based VHFI [10]. High order filter design that produces high frequency output is explained in the proposed study. For

the proposed VHFI, an experimental setup based on a 300 W GaN HEMT (Gallium Nitride High Electron Mobility Transistor) with an output frequency of 390 kHz was designed and the studies were developed according to this experimental setup. This study applied pure cutting, blend and coagulation modes required in electrosurgery operation [10].

In order to provide high efficiency alternate current generator for electrosurgery applications, resonant inverters are usually preferred due to their soft switching advantages. The most used inverters are class E, class DE and class D [9]. Class E inverter can also increase efficiency as it provides ZVS. However, the disadvantage of class E inverter is that it has high current and voltage stress across the switch [9, 14]. Class DE inverter performs ZVS like class E inverter, also it has low current and voltage stress. It also provides the appropriate AC voltage for the tissue at high frequencies, but the output voltage is difficult to control because the switching losses increase in a wide control range [14, 15]. Class D inverter has low voltage and current stress, and provides ZVS if certain conditions are met [14, 16].

In this study, class D resonant inverter topology was selected taking into consideration the its advantages mention earlier and an operation at higher frequency was preferred compared to similar works proposed in the literature. In the operation of the high frequency class D inverter, pure cutting, blend and coagulation modes were examined by concentrating on the second stage circuit. As a result, this study aims to design a high-efficiency, high-frequency, broad scale and low-volume class D resonant inverter for electrosurgery applications.

2. Operation Principles of High Frequency Class D Inverter

Class D resonant inverters were developed by Baxandall in 1959 and are widely used in a variety of applications to convert DC energy to AC energy [14].

The circuit schematic of the class D resonant inverter is shown in Fig. 2. A voltage source (V_{in}) contains four full-bridge MOSFETs (S_1, S_2, S_3, S_4), a series resonant (L_r, C_r) and a load (R_L). In addition, an isolated circuit has been realized by adding a transformer (T) at a turns ratio (n) of 1:1 to the circuit. The switching signals S_1 - S_2 and S_3 - S_4 are complementary to each other. The hard-switching feature offered by traditional class D inverter has been enabled to reach ZVS by changing certain conditions.

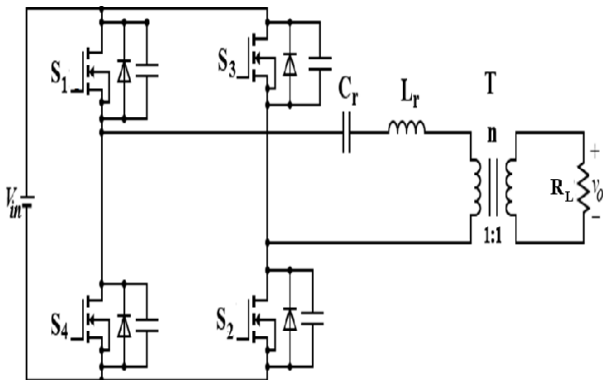


Fig. 2. The circuit schematic of class D resonant inverter.

The switching frequency can be at the resonant frequency, below the resonant frequency or above the resonant frequency. The circuit has capacitive characteristic if the switching frequency is selected below the resonant frequency. In this case, there is no loss at the turn-off transition of the switches, but switching losses occur at the turn-on transition. The opposite case the circuit is inductive. In this case, no loss occurs at the turn-on transition of the switches, but switching losses occur at the turn-off transition of the switches [17]. However, the inductive circuit provides soft switching if certain conditions are met [14]. The circuit is pure ohmic if the switching frequency is equal to the resonant frequency and the impedance of the circuit is at its lowest. In this case, the switches turn on and turn off under soft switching conditions. Therefore, the maximum power transfer to the load is ensured [17]. The resonant frequency of the class D resonant inverter is expressed as follows:

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (1)$$

Where L_r represents the inductance value of the series resonant inductor, C_r is the capacitance value of the series resonant capacitor.

High quality factor is preferred to achieve better THD. The quality factor can be found as follows:

$$Q = \frac{\omega L_r}{R} = \frac{1}{\omega C_r R} = \frac{Z_o}{R} = \frac{\sqrt{\frac{L_r}{C_r}}}{R} \quad (2)$$

Where Z_o is the resonant impedance value and ω is the angular frequency.

The series resonant inductor and the series resonant capacitor values can be extracted by

$$L_r = \frac{QR}{\omega} \quad (3)$$

$$C_r = \frac{1}{\omega QR} \quad (4)$$

3. Simulation Result

A preliminary study has already been carried out on this subject. The simulated circuit diagram of high frequency class D resonant inverter is given in Fig. 3. The circuit provides continuous sine wave output voltage at 600 kHz operation frequency while the output this power is 300 W and the input voltage is 200 V. Thus, pure cutting mode required in the electrosurgery operation is provided.

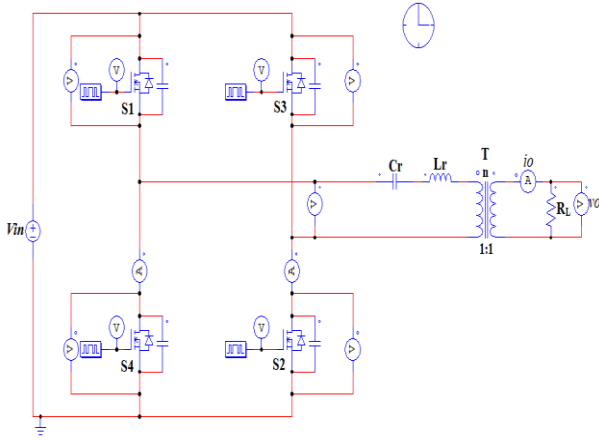


Fig. 3. The simulated circuit of proposed class D resonant inverter.

The component values used in the circuit diagram given in Fig. 3 are listed in Table 1.

Table 1. Simulation Parameters and Values

Parameter	Symbol	Value
Resonant capacitor	C_r	750 pF
Resonant inductor	L_r	100 μ H
Transformer turns ratio	n	1:1
Load resistor	R_L	50 Ω ~ 100 Ω
Switching frequency	f_{sw}	600 kHz

The currents waveforms of $S_1 - S_2$ and $S_3 - S_4$ switches are given in Fig. 4. As shown in the waveforms, $S_1 - S_2$ and $S_3 - S_4$ switches turn-on with ZVS.

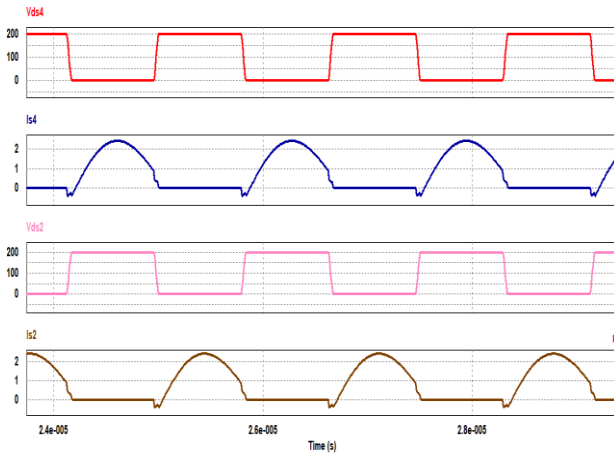


Fig. 4. The ZVS operation of $S_1 - S_2$ and $S_3 - S_4$ switches under pure cutting mode.

In Fig. 5 (a) and (b), the primary voltage waveforms and also continuous sine wave output voltage waveforms required for pure cutting mode at 50 Ω and 100 Ω load conditions are given.

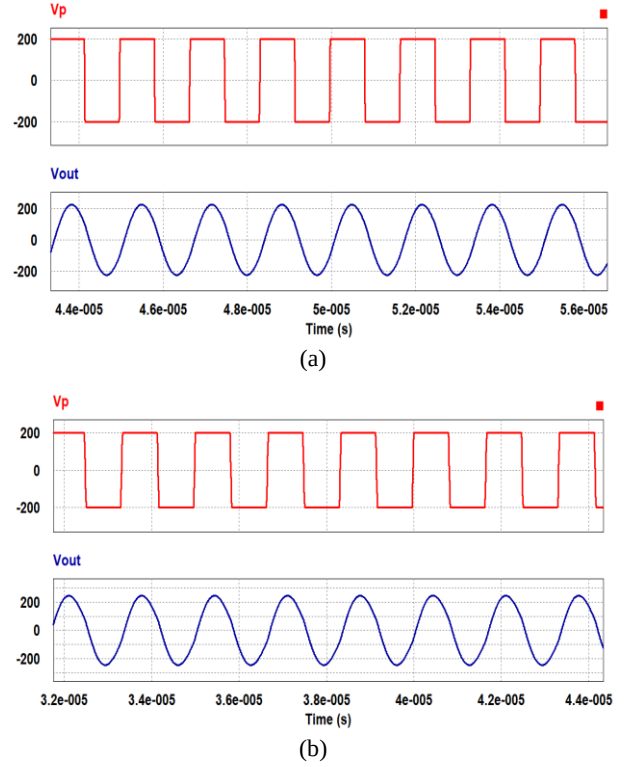
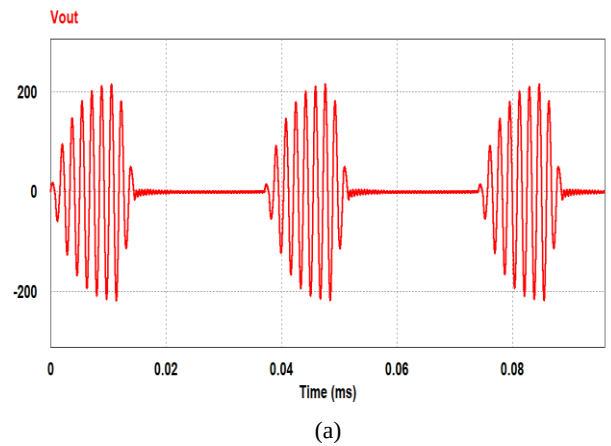


Fig. 5. The primary voltage and continuous sine output voltage waveforms for pure cutting mode. (a) $R_L=50 \Omega$, (b) $R_L=100 \Omega$.

When it comes to the blend mode for electrosurgery, there is no continuity in output voltage as in pure cutting and blank period occurs when the output voltage. After the blank period, electrosurgery gives a sine waveform to the output for a certain period of time, thus creating the blend effect.

In Fig. 6 (a) and (b), typical output voltage waveforms for blend operating mode at 50 Ω and 100 Ω are given, respectively. In this study, the device catalog was examined based on the Force FXTM-C electrosurgical device and the repetition frequency is determined as 27 kHz [8].



(a)

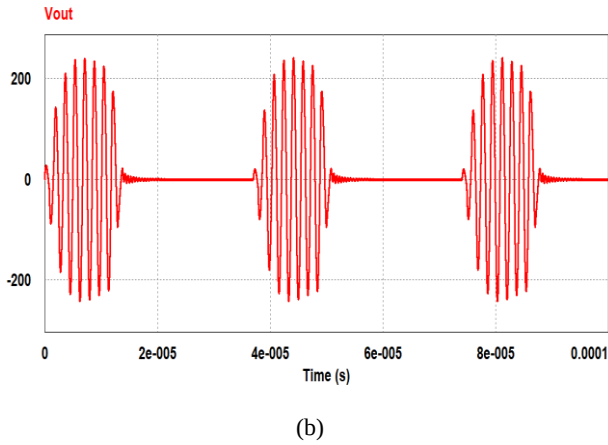


Fig. 6. Blend mode output voltage waveforms. (a) $R_L=50 \Omega$, (b) $R_L=100 \Omega$.

In coagulation operating mode for electrosurgery, a sudden sine output is observed. This sudden output from the sine is necessary to coagulate human tissues. This causes the tissue to heat up less, resulting in dehydration that clogs the blood vessels.

In Fig. 7 (a) and (b), typical output voltage waveforms for coagulation operating mode at $R_L=50 \Omega$ and $R_L=100 \Omega$ are given, respectively. In this study, the repetition frequency is determined as 39 kHz using the electrosurgical device catalog for coagulation [8].

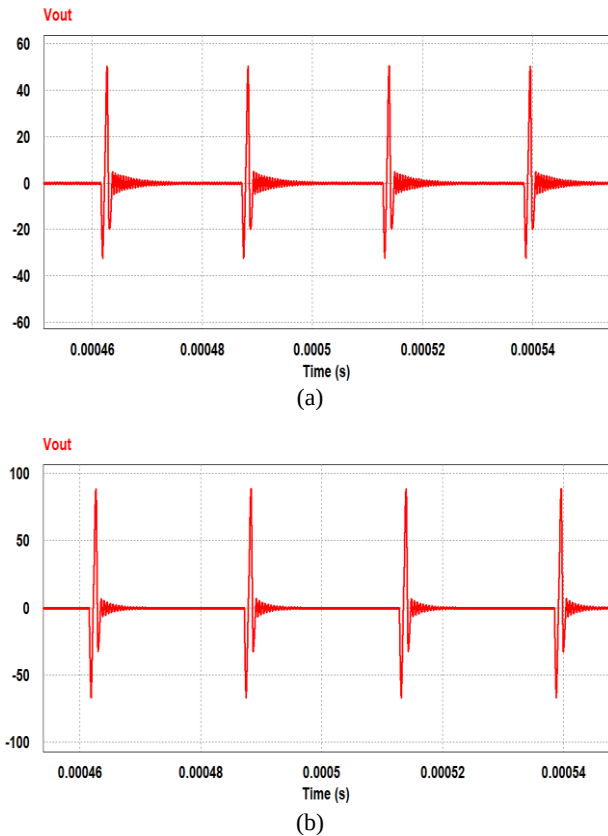


Fig. 7. The coagulation mode output voltage waveforms. (a) $R_L=50 \Omega$, (b) $R_L=100 \Omega$.

4. Conclusion

This study focuses on GaN based class D resonant inverter design for electrosurgery. A 300 W electrosurgery circuit model simulation has been carried out with variable loads to validate the proposed electrosurgery topology. The simulation results are given for pure cutting, blend and coagulation modes. The switching frequency of the class D resonant inverter is maintained at 600 kHz. 27 kHz and 39 kHz repetition frequency values are applied to the switches for blend and coagulation modes. The ZVS operation is provided for the inverter switches. Therefore, it is expected that presented design can be good solution to obtain high efficiency and high-power density design of electrosurgery.

5. Acknowledgement

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6. References

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