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Design and Simulation Model of Implantable Wireless Neural Stimulator

Pooja Arunkumar Bini[1], Aravinth VK[2], Kezia Susan Mathew[3], Rosmy Francis[4], Jithin Krishnan[5], Vishnu D[6], Anu Assis[7], Sajeena[8]
[1,2,3,4] UG - Electronics and Communication Engineering, TKM College of Engineering, Kollam, Kerala
[5]Sree Chitra Tirunal Institute for Medical Sciences and Technology, Trivandrum
[6,7,8]Associate Professor, Electronics and Communication Engineering, TKM College of Engineering, Kollam, Kerala
Emails: *abpooja85@gmail.com[1], vk.aravi3@gmail.com[2], kzsusanmathew@gmail.com[3], rosmyfrancis369@gmail.com[4], jithinkrishnan@sctimst.ac.in[5], vishnud2118@gmail.com[6], anuassis@tkmce.ac.in[7] sajeena@tkmce.ac.in [8]*

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Abstract
Implantable wireless neural stimulators have emerged as a critical technology in modern biomedical engineering due to their ability to eliminate battery dependency and repeated surgical procedures. This paper presents the detailed design and LTspice simulation of an implantable wireless neural stimulator powered using magnetic resonant inductive wireless power transfer. Remotely powered IMDs that enable safer and smaller neural interfaces are especially useful to freely moving animals and human subjects. Even more so for chronic applications, since rigid tethered electrodes suffer from micromotion, which results in tissue inflammation and scar formation around the electrodes. The simulation model is tailored for the development of neurostimulators characterized by swift settling times, intended for applications in the treatment of conditions such as Parkinson's disease, chronic pain, epilepsy, etc. The proposed system integrates a high-efficiency buck converter, Class-E inverter, four-coil resonant wireless power transfer link, Class-E rectifier, and a monostable multivibrator-based pulse generator. The system is designed to operate at 150 kHz to achieve optimal power transfer efficiency while maintaining safe operating conditions for biological tissues. Simulation results demonstrate stable voltage regulation, efficient wireless power delivery, and reliable generation of neural stimulation pulses with a pulse width of 50 ms and amplitude of 4.77 V. The results validate the feasibility of the proposed architecture for long-term implantable neural stimulation applications.

1. Introduction

Neural stimulation using implantable medical devices has significantly advanced the treatment of neurological disorders such as Parkinson's disease, epilepsy, spinal cord injuries, and chronic pain [1], [2]. Conventional implantable stimulators rely on internal batteries, which have limited lifespans and necessitate repeated surgical replacement, increasing both patient risk and healthcare costs [3], [4]. These limitations have driven extensive research into battery-less implantable systems powered wirelessly.

For vagus nerve stimulators that are currently implanted in patients, the pulse generator contains a battery that powers the system. With typical stimulator settings, the battery life range may be as long as 6.6 to 10 years, but maybe as short as less than two years. Eventually the battery must be surgically replaced when it is at or near the limit of its lifetime. To avoid periodical surgeries, the need for wirelessly powered IMDs arises [5]. The various wireless power transfer methods include the inductive wireless link, capacitive wireless link, ultrasonic wireless link and the magnetoelectric wireless link [6], [7]. Each type of wireless link is detailed in Figure 1.

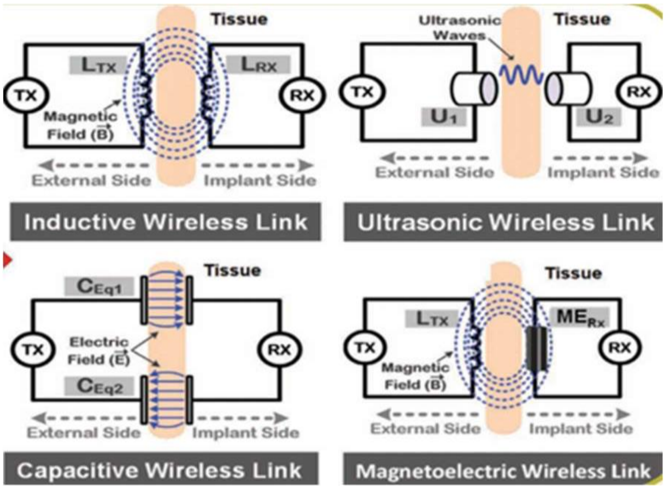

Figure 1 Types of Wireless Link

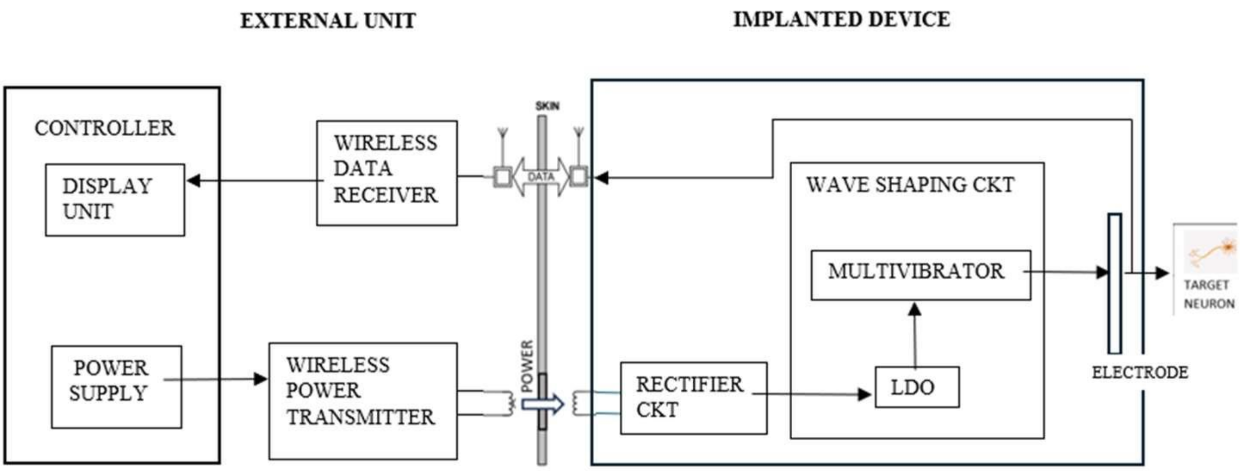

Figure 2 Block Diagram

Wireless power transfer (WPT) technologies provide a promising solution by enabling continuous power delivery without physical connectors. Among various WPT techniques, magnetic resonant inductive coupling offers high efficiency, tolerance to misalignment, and improved safety, making it highly suitable for biomedical implants [8]. The integration of high-efficiency power electronic converters with resonant WPT links further enhances system performance [9]. Fig 1.2 details the proposed block diagram. The intended topology consists of an external controlling unit and an implanted functional unit. The external controlling unit has a controller that controls the implanted functional unit and a power unit that transmits the required power to the implanted unit. The controller contains the user interface and the display unit section. The functional unit consists of a pulse-generating circuit or a wave-shaping circuit and a feedback data path section.

This paper focuses on the complete design and simulation of an implantable wireless neural stimulator that combines efficient power conversion with precise neural pulse generation. The system is modeled and validated using LTspice, ensuring practical feasibility for future hardware implementation.

2. Proposed System Architecture

The proposed implantable wireless neural stimulation system consists of two major units: an external power transmission unit and an implanted functional unit. The external unit includes a buck converter that steps down the input DC voltage and a Class-E inverter that converts the regulated DC into high-frequency AC power [9],[10]. This AC power is transmitted wirelessly using a four-coil magnetic resonant coupling structure. This conversion is controlled by the switching period of

NMOS and the resonant circuit. The buck converter mainly consists of two parts. The primary section comprises essential converter elements, including a switch, inductor, capacitor, and resistor. The secondary part involves the controller, which oversees and regulates the operation of the switching device. Designing of Buck converter includes specifying the duty cycle, the inductor value in corresponding to the inductor ripple current value, and finally the design of output capacitance. The formulation of the design adheres to the following equations.

Duty cycle of switching device, $D = V\ out/Vin\times\eta$
Inductor Ripple Current, ΔIL = (0.2 to0.4)$Iout$
Inductor, $L = V\ out\times(Vin - V\ out\ )/\Delta IL\times f\ s\times Vin$
Output Capacitance, $Cout = \Delta IL/8\times f\ s\times\Delta V\ out$

The implanted unit comprises a Class-E rectifier that efficiently converts the received AC signal into DC voltage [11] and a monostable multivibrator circuit that generates controlled stimulation pulses. Designing this class power converter is based on the desired quality factor and the frequency of operation or the resonant frequency.

Quality Factor, $Q = \omega L/R$

Resonant Frequency, $fr = 1/2\pi\sqrt{LC}$

The four-coil resonant structure enhances power transfer efficiency while minimizing losses due to misalignment and tissue separation. In the design phase of a two-coil inductive link the coupling coefficient, the quality factor of the coil, and the load resistance need to be kept in mind. Here a step-down power transfer mechanism is taken into account. The number of turns, the inductance value, and the corresponding voltage value are related to the below equation.

$L_1/L_2 = (N_1/N_2)^2 = V_1/V_2$

Here L1, N1 and V1 correspond to the transmitter side inductance, number of turns, and the voltage across it respectively. Similarly, L2, N2 and V2 correspond to the receiver side inductance, number of turns, and the voltage value respectively.

The wave-shaping circuit outputs a signal that is used to excite the target neuron based on the required specification. The shape of the signal can be of any form, it can be sinusoidal, pulse form, triangular, or even impulse signal. The excitation of neurons was primitively done by varying the amplitude level of the output signal. Here, the pulse shape is obtained from a monostable multivibrator, wherein the required pulse width is wirelessly transmitted from the controller to the waveshaping circuit through the inbuilt control circuit. The pulse width determines the triggering behavior of neurons and is designed based on application-specific neural excitation requirements [1], [12].
The design equations for the monostable multivibrator are discussed below.

Pulse Width, $TP = 0.693RTCT$
$R4C1 \leq 0.016T$
$Xc \geq 10R4$
Base Current value, $IB = (V\ cc - V\ BE)\ RT$

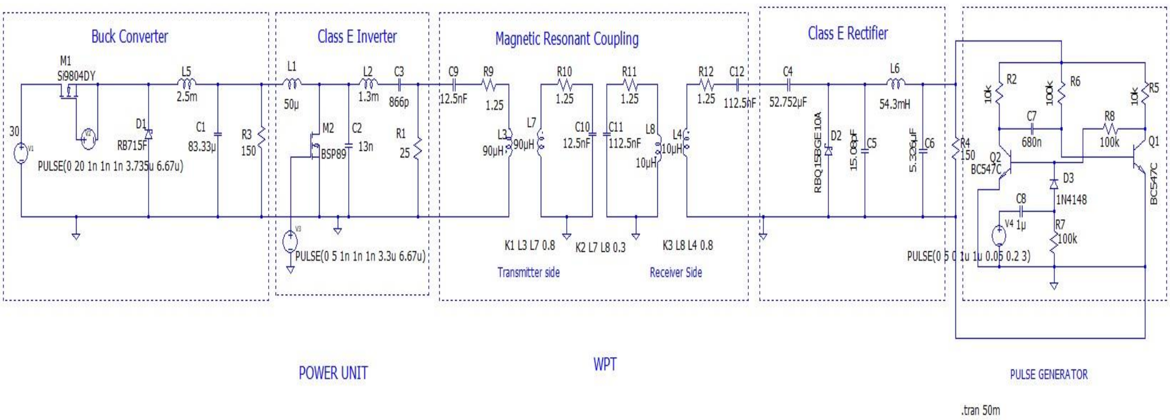

Figure 3 **LT Spice Simulation Model**

3. Results and Discussion

The complete system was simulated using LTspice, a widely used electronic circuit simulation tool for analyzing power electronic and biomedical circuits [13]. LTspice is a popular and widely used electronic circuit simulation software developed by Linear Technology (now part of Analog Devices). It allows engineers, researchers, and students to design, simulate, and analyse electronic circuits before building physical prototypes. LTspice is known for its user-friendly interface, powerful simulation capabilities, and extensive library of electronic components. Simulation results confirm stable operation and efficient power transfer throughout the system. LTspice is widely used in academia, industry, and hobbyist communities for circuit design, analysis, and educational purposes. Its intuitive interface, powerful simulation capabilities, and extensive documentation make it a valuable tool for both beginners and experienced engineers.

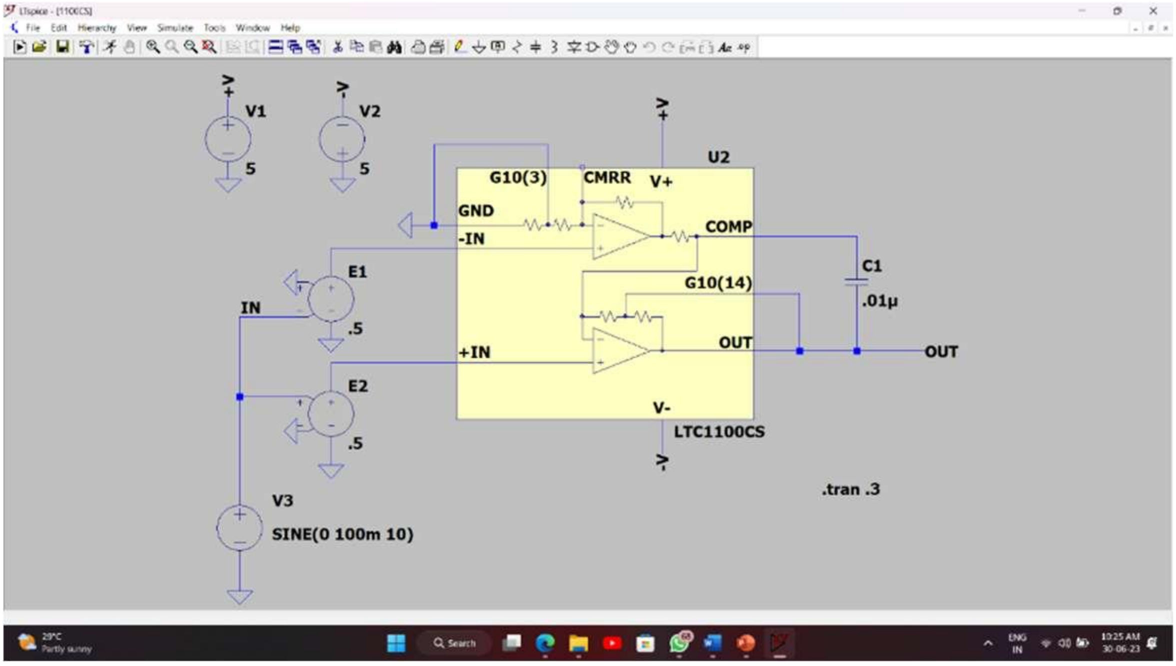

Figure 4 **LTspice GUI**

The buck converter successfully reduces the input voltage from 30 V to approximately 13.95 V DC with minimal ripple voltage of around 6 mV [10], [14]. This stable output ensures reliable operation of the inverter stage.

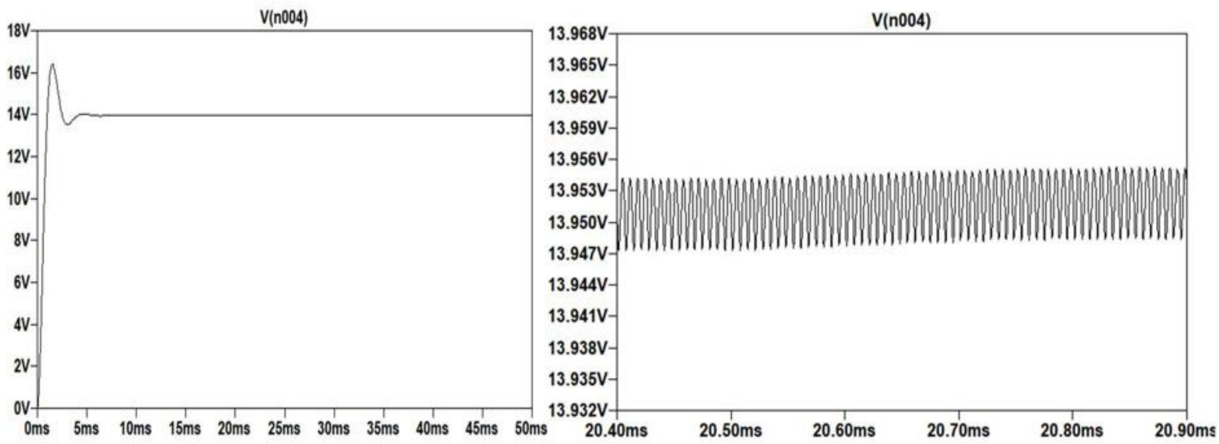

Figure 5 **Buck Converter Output**

The Class-E inverter operates at 150 kHz and generates a high-frequency AC output with a peak amplitude of 13.2 V. Zero-voltage switching behavior significantly reduces switching losses, improving overall system efficiency [9].

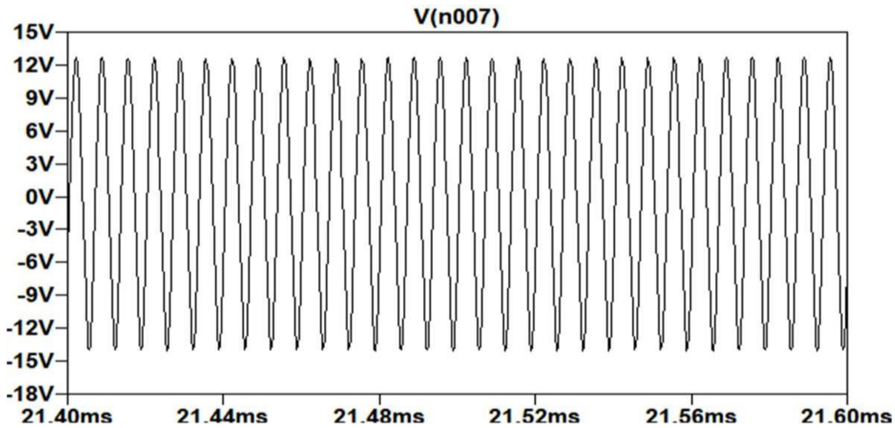

Figure 6 **Class E Inverter Output**

Figure 7, shows the wireless power transfer through the four-coil resonant link demonstrates effective energy delivery to the implanted receiver coil, even under moderate coupling conditions [6], [8]. The Class-E rectifier provides a stable DC output of 5.17 V with low ripple and fast settling time [11]. Figure 8, shows the output waveform generated at the receiver coil placed within the implanted unit. It was designed to reduce the voltage range by a factor of 3. The obtained waveform has the voltage range from 0 to 11.67 volts and frequency of 150KHz.

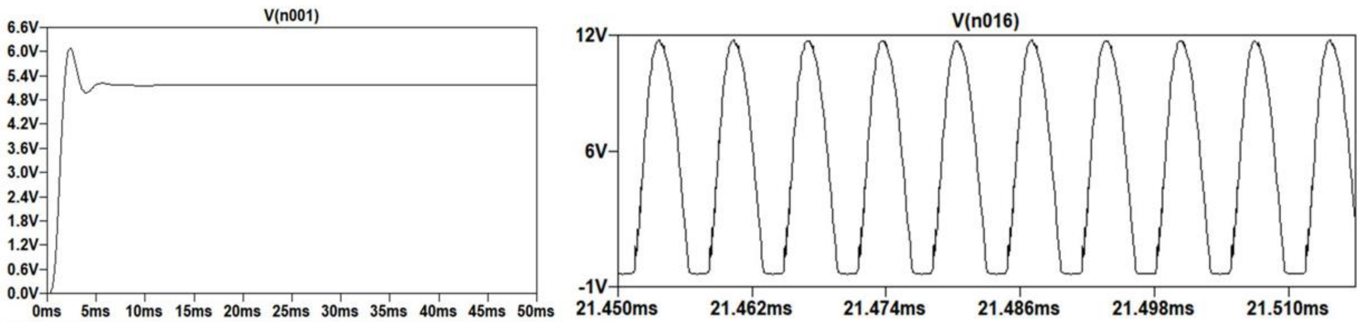

Figure 8 **Class E Rectifier Output Receiver Coil Output**

Finally, the monostable multivibrator generates a stimulation pulse with a width of 50 ms and amplitude of 4.77 V shown in Fig 1.8, which falls within acceptable neural excitation limits [1], [12], [2].

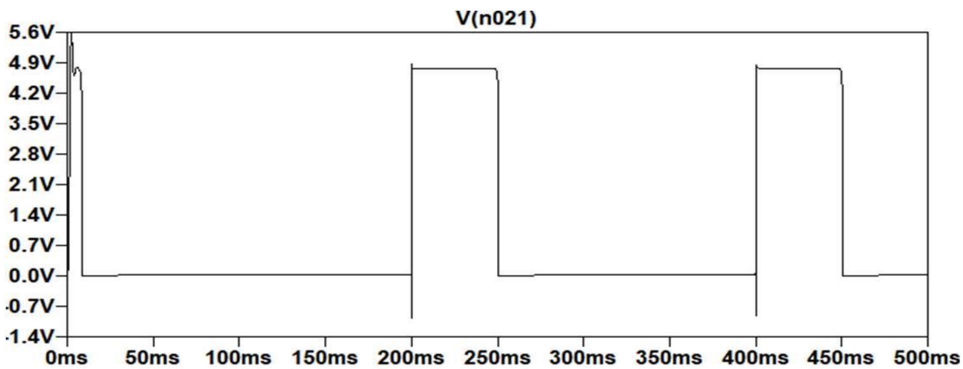

Figure 9 **Multivibrator Stable Output**

Conclusion

This paper presented a comprehensive design and simulation of an implantable wireless neural stimulator powered using magnetic resonant inductive wireless power transfer. In this project, an effective, and thoroughly integrated system for nerve stimulation is designed and simulated that incorporates diverse power converters, including the Buck Converter, Class E inverter, rectifier, and a pulse shaping circuit. The integration of high-efficiency Class-E power converters [9] and a four-coil resonant coupling structure enables reliable wireless power delivery without batteries. Simulation results validate stable voltage regulation, efficient power transfer, and precise neural pulse generation. The proposed system demonstrates strong potential for long-term implantable biomedical applications [15], [16].

Future Scope

Future work will focus on CMOS-based miniaturization of the proposed system to achieve a fully implantable microscale device [15]. Experimental validation using tissue-equivalent phantoms and in-vivo testing will be conducted to assess safety and performance [7]. Further enhancements include the development of closed-loop neural stimulation with real-time feedback [4], optimization of coil geometry, and adaptive power control techniques to improve efficiency while minimizing tissue heating [8]. Finally, in order to realize truly implantable devices, wireless power transfer is crucial to prevent repeated surgeries, disturbing the device and its surrounding tissues, and move past the reliance on battery powered medical implants. With daily advances in research, there is potential for these novel, sophisticated implants to be implemented for clinical application, to treat patients with neurological diseases, and provide better alternatives for the future [16].

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