Pulse Transformer based Portable Transcutaneous Electrical Nerve Stimulator for Pain Management

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***Abstract*—Transcutaneous electrical nerve stimulators (TENS) employ a non-invasive method of electrical stimulation to provide symptomatic pain relief for patients suffering from various ailments and medical conditions. These devices generate electrical pulses with specific duty cycles to induce relaxation in targeted muscles. Pulses can be symmetrical or asymmetrical, and unipolar or bipolar, depending on the desired waveform pattern and type of treatment. This paper presents the implementation of a monopolar square wave type TENS with controlled pulse width and current. The required output voltage and current pulses vary depending on the type of application, such as transcutaneous, percutaneous, or invasive. For surface functional electrical stimulation (FES), the device required to generate voltages up to 150 V with a current pulse intensity between 10 mA to 100 mA. The width of pulse varies between 0.2ms and 1ms and frequencies between 1 Hz and 100 Hz to account for skin impedance. Considering these requirements, a portable, pulse-transformer-based TENS device powered by a lithium-ion battery has been developed, featuring wireless connectivity to smartphones via Bluetooth for operation mode selection. The developed device is tested using an electrical model (R_s-$R_{SC}C_{SC}$ model) of human skin. The results demonstrate ability of pulse transformer-based TENS to deliver customizable therapeutic electric stimulations.**

Keywords*— *TENS, portable medical device, pulse transformer, therapeutic applications, electrical stimulation, FES, skin model, STM32 microcontroller.

I. Introduction

TENS works by applying electrical impulses through electrodes placed on the skin to stimulate the underlying nerves. This electrical stimulation triggers the release of endorphins, the body's natural pain-relieving chemicals, which can help to block the transmission of pain signals to the brain [1]. The effectiveness of TENS therapy is highly dependent on the optimization of various stimulation parameters, such as the intensity of the electrical current, the duration of each pulse, and the frequency of the pulses. TENS is a widely utilized non-invasive therapy for managing chronic pain and various other medical conditions. Pain caused by physical strain on the muscles and localized tissue damage can be managed without the use of opiates. This non-invasive stimulation technique helps patients to get relief from both chronic and acute pain in conditions such as osteoarthritis, tendinitis, fibromyalgia, labor pain, and bursitis [2]-[3].

In literature various circuits are presented to develop TENS devices. They are grouped under the category of FES circuit. These circuits are typically designed using analog circuitry or microcontroller-based architectures, with the latter typically utilizing a digital-to-analog converter (DAC) generating the required waveform pattern. FES with dual 555 timer ICs, to generate required pulse is presented [4]. A transformer is incorporated to amplify the stimulation voltage from 9V to 200V while maintaining a current of 100mA an alternative design replaces the transformer with a resonant converter, utilizing two transistors and resonant components. This approach eliminates the need for bulky magnetic elements, resulting in a more compact circuit [5].

The network-based FES system employs a comprehensive architecture for generating square pulses. It consists of a master control unit, multiple distributed stimulation-sensor units, a boost converter, and a computer for overall management. The system's output stage utilizes a motor drive H-bridge configuration, capable of producing biphasic waveforms with a current output ranging from 1 mA to 58 mA. Operating at a driving input frequency between 5 kHz and 50 kHz and a voltage of 100 V, this design allows for precise control and distributed stimulation across a network. Such a configuration makes the system well-suited for complex FES applications, offering flexibility and adaptability in stimulation parameters [6].

A multichannel stimulator employs direct synthesis techniques and element-envelope methodology to generate flexible waveforms through digital signal processing. The output circuit produces biphasic current pulses using a Holland architecture enhanced by a Wilson current mirror. This design achieves impressive performance metrics: a peak output voltage of 88 V, an adjustable frequency ranges of 3-100 Hz, and a variable current output of 0-110 mA. To facilitate multiple stimulation channels, the system incorporates multiplexers, allowing for targeted and simultaneous stimulation across various sites. This versatile setup enables precise control over stimulation parameters, making it adaptable for a wide range of functional electrical stimulation applications [7].

The design of wireless TENS for the smartphone with a boost converter, battery level detector, current monitor, and output H-bridge drive is illustrated in [8]. Similar design based on oscillator circuit, DAC and power amplifier is presented in many literature [9] [10] [11]. This paper presents the design and implementation of a pulse transformer-based TENS device. The higher switching frequency enables the creation of a more compact pulse device with less passive elements. The organization of the paper is as follows: Section I provides a basic introduction and literature review, Section II deals with the fundamental working principles, mathematical modeling, and a detailed description of the proposed system, Section III explores the simulation of the system and presents the simulation results, Section IV provides an overview of the project, design specifications, and practical results, and Section V discusses the conclusion of developed system.

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II. Working Principle

The pattern of pulse applied to the skin defines the effective use of TENS. The pattern is characterized by width of the pulse, frequency of occurrence, current and voltage value. Conventional FES circuit operates in frequency range of 1 to 100Hz with modulated pulse width ranging from 0.2ms to 1ms. A specific pulse mode known as Russian current demands a sinusoidal variation of pulses at a base frequency of 2.5 kHz [11]. Larger magnetic circuit required to implement pulse transformer-based TENS of these pulse width and frequency specification. However, using higher switching frequency compact pulse transformer with less magnetic circuit is possible to design. The nerve system is sensitive to electric pulse frequency lesser than 10kHz and acts insensitive to frequencies above 10 kHz [3]. Thus, by switching pulse transformer at 100kHz frequency for a duration of 0.2ms to 1ms will give same effect to the skin which conventional TENS devices are generating. These 100kHz based pattern generation simulated and verified by considering the electrical model of human skin.

A. Mathamatical analysis

TENS essentially requires voltage pulses ranging from 0.2ms to 1ms, with a frequency of occurrence between 1 Hz and 100 Hz [3]. To implement the pulse transformer, the required primary inductance (L) to accommodate the minimum pulse width of (dt) 0.2ms evaluated. Inductor emf equation could be written as:

$$e = L\frac{di}{dt} \tag{1}$$

where *e* indicates induced emf across primary winding of the pulse transformer. The primary of the pulse transformer is operated at 12V and turns ratio is considered as 15 to step-up voltage at secondary to 180V. Minimum transformer primary inductance could be obtained rearranging (1) as:

$$Lmin = \frac{e}{\frac{di}{dt}} \tag{2}$$

The maximum current requirement of 150mA [11] at the secondary, is corresponds to 2.25A primary current. Considering maximum current rise (di) of 2.25A in the primary the minimum primary inductance is calculated using (2) and inductance is obtained as $Lmin = 1.066mH$. Using ferrite core of size EE 13/7/4 with μ_r 6840, pulse transformer designed to have primary side inductance of L=2.4mH and primary winding resistance R= 0.5Ω. Thus, the system intended to have time constant of 4.8ms. The instantaneous primary current for maximum pulse width of 0.2ms evaluated using standard inductor current equation for L-R circuit given as:

$$i = I\left(1 - e^{-t/\left(\frac{L}{R}\right)}\right) \tag{3}$$

$$i = 0.48A$$

where I correspond to steady state value of 12A. Thus, it clearly indicates inability of the pulse transformer to deliver the full load current of 2.25A. Designing transformer to carry required full load current requires a bulk core. This could be addressed by increasing the switching frequency and opting peak current mode controller without affecting the performance.

In line with the system time constant of 4.8ms, the primary of the pulse transformer was switched at 100 kHz, which is nearly 500 times faster than the system response. This allowed the pulse transformer to build the primary voltage and step up the voltage at the secondary for all possible electrical model of human skin. Due to the fact that nerve system is insensitive to the 100 kHz switching frequency [3], which indicates nerve will effectively sense the time period of 100 kHz burst as a single pulse. This particular approach leads to the design of a pulse transformer with smaller inductance and thus a compact portable device.

B. Description of developed system

The block diagram of the proposed system is shown in Fig. 1. The primary of the pulse transformer switched with the help of power MOSFET. The system consists of 3.7V Li-ion battery which is boosted to 12V by the power circuit. Current sense resistor is used to measure primary current. Secondary of the transformer is connected to electrical model of human skin represented by R_s-$R_{SC}C_{SC}$ [12].

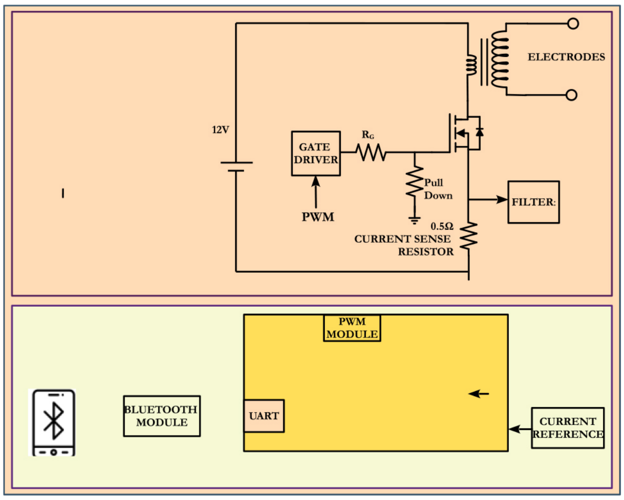


Fig. 1 System block diagram

The android app is used to configure required pulse width. The device is connected via Bluetooth to receive the settings from the android app. PWM module generate burst of 100kHz PWM for the duration set by the user's input. At each switching cycle primary current is monitored through comparator of the microcontroller. This current feedback signal is passed through a filter with cutoff frequency of 78kHz and compared with the reference current input set by the user. When the current peak crosses the current reference, PWM will be turned off within the duty cycle and reinitiate PWM after switching period. The battery voltage information is fed to the android app and the device will turn off if the battery voltage level less than the pre-set value.

III. SIMULATION OF THE SYSTEM

The designed system is simulated using the Matlab/Simulink. Fig. 2 shows implemented Simulink model of the TENS. The human skin model with combination of R_s-$R_{SC}C_{SC}$ model taken as reference load[12].

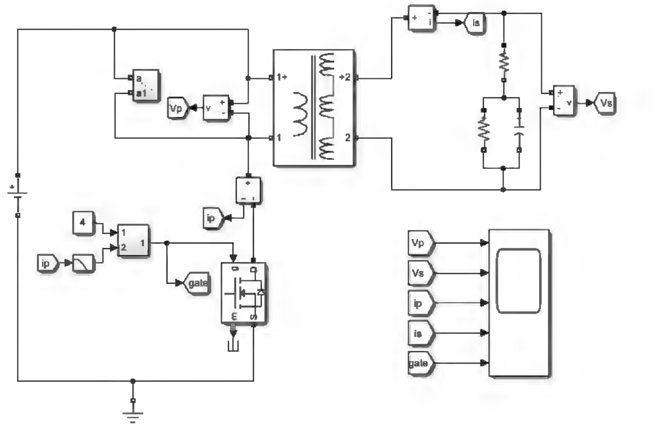


Fig. 2 Simulink model of the system

The standard value chosen for skin model are R_s=1kΩ, R_{SC}= 2.7kΩ C_{SC}=100nF. Different modes of generating pulses are simulated using Matlab/Simulink model. The different modes possible to configure are tabulated in Table I. Peak current control technique also validated for set reference current. The Fig. 3 depicts the mode 1 operation with steady state output of 200µsec pulse with 1 Hz frequency. The magnitude of the pulses is in line with standard requirement of TENS [11], [13].

TABLE I. DESCRIPTION OF MODES AVAILBALE IN TENS

Sl. No.	*Mode*	*Description*
1	1 Hz	200us burst pulse at 1Hz rate
2	5 Hz	200us burst pulse at 5Hz rate
3	10 Hz	200us burst pulse at 10 Hz rate
4	Russian current	2kHz base frequency sine with 50Hz rate
5	Intensity control	To vary duty of 100kHz switching

This train of pulses required to produce relaxation in targeted nerve. The time scaled waveforms of the primary side, secondary side voltage and current waveforms of the mode 1 operations is shown in Fig. 4. It is evident that primary side voltage stepped up and reflected at the skin load.

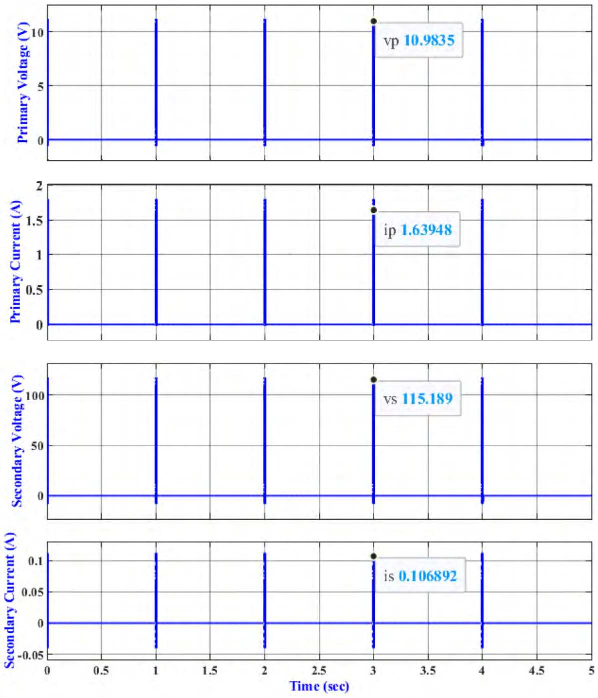


Fig. 3 Pulse transformer waveform for mode 1 operation

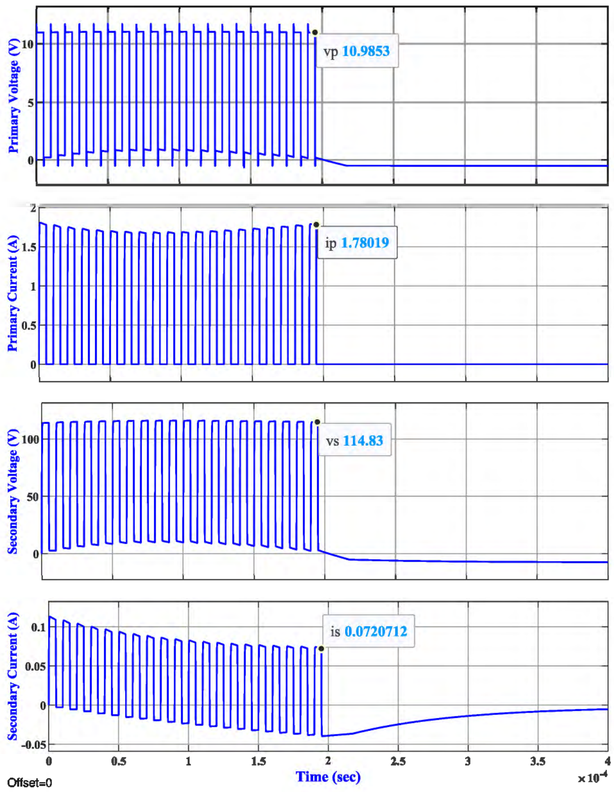


Fig. 4 Pulse transformer waveform for mode 1 operation

Fig. 5 shows output of Russian current mode with 2.5kHz sinusoidal base frequency. The output voltage level is within permissible level of 150V in all simulation results.

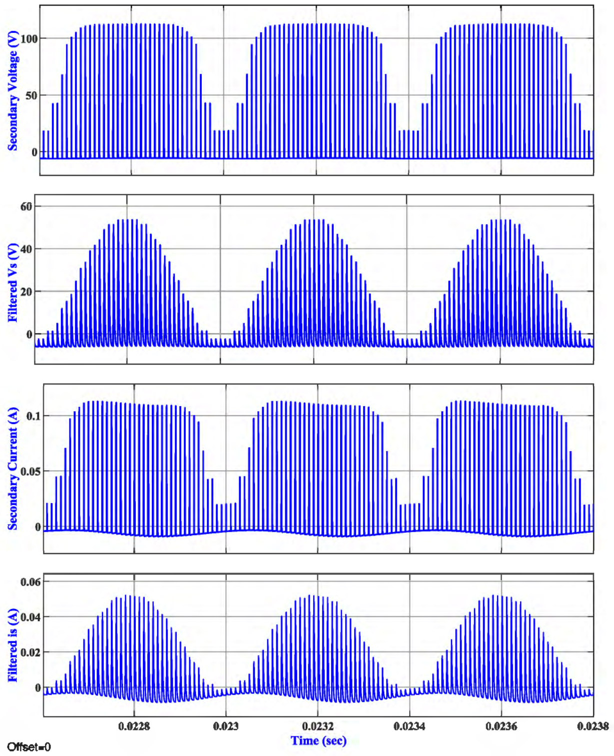


Fig. 5 Pulse transformer waveform for Russian current mode

To validate current control system is simulated using 1A primary current setting. The primary current, average current and the gate signals are shown in Fig. 6. From the simulation result it can be visualised that the gate signal is turned off whenever the actual current reaches reference value. Otherwise switching pulse would reach 50% duty for normal operation. This control provides safety feature for the TENS in the implementation.

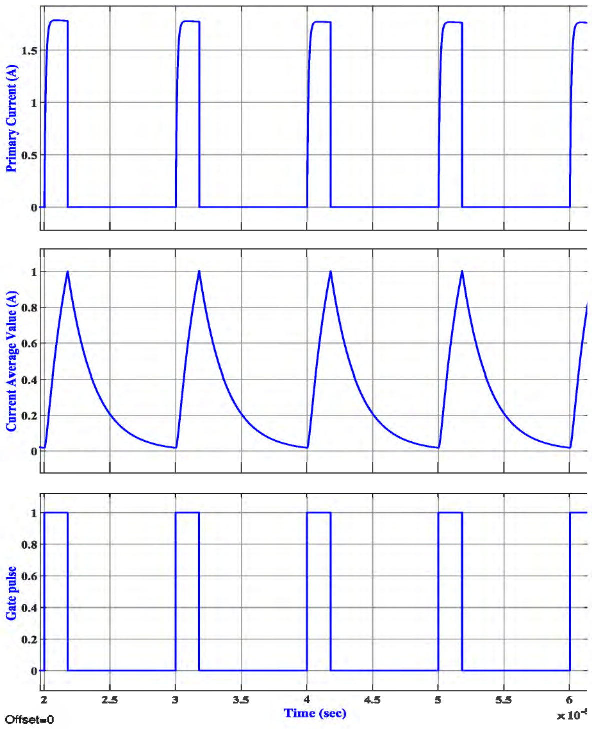


Fig. 6 Current control simulation result

IV. Hardware Implementation and Results

The developed hardware system of pulse transformer-based TENS is shown in Fig. 7. The overall dimension of the device is 8cmX4cmX2cm. The major component included are includes microcontroller, Bluetooth module, power MOSFET, pulse transformer, potentiometer to set current reference, socket to connect electrode and Li-ion battery.

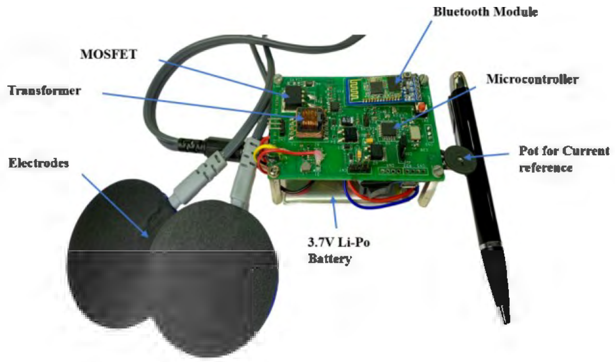


Fig. 7 Hardware setup of TENS

The hardware implemented using STM32F303K8T6 microcontroller. The rich peripherals of the microcontroller helped to implement desired switching and control actions. The microcontroller connected through HC05 Bluetooth module to receives different mode information from an android app. UART of the controller is used to data communication. The inbuild comparator of the microcontroller is used to implement the current control. The user current setting value acquired by ADC and after processing the signal the equivalent analog signal is generated using DAC which is treated as a reference value for the comparator. The comparator monitors the current peak and responds whenever measured current crosses the reference value. In each switching cycle. Based on comparator output, PWM module varies the duty. Thus, the actual current is always monitored in each switching cycle and provides safe operation by cycle-by-cycle current limit. The design parameters of the TENS are listed in Table II.

TABLE II. DESIGN PARAMETERS

Sl. No.	*Description*	*Value*
1	Primary inductance	2.4mH
2	Turn ratio	1:15
3	Switching frequency	100kHz
4	Current sense resistance	0.5 Ω
5	Li-ion battery	3.7V
6	Maximum output voltage	180V

To configure the TENS, an android app is developed using MIT platform. The layout of the app is shown in Fig. 8.

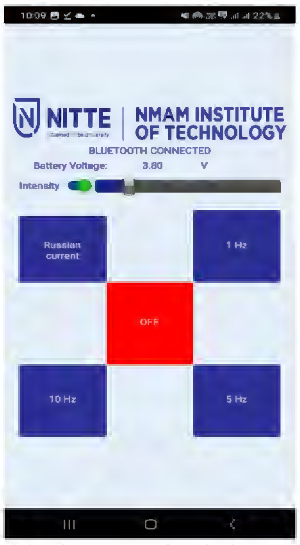


Fig. 8 Layout of android app

The different modes possible to configure are tabulated in Table I. After establishing connection with TENS device, the mode selection, intensity control and battery voltage are monitored through the developed android app.

The output waveform of transformer secondary with standard skin load for mode 1 operation is shown in Fig. 9.

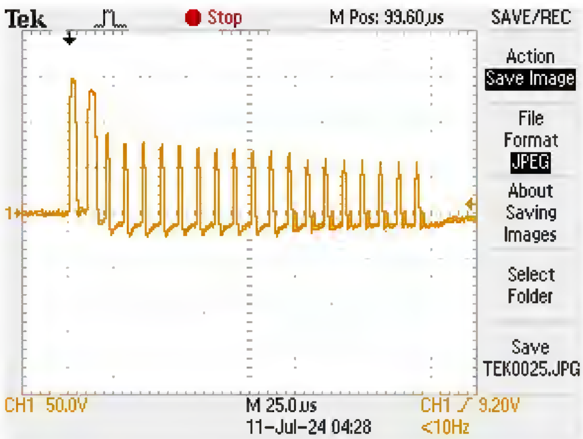


Fig. 9 Pulse transformer output voltage for skin load

Fig. 10 Transformer output voltage for Russian current mode

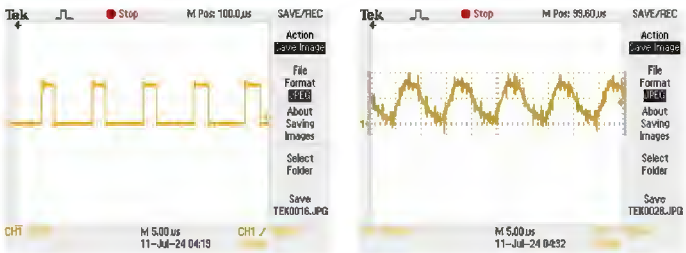
Average 50V is delivered to the skin load in mode 1 operation. The amplitude of the voltage found stable for all the other operating mode.

a. *b.*

Fig. 11 PWM and current sense output

The output waveform for Russian current is shown in Fig. 10. For the mode 1 operation with current setting above the actual current, duty cycle and filtered current waveform are shown in Fig. 11. The 50% duty cycle generated by the PWM shown in Fig.11a, indicates the comparator allowing the required current to the load. The corresponding average current waveform is shown in Fig. 11b.

For the same condition reducing the current reference causing reduction in PWM width is shown in Fig. 12. The deceased width of the PWM less than 50% shown in Fig. 12a. Corresponding peak current with magnitude clamped to the refence value is shown in Fig. 12b. The results obtained in the hardware are in par with simulated system.



a. *b.*

Fig. 12 Waveform indicating Current control

V. Conclusion

The pulse transformer-based TENS circuit design and implementation is presented. By employing a monopolar square wave pulse generator, the device offers flexibility in generating adjustable multi-frequency stimulations tailored to different therapeutic applications. Key technical specifications include the ability to deliver voltages up to 150 V and current pulses ranging from 10 mA to 100 mA, with precise control over pulse width and frequencies spanning from 1 Hz to 100 Hz is achieved. The pulse transformer and lesser passive component to build the system made it compact and cost-effective solution for TENS device. The development of a portable device powered by a lithium-ion battery, equipped with Bluetooth connectivity for smartphone operation, enhances usability and enables real-time parameter adjustment, thereby improving convenience for both clinical and experimental settings. Experimental validation using an electrical model of human skin (R_s-$R_{SC}C_{SC}$ model) underscores the device's capability to deliver customizable therapeutic electrical stimulations effectively.

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REFERENCES

[1] Johnson MI, Paley CA, Howe TE, Sluka KA. Transcutaneous electrical nerve stimulation for acute pain. Cochrane Database Syst Rev.2015 Jun15; 2015 (6):CD006142. doi:10.1002/14651858. CD006142.pub3. PMID: 26075732; PMCID: PMC8094447.

[2] Van der Spank JT, Cambier DC, De Paepe HM, Danneels LA, Witvrouw EE, Beerens L. Pain relief in labour by transcutaneous electrical nerve stimulation (TENS). Arch Gynecol Obstet. 2000 Nov;264(3):131-6. doi: 10.1007/s004040000099. PMID: 11129512.

[3] Rogers ER, Mirzakhalili E, Lempka SF. Model-based analysis of subthreshold mechanisms of spinal cord stimulation for pain. J Neural Eng. 2023 Nov 9;20(6):066003. doi: 10.1088/1741-2552/ad0858. PMID: 37906966; PMCID: PMC10632558.

[4] X. Li, X. Peng, M. He, R. Wang and J. Guo, "Design of Portable Transcutaneous Vagus Nerve Stimulator Based on Microcontroller," 2018 12th IEEE International Conference on Anti-counterfeiting, Security, and Identification (ASID), Xiamen, China, 2018, pp. 231-235, doi: 10.1109/ICASID.2018.8693137.

[5] A. Slepyan, S. Krishnan, T. Li and N. Thakor, "A Multi-Channel, Low-Voltage, High-Frequency Programmable Electrical Stimulator for Sensory Feedback," 2023 IEEE Biomedical Circuits and Systems Conference (BioCAS), Toronto, ON, Canada, 2023, pp. 1-5, doi: 10.1109/BioCAS58349.2023.10388769.

[6] T. Udomlertsirikul and Y. Wongsawat, "Multi-Purpose Power Amplifier Board for Custom-Designed Electrical Stimulation System Development," 2022 37th International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC), Phuket, Thailand, 2022, pp. 597-600, doi: 10.1109/ITC-CSCC55581.2022.9895103.

[7] K. W. E. Cheng, Y. Lu, K. Y. Tong, A. B. Rad, D. H. K. Chow, and D. Sutanto, "Development of a Circuit for Functional Electrical Stimulation," IEEE Trans. Neural Syst. Rehabil. Eng., vol. 12, no.1, pp. 43–47, 2004.

[8] L. Zeng et al., "Design of a high voltage stimulator chip for a stroke rehabilitation system," 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Osaka, Japan, 2013, pp. 834-837, doi: 10.1109/EMBC.2013.6609630.

[9] C. Wu, S. T. Young, and T. S. Kuo, "A versatile multichannel direct-synthesized electrical stimulator for FES applications," IEEE Trans. Instrum. Meas., vol. 51, no. 1, pp. 2–9, 2002.

[10] H. J. Park, S. H. Woo, Z. M. U. Din, M. N. Kim, and J. H. Cho, "Design and implementation of wireless transcutaneous electrical nerve stimulator (TENS) for smart phone," IEICE Electron. Express, vol. 6, no. 22, pp. 1587–1594, 2009.

[11] David Prutchi Michael Norris, Design And Development Of Medical Electronic Instrumentation-A Practical Perspective of the Design, Construction, and Test of Medical Devices. John Wiley & Sons, Inc., Hoboken, New Jersey, 2005.

[12] Bora DJ, Dasgupta R. Various skin impedance models based on physiological stratification. IET Syst Biol. 2020 Jun;14(3):147-159. doi: 10.1049/iet-syb.2019.0013. PMID: 32406379; PMCID: PMC8687402.

[13] Johnson MI, Paley CA, Jones G, Mulvey MR, Wittkopf PG. Efficacy and safety of transcutaneous electrical nerve stimulation (TENS) for acute and chronic pain in adults: a systematic review and meta-analysis of 381 studies (the meta-TENS study). BMJ Open. 2022 Feb 10;12(2):e051073. doi: 10.1136/bmjopen-2021-051073. PMID: 35144946; PMCID: PMC8845179.