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Electric Therapy System Based on Discontinuous Conduction Mode Boost Circuit

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Abstract
The human body and nervous system transmit information through electric charges. After the electric charge transmits information to the brain, we can feel pain, numbness, comfort, and other feelings. Electric therapy is currently used widely in clinical practice because the field of examination is more representative of electrocardiogram, and in the field of treatment is more representative of electrotherapy. In this study, we design a system for neurophysiological therapy and conduct parameter calculation and model selection for the components of the system. The system is based on a discontinuous conduction mode (DCM) boost circuit, and controlled and regulated by a single-chip microcomputer. The system does not only have a low cost but also fully considers the safety of use, convenience of the human-computer interface, adjustment sensitivity, and waveform diversity in the design. In future, it will have strong implications in the field of electrotherapy.

Index Terms: DCM boost, Electrotherapy, Microcomputer, Single-chip

I. INTRODUCTION

With the development of science and technology, the application of electric energy in the human body such as electrocardiogram examination, cardiopulmonary resuscitation during emergency treatment, electrotherapy and massage, nerve rehabilitation treatment, and so forth, has been increasing. Presently, electrotherapy is widely used in the clinical treatment of various diseases, such as analgesia and pain, improvement of blood circulation, wound healing delay, prevention, and treatment of disuse atrophy [1-3].

Currently, electric pulse therapy is generally divided into low, medium, and high frequency. Low and medium frequency are generally used in contact therapy. The pulse frequency in low, medium, and high or ultra-high frequency electrotherapy is 0-1,000 Hz, 1,001 Hz–100 KHz, and above 100 KHz, respectively [4]. Generally, the intensity selection of pulse therapy instruments is not continuous; only some intensity gears are designed for selection, the frequency range that can be selected is relatively small, and the pulse width adjustment is missing.

The system can easily output a low frequency and a part of the intermediate frequency pulses. Using a boost circuit is simpler than using a transformer circuit. The boost circuit only needs to adjust the duty cycle of the control pulse to the output voltage and current of various intensities. Because only a few IC components are needed, the cost is low and the potential fault points are less. The discontinuous conduction mode (DCM) boost method used in this system has a higher multiple than the continuous boost method, which is suitable for this kind of pulse output physiotherapy equipment [5-6].
The system is controlled by a single-chip microcomputer, which can support many types of waveforms, voltage intensities, frequencies, and other functions, and is especially convenient for adjusting the frequency, amplitude, and duty cycle of the output pulse.

Using a touch screen as a man-machine interface makes the operation more intuitive, convenient, and expandable. Because the combination of a single-chip computer and touch screen is adopted, it is only necessary to upgrade with few changes in the system hardware when it is necessary to add new functions, such as using the esp8266 module to facilitate WIFI networking [7]. The system uses a low-voltage DC power source input, and considers the equipment and user safety in many aspects.

II. SYSTEM ARCHITECTURE AND MAIN CIRCUIT DESIGN

A. System Architecture

The system mainly includes power, boost circuit, output pulse control, voltage, and current measurement modules, two single-chip microcomputers, MCU1 and MCU2, an alarm, and a touch screen, as shown in Fig. 1.

The input power supply of the system is 12 V DC. To ensure the stability and safety of boosting, two types of power supply boosting are adopted, and are divided into levels 1 and 2. The first level uses a 5 V power source by the 7805 chip, and boosts the 5 V to 5-100 V. The second level directly uses a 12 V power supply for boosting to 100–200 V. This type of differentiation is also safer. Ordinary people need to use only pulses within 100 V, and in special cases, pulses above 100 V such as high-voltage pulsed current stimulation are needed in low-frequency and high-voltage electrotherapy.

The detection, alarm, and protection circuits are designed in the system. The front-end power supply voltage, current, voltage after boosting, and temperature in the equipment are detected and collected to ensure the safety of the voltage and current. When one of these parameters is abnormal or out of range, the alarm and control relay is used to cut off the input power of the boost circuit, and the alarm can be displayed on the screen detailed information to ensure the safety of the personnel and equipment.

The system is controlled by two STC MCUs. MCUs with good stability [8], a wide range of applications, and low prices are often selected. STC15f2k48s2 is used as MCU1, and is approximately $0.6, whereas STC15408 as is used as MCU2, and is approximately $0.3 [9]. MCU1 is responsible for the output PWM waveform to drive the boost circuit voltage regulation, output pulse frequency, output pulse voltage detection, touch screen communication, etc. MCU2 is mainly responsible for power safety. In case of MCU1 failure, MCU2 can still measure and control the circuit, including input power detection, temperature detection, output pulse voltage detection, buzzer control, etc. A sound alarm can help identify a problem in time, and automatically cutting off power can promptly protect the safety of personnel and equipment. MCU1 and MCU2 communicate with each other through serial communication.

MCU1 can communicate with DWIN’s touch screen through a serial port TTL [10]; we can then set and control all functions and parameters of the system through a touch screen.

B. Boost Circuit Design and Inductance Parameter Calculation

Fig. 2 shows the boost circuit. The PWM1 is the pulse, the input power is the output voltage, and the AD is used to measure the voltage value after boosting. It is mainly composed of inductance L11, Schottky of a fast diode, PWM1 pulse output from NMOS Q1 and MCU1, and other electronic components such as resistance and capacitance. Among them, photoelectric isolation is used between the PWM1 and NMOS transistor bases, which can improve the anti-interference and stability.

The circuit is a boost circuit, and the MAN of the MCU1 system adopts 24 M. The main frequency MAN is the frequency f of the periodic wave, the product of the duty cycle adjustment wave number N, and the frequency division

Fig. 1. System topology and PCB design simulation diagram.

Fig. 2. Boost circuit.
number PCA_Clock, as shown in eq. (1).

$$MAN_{F osc} = f * N * \text{PCA}_\text{Clock}$$  \hspace{1cm} (1)

The frequency division number PCA_Clock can be 1, 2, 4, 6, 8, or 12 PCA_Clock. When the clock takes the minimum value of 1, it creates the frequency of the periodic wave $f$, and the duty cycle adjusts the wave number $N$ to create a larger adjustment range. To ensure that the voltage has better continuity after boosting, it is necessary to adjust the duty cycle within a larger range. Increasing the duty cycle to adjust the wave number $N$ reduces the frequency of the periodic wave $f$, which reduces the frequency of the PWM wave driving the boost. Therefore, the system adopts a PWM wave with a lower frequency, the frequency $f$ is 1 KHz, and the duty cycle can be adjusted in the PWM theory to 0-24,000 pulses.

Generally, the resistance of the human body is considered to be approximately 1,000 Ω [11]. When selecting the first gear as 5-100 V, the maximum pulse current $I_1$ is 100 mA. When the second gear is selected as 100-200 V, the maximum pulse current $I_2$ is 200 mA. Here, $I_1$ and $I_2$ are only pulsed currents, and the average current is very small.

The maximum duty cycle can be determined based on the input and output voltages. The duty cycle $Don$ is given by eq. (2).

$$Don \approx \frac{V_0 - V_i}{V_0}$$  \hspace{1cm} (2)

When the first gear parameter $V_i = 5$ V, and $V_0 = 100$ V, the value of $Don1 = 0.95$. When the second gear parameter $V_i = 12$ V, $V_0 = 200$ V, the value of $Don2 = 0.94$.

Generally, the duty ratio of the boost converter when the inductor current is continuous is not greater than 0.9, and the boost ratio is less than 10 times. Therefore, to increase the boost ratio by more than 10 times, the system adopts the boost converter with the discontinuous inductor current. The inductance current of the boost circuit works intermittently, as shown in Fig. 3, and $T$ is a cycle time of 1 ms; $ton$ is the energy storage time of the inductor, and $toff$ is the energy release time of the inductor. Considering the inductor release time and intermittent time, $t$ is set to less than 0.4 ms.

When the circuit is static, the output current is the output voltage divided by the resistance, ignoring the pulse loss. The resistance is mainly $R_{13}$ and $R_{14}$ of the voltage measuring circuit. The output current is then expressed as (3).

$$I_0 = \frac{V_0}{R_{13} + R_{14}}$$  \hspace{1cm} (3)

Because the input power is equal to the output power in a period, eq. (4) can be obtained. The $I_{L_{max}}$ is the maximum inductor current.

$$V_i * \frac{I_{L_{max}} * ton + toff}{2T} = V_0 * I_0$$  \hspace{1cm} (4)

The inductor current increment $I_1$ during $t=0$ to $ton$ (the switch tube NMOS conduction period) is expressed as (5).

$$I_{L_{max}} = \frac{V_i * ton}{I_1}$$  \hspace{1cm} (5)

Eq. (5) is transformed to obtain eq. (6).

$$L = \frac{V_i}{I_{L_{max}}} * ton$$  \hspace{1cm} (6)

Considering that the winding of the inductor and wiring of the circuit board should not be too thick, the inductor current is less than 500 mA, and according to (5), when $V_i$ is equal to 12 V, $t$ is equal to 0.4 ms, and $I_{L_{max}}$ is less than 500 mA, then $L > 9.6$ mH.

Eqs. (3), (4), and (5) are used to obtain (7).

$$L = \frac{V_i}{I_{L_{max}}} * \frac{ton * \frac{ton + toff}{2T - V_0 * (V_0 - V_i)}}{ton + toff}$$  \hspace{1cm} (7)

When the first gear parameter $V_i = 5$ V, $V_0 = 100$ V, and $ton$ is less than 0.4 ms, the value of $L < 32$ mH.

When the second gear parameter $V_i = 12$ V, $V_0 = 200$ V, and $ton$ is less than 0.4 ms, the value of $L < 47$ mH.

According to the calculation, the inductance value should be between 9.6 mH and 32 mH; therefore, the 20 mH inductor is selected as the boost circuit. Iron silicon aluminum core has the characteristics of high flux, low loss, and a low price. It has a high energy storage capacity and is suitable for large capacity manufacturing. Therefore, an iron silicon aluminum core is used for the boost circuit inductors [12].

**C. Output Waveform Circuit**

The pulse output circuit is shown in Fig. 4. PWM2 is the waveform output of MCU1. Its function is to control the frequency and width of the final output waveform. PWM2 drives the Q12 NPN triode after passing through the protective resistor R18, and the Q13 PNP triode is driven by Q12. Q13 is a high-voltage diode, which can withstand voltages above 200 V. The waveform frequency and duty cycle of the system output pulse will be the same as PWM2, and the ampli-
III. SYSTEM SOFTWARE DESIGN

A. Step up Procedure Flow Design

Because boost and output waveshaping require two independent PWM waves, the clock frequency of the two PWM waves may be different, thus, different methods are used to generate the PWM waves.

The boost part of PWM1 uses the system clock and T0 interrupt of MCU1 to generate the PWM1 waveform. The main frequency of MCU1 is 24 MHz, and the PWM1 frequency \( f_1 \) is 1000 Hz. According to (8), the \( 24000 \) system pulses represent one PWM1 counting cycle.

\[
PWM1\_DUTY = MAN\_FOSC \div f_1 = 24000 \quad (8)
\]

When the high-level number of pulses is \( i \), the high-level time is \( i \div 24000 \) ms and the low level is \((24000-i)\div24000 \) ms for every cycle, and the duty cycle is \( (1/24000) \times \times100\% \).

When setting the voltage from the touch screen, the human–computer interface sends the set voltage value to MCU1 through the serial port. When the voltage value read by MCU1 changes, it calculates the duty cycle of PWM1 according to the changed voltage value, and then transfers the new duty cycle value to the parameters Th0 and Tl0 of the interrupting T0 of MUC1. The interrupting T0 outputs the PWM1 waveform according to the new duty cycle parameter, making the boost circuit. The output voltage value changes, as shown in Fig. 5.

B. Design of Output Pulse Frequency

The MCU uses a CCP/PCA pulse or timer output function to realize PWM with less system time; therefore, a CCP/PCA pulse or timer output pulse is preferred. However, because the system frequency is relatively high, it is difficult to directly output low-frequency PWM waves. At this time, the counterinterrupt method can be used. Fig. 6 shows a flow chart of the output waveform.

The PWM2 pulse is generated by the PCA interrupt of the PWM pulse generator on-chip. The man-machine interface sends the set output wave frequency and pulse width value to MCU1 through the serial port. When MCU1 reads the frequency change, it changes the PWM2_DUTY value (single-cycle pulse number) of PWM2. According to (8), PWM2_DUTY changes, then the PWM2 frequency changes. When the output pulse width changes to \( N \), CCAP1h of PWM2 is \( N \), CCAP1l is PWM2_ DUTY-N, the PCA1 parameters are updated, and the new PWM2 waveform is output.

The system maximum frequency is 24M; according to the frequency division function of the chip, the frequency division number PCA_Clock can select 1, 2, 4, 6, 8, or 12, so PWM2 can be divided into frequencies: 24M, 12M, 6M, 4M, 3M, and 2M. Because PWM2 counter PWM2_DUTY is only 16bit and the maximum is 65536, the minimum PWM2 frequency \( f_{\text{min}} \), and min single pulse time \( T_{\text{min}} \) can be obtained as (9) and (10).

\[
f_{\text{min}} = \frac{2^{16}}{\text{PCA}\_\text{Clock}} \quad (9)
\]

\[
T_{\text{min}} = \frac{1}{\text{PCA}\_\text{Clock}} \quad (10)
\]

Table 1 shows the usable frequency, minimum frequency, and single pulse time of PWM2 generated by the PCA interrupt after frequency division. The output frequency range of PWM2 generated by the PCA interrupt of this system is between 31 Hz-24 MHz. The parameters can be adjusted on the touch screen for the output frequency and duty cycle.
A PWM of less than 31 Hz cannot be output by the PWM2 PCA interrupt, so the I/O port mode of the PWM2 pin output is set to push the free output mode through parameters when the output pulse frequency is less than 31 Hz, enabling the T2 timer function.

If a PWM2 with a frequency of \( F (f < 31) \) is needed, the duty cycle is \( D_{on2} \), T2 uses a frequency of 24M, and a T2 interrupt is generated by counting to 24000; the 1 ms time is a T2 interrupt. Therefore, the output of P3.5 requires a high number of T2 interrupts for a high level, and a low number of the interrupts for a low level. \( H_n \) and \( L_n \) are expressed as eqs. (11) and (12), respectively.

The T2 interrupt is then cyclically run using P3.5 to output high and low levels, thereby outputting the set waveform.

### IV. SYSTEM TEST

#### A. Boost Circuit Test

The circuit board prototype was constructed after the circuit design was completed, as shown in Fig. 7. After the circuit board is connected to the touch screen, the system parameters can be adjusted through the touch screen.

Selecting the first gear as 5-100 V by the touch display screen, the 5 V power is automatically connected as the boost input power. By adjusting the duty cycle, the voltage value after the boost was monitored by a voltmeter, and the data were recorded at 5 V as a record point.

Selecting the second gear at 100-200 V by the touch display screen, the 12 V power was automatically connected as the boost input power. By adjusting the duty cycle, the voltage value after the boost was monitored by a voltmeter, and the data were recorded at 5 V as a record point. The measurement results are shown in Table 2. The duty cycle was between 0-35.7% in the first gear and 14.3-29.4% in the second gear.

Taking the voltage as the abscissa, and the pulse number of the PWM1 duty cycle as the ordinate, we marked the point of the measurement results, drew the measurement results into a line, and obtained Fig. 8. It can be observed from (7) that \( ton^2 \) and \( V_o^*(V_o-V_i) \) have a proportional relationship. When \( V_o \) is greater, the linearity of \( ton \) and \( V_o \) is better, thus they can be approximated as a straight line. Fig. 8 shows that the first and second gears have good boost linearity, which conforms to the original design idea.
For more convenient use and less computational expenses, a one-dimensional linear function is used to express the relationship between the pulse and voltage. Through linear regression fitting, \( z \) is the number of duty cycle pulses, and \( y \) is the voltage value variable; the formulas below are obtained.

Eq. (13) is the 1st gear at 5-100 V:

\[
(13) \quad z = 89.581y - 461.91
\]

Eq. (14) is the 2nd gear at 100-200 V:

\[
(14) \quad z = 37.327y - 313.36
\]

It can be deduced that the accuracy of the 1st gear can reach 0.01 V from (13), whereas the accuracy of the 2nd gear can reach 0.03 V from (14).

**B. Output Waveform Test**

Based on the circuit design in Figs. 2 and 4, the waveform after simulation with the circuit design and simulation by DXP software is shown in Fig. 9. In Fig. 9, the abscissa represents time, whereas the ordinate represents the voltage. The upper red curve is the boost curve, and the lower blue line is the system output pulse wave. It takes only 14 ms to boost the voltage from 5 V to 55 V, and the wave after boosting is also stable. The simulated human body load was 1,000 Ω.

**C. Several Typical Waveform Designs**

In the field of electrotherapy, the common waveforms are the density wave, sine wave, triangle wave, etc., which can be output by controlling PWM1 and PWM2. In the first gear, sine or triangle waves with different frequencies and amplitudes can be output by setting; however, according to (13), when \( x \) is less than a certain value, it may be calculated as a negative, and should be set as 5 V when \( y \) is equal to 0, and 0 V when \( y \) is less than 0.

1) **Density Wave**

It is composed of two or more PWM2 waveforms with dif-
different frequencies. For example, if the voltage strength is 60 V, 5 Hz is executed for 1 s, 1 Hz is executed for 2 s, and the cycle output is carried out. The abscissa represents the time, whereas the ordinate is the voltage intensity. Fig. 10 can then be obtained.

2) Sinewave

The change in sine wave mainly consists of amplitude $A$, the time required for reciprocating vibration $T = \frac{2\pi}{\omega}$, $\varphi$ is referred to as the initial phase (i.e., phase when $x = 0$), and $b$ is the height, as shown in eq. (15).

$$y = A \sin \left( \frac{2\pi}{T} \times x^2_n + \varphi \right) + b \quad (15)$$

In this design, $\varphi = 0$ and $b = 0$, but $A$ and $T$ can be changed. $x^2_n$ can be obtained based on Eq. (15).

$$x^2_n = x^2_{n+1} + \Delta x^2 \times ((x\%\left(\frac{T}{4}\right) \leq \frac{T}{4}) \&\& (x\%\left(\frac{T}{4}\right) > 0)) - \Delta x^2 \times ((x\%\left(\frac{T}{4}\right) > \frac{T}{4}) - \Delta x^2 \times (x\%\left(\frac{T}{4}\right) = 0) \quad (16)$$

$\Delta x^2$ is the cycle time $T$ divided by the number of voltage changes. If the number of voltage changes is $K$, eq. (17) is obtained. For example, if the voltage changes to 40 times within 8 s of a cycle, then $\Delta x^2$ equals 0.2.

$$\Delta x^2 = \frac{T}{K} \quad (17)$$

Eq. (18) is obtained based on eqs. (13) and (15). Because there is no negative voltage, the absolute value is considered; $z$ is the number of duty cycle pulses required by PWM1.

$$z = 89.581 \left| A \sin \left( \frac{2\pi}{\frac{T}{4}} \times x^2_n \right) \right| - 461.91 \quad (18)$$

As $A=60$ V, $T=8$ s, $\Delta x^2 = 0.4$ s, and the period of PWM2 is equal to $\Delta x^2$. Time is the abscissa, and the system output pulse wave is the ordinate, as shown in Fig. 11.

3) Trigonometric Wave

Trigonometric waves are also critical in treatment. Trigonometry-wave neuromuscular electrical stimulation plays a unique stimulating effect in the treatment of denervation and also does not cause pain in normal neuromuscular contraction. Eq. (19) is the trigonometric wave's formula. $T$ represents the triangle wave period, $A$ represents the triangle wave height, and $x^2_n$ is the same as that in (16).

$$y = \frac{2A}{T} \times x^2_n \quad (19)$$

Eq. (20) is obtained based on (13) and (19); $z$ is the number of duty cycle pulses required by PWM1.

$$Z = 2687.43 \times x^2_n - 461.91 \quad (20)$$

As $A=60$ V, $T=4$ s, $\Delta x^2 = 0.4$ s, and the period of PWM2 is equal to $\Delta x^2$. Time is the abscissa, and the system output pulse wave is the ordinate, as shown in Fig. 12.

V. CONCLUSION

With the development of physiotherapy medicine and the demand of the physiotherapy market, an electrotherapy system based on a boost circuit was proposed. The system adopted an embedded and relatively simple circuit structure, which reduces cost as well as potential failure points.

The circuit design of the system was carried out, and the DC/DC boost and output wave circuit were designed in detail. The DCM boost method was adopted because the boost multiple was large and the load was small, and the inductance of the DCM boost circuit was calculated. The
boost PWM1 program and waveform PWM2 program were designed according to the MCU platform. Before the product was made, PCB 3D, circuit boost, and output pulse wave simulations were carried out using DXP software.

Technologies such as photoelectric isolation and dual MCUs were used in the system design, and the safety and reliability of the circuit were fully considered. The system had two gears: the normal 1st gear was 5-100 V, which was suitable for general scenarios, and the special 2nd gear was 100-200 V, which was suitable for various special needs. Separating them could reduce misuse and prevent side effects caused by using larger currents in ordinary physical therapy.

A production sample and MCU program were created according to the design, the graph was plotted by voltage monitoring, and the relationship between the PWM1 duty cycle pulse and voltage was obtained through linear regression. Density, sine, and triangle waves are often used in physiotherapy. Therefore, these three waves were calculated and designed according to their waveform characteristics and parameters.

The system can easily output low-frequency and partial intermediate-frequency pulses, which is equivalent to integrating the functions of low-frequency and intermediate-frequency physiotherapy instruments.

The system operates intuitively and conveniently. Users only need to adjust the touch screen to output various waveforms, intensities, and frequencies of the output waves, instead of using button and knob adjustments as is the case in traditional physiotherapy instruments, which are more in line with modern people’s habits.

The system boosts the PWM1 duty cycle pulse for adjustment in a large range, thus the continuity of the voltage regulation is good, and the accuracy of the ordinary 1st gear can reach 0.01 V, whereas that of the special 2nd gear can reach 0.03 V.

The system has good scalability, MCU1 has two independent serial ports, and can be used as five serial ports through time-sharing switching, which is convenient for expanding modules such as networking and radio frequency cards.

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