

Bipolar Triangular Wave Current Pulse Inverter for Shallow TEM Survey

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Abstract. A bipolar triangular wave current pulse inverter for shallow TEM survey is described. It can generate a peak current more than 10A and the PRF of the bipolar current pulse is between 1Hz and 10kHz. The proposed inverter contains a high voltage source circuit for the rising edge and a Zener diodes circuit with constant voltage clamping for the falling edge. Measurement results are presented, which show the high quality triangular wave current pulse with linear rising edge and rapidly turnoff falling edge.

1 Introduction

Triangular wave current pulse can be used for mineral exploration, unexploded ordnance exploration, hydrogeological survey, engineering geological survey, geological mapping and so on[1]. It also has several merits against square wave in ground penetrating. It has the advantage that the primary field is simple and it is suitable for shallow low-resistivity target detection, as well as early signal acquisition and processing[2].

In this letter, a high voltage source circuit and inverter bridge circuit are designed to generate the bipolar triangular wave current pulse. For high voltage source circuit, five power modules are connected in series to provide the high power with stable DC voltage. For the inverter circuit, it has a full-bridge circuit of four MOSFETs, which are driven by four isolated PWM signals given by MCU. High and constant voltage clamping circuit is the essential part of this inverter to make the current pulse rise lineally to peak current and fall down rapidly to zero during the turn-off time. Finally, we can obtain periodic triangular wave current pulse with peak values more than 10A and PRF of 1Hz to 10kHz for different applications.

2 Theoretical Analysis

For a load such as small air-core coil, it is typically equal to a resistor and an inductor connected in series[3]. For a current pulse with linear edges, the corresponding voltage of the coil should be linear too. The reason will be described soon. A positive triangular wave current pulse is depicted in formula (1), and the negative cycle is the same to the positive one, except the polarity is different.

$$i(t) = \begin{cases} \frac{I_m}{t_r} t, & 0 \leq t < t_r; \\ I_m \left(1 - \frac{t - t_r}{t_f}\right), & t_r \leq t < t_r + t_f; \\ 0, & t_r + t_f \leq t < \frac{T}{2}. \end{cases} \quad (1)$$

where t_r is the rising time of the current pulse and t_f is the falling time of the current pulse. I_m is amplitude of the peak current. T is the period of the current pulse. The corresponding equations of the coil is as following

$$\begin{cases} u_L(t) = L \frac{di(t)}{dt} \\ u_R(t) = Ri(t) \\ u(t) = u_L(t) + u_R(t) \end{cases} \quad (2)$$

where $u(t)$ is the voltage of the coil. L and R are the inductance and resistance of the load respectively. According to the formula (1) and the formula (2), the $u(t)$ is shown as formula (3)

$$u(t) = \begin{cases} \frac{LI_m}{t_r} + \frac{RI_m}{t_r} t, & 0 \leq t < t_r; \\ \frac{LI_m}{t_f} + RI_m \left(1 - \frac{t - t_r}{t_f}\right), & t_r \leq t < t_r + t_f; \\ 0, & t_r + t_f \leq t < \frac{T}{2}. \end{cases} \quad (3)$$

In practical application, it is difficult to generate this kind of voltage, so an approximate solution is applied. For a small air-core coil, it can be inferred that $Ldi(t)/dt \gg Ri(t)$, that is $u_L(t) \gg u_R(t)$, so $u(t)$ can be simplified to a constant voltage in formula (4)

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$$u(t) = \begin{cases} \frac{LI_m}{t_r}, & 0 \leq t < t_r; \\ \frac{LI_m}{t_f} + RI_m \left(1 + \frac{t_r}{t_f}\right), & t_r \leq t < t_r + t_f; \\ 0, & t_r + t_f \leq t < \frac{T}{2}. \end{cases} \quad (4)$$

With a constant voltage, the exact formula of the current is showed below. The time constant τ of the coil can be get from $\tau = L/R$, U_z is the constant clamping voltage of the falling edge.

rising edge

$$i_r(t) = \frac{U}{R} \left(1 - e^{-\frac{t}{\tau}}\right), 0 \leq t < t_r \quad (5)$$

Falling edge

$$i_f(t) = \left(I_m + \frac{U_z}{R}\right) e^{-\frac{t-t_r}{\tau}} - \frac{U_z}{R}, 0 \leq t < t_r \quad (6)$$

The value of t_r and t_f is shown in formula (7)

$$t_r = \tau \ln\left(\frac{U}{U - RI_m}\right), t_f = \tau \ln\left(1 + \frac{RI_m}{U_z}\right) \quad (7)$$

The derivative of the rising stage and the falling stage can be obtained by formula (8) and formula (9)

$$\frac{di_r(t)}{dt} = \frac{U}{L} e^{-\frac{t}{\tau}}, 0 \leq t < t_r \quad (8)$$

$$\frac{di_f(t)}{dt} = -\frac{1}{L} (RI_m + U_z) e^{-\frac{t-t_r}{\tau}}, t_r \leq t < t_r + t_f \quad (9)$$

In general, if $e^{-\frac{t}{\tau}} > 0.95$ [4], that is $t/\tau < 0.0513$, the $i_r(t)$ and $i_f(t)$ are deemed to be linear. The condition of the resistance of the coil can be simplified as (10)

$$\ln\left(\frac{U}{U - RI_m}\right) < 0.0513, \ln\left(1 + \frac{RI_m}{U_z}\right) < 0.0513 \quad (10)$$

3 Inverter Circuit

From the analysis above, it is obviously that how to provide a high and constant voltage is the key point of the circuit. For the triangular wave current pulse, high voltage can be applied to make the current rise up and fall down linearly. Therefore, we apply active constant voltage[5] clamping to the rising edge and passive constant voltage clamping to the falling edge. The high voltage generation circuit for active constant voltage clamping is shown in Fig. 1.

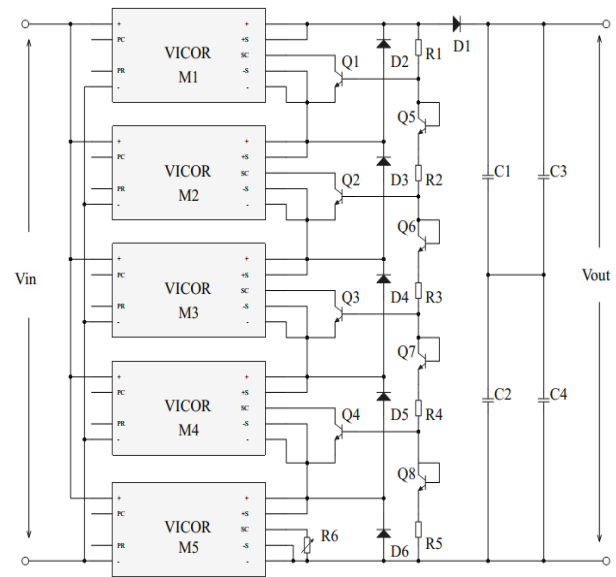


Fig. 1. High Voltage Generation Circuit.

VICRO module V24B48C250BL is chosen for the triangular wave pulse generation. It has input voltage of 24V, maximum output voltage of 48V. The power of this module is 250W and the maximum current output is 7A. 5 modules connected in series are needed to generate rising edge of the triangular wave. The total clamping voltage of the 5 modules is up to 240V. In this circuit, the diode D1 isolates the high voltage source and the inverter circuit. Diodes D2 to D6 protect each power module. Capacitors C1 to C4 are applied to store energy and increase the maximum current limit and their values are 220 μ F.

For this application, the output voltage of the module is required to be adjusted. The configuration of Fig. 1 provides a reliable and inexpensive solution to realize voltage adjusted by R6 with a value of 10k Ω . In this solution, resistors R1 to R5 are all equal and their values are 10k Ω . All the transistors Q1 to Q8 are 2N222. The effect of Q1 to Q8 is to adjust the voltage of each converter. When the output voltage of the converter M5 is adjusted, the voltages of convert M1 to M4 also change until they are all equal to the voltage of M5. Thus, the five converters have an effect on the total output voltage.

The full bridge circuit is shown in Fig. 2 and it has four MOSFETs[6]. The MOSFET module is SCT2280KE of ROHM Semiconductor. As mentioned above, a high-voltage passive clamping is used to the falling edge because the current must turn off as soon as possible to provide wide-band high frequencies for shallow TEM explorations.

When the power is supplied, QUL and QDR are turned on first, and the current passes D7, QUL, L, R and QDR to generate positive pulse[7]. Because the coil is inductive, the current rises in linear rule by the work of the high voltage circuit. When the current reaches the peak amplitude, QUL and QDR are turned off and QSW is turned on to let the current in the coil to go through the damping resistor RESn. At this time, the current has two ways to go. One way is to pass through the diode of QUR and QDL, diode D8 and Zener diodes circuit, the other one is to pass through QSW and RESn. The Zener diodes

circuit form the high-voltage passive clamping circuit. The Zener diodes are 1N5369B which has Zener voltage of 51V, so the total clamping voltage of 10 diodes is about 510V. The capacitors C9 and C10 in parallel to the Zener diodes are used for protecting the Zener diodes from damage if the power is too large. The resistors R11 and R12 with value of 100kΩ are used to discharge the contour of C9 and C10. The effect of the damping resistor RESn is to suppress current overshoot when the current decays to zero. What the value of RESn is selected depends on the coil.

Due to stray parameters[8] of the entire system, there is a high frequency oscillation at the early part of the turn-off current when the switch is suddenly cut off. The oscillation will affect the early electromagnetic data, so a RCD circuit parallel to each MOSFET is added to absorb and decrease the oscillation current[9].

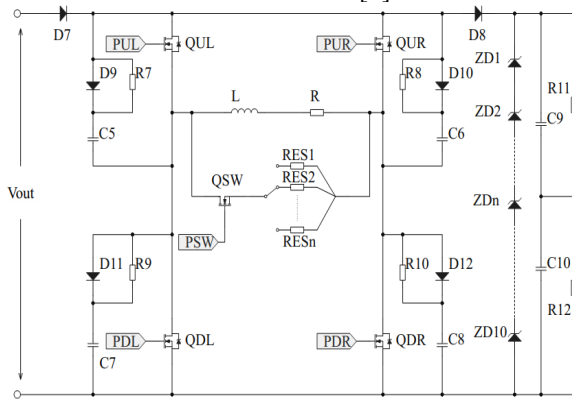


Fig. 2. Circuit Diagram.

4 Measurement

We use two different coils, the Coil A and Coil B to test the triangular wave current inverter. Both of the coils are 1m×1m square shape. The Coil A has 30 turns and the cross section of the wire is 2.5mm². It is equal to a 2Ω resistor connected in series with a 3mH inductor. The Coil B has 25 turns and the cross section of the wire is 4mm². It is equal to a 281mΩ resistor connected in series with a 1.65mH inductor. A high-accuracy current probe and high-voltage differential probe are used to measurement the current and the voltage waveforms of the coils.

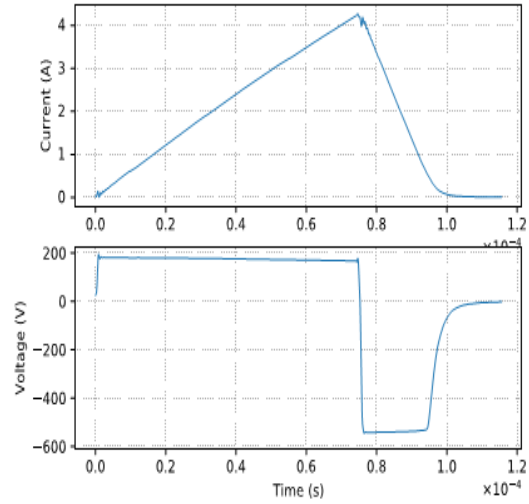


Fig. 3. Current and Voltage of Coil A.

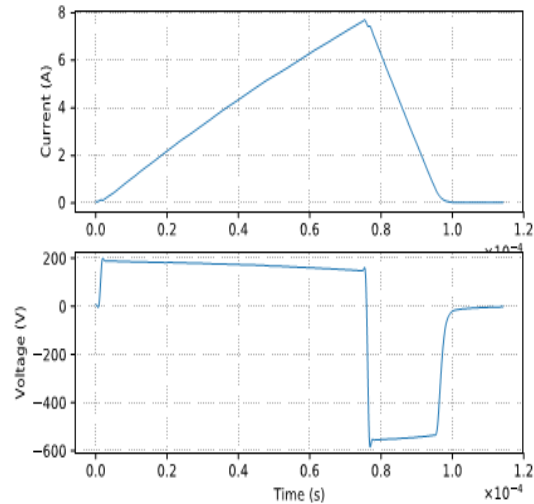


Fig. 4. Current and Voltage of Coil B.

The results of Coil A are shown in Fig. 3 and the results of Coil B is shown in Fig. 4. From Fig. 3 and Fig. 4, the current rises linearly to the peak in 75μs with the constant clamping voltage of 200V. The current in Coil A reaches 4.3A and decays to zero in 24.5μs. The current in Coil B reaches 7.7A and decays to zero in 22.6μs. The turn-off current in both coils decay linearly and rapidly with the constant clamping voltage of 510V. Because they both have high linearity rising edge and falling edge, the quality of the triangular wave current is very good for applications.

However, there is a flaw of small oscillation in the current waveform due to the stray parameters and the oscillation of Coil B is smaller than Coil A. The designed RCD circuit could reduce but cannot completely remove the oscillation, so there will be a future work to suppress the oscillation and further enhance the quality of the current waveform.

5 Conclusions

The key point of the present circuit is how to generate triangular wave pulse current in practical application. At all, the circuit present above is able to produce a high

quality triangular wave pulse current with linear rising edge and linear and rapid falling edge. The peak current is more than 10A and its peak power is 1000W. The PRF of the pulse inverter is between 1Hz and 10kHz. It can completely meet the requirements of the practical application.

Acknowledgements

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References

1. G. Hodges, T. Chen, *Exploration Geophysics*, **46**, 58-63(2014)
2. B. Nikls, H. Garbe, M. Schaarschmidt, *International Symposium on Electromagnetic Compatibility - Emc Europe*, 1-6(2017)
3. B. K. Sternberg, S. L. Dvorak, W. Feng, *Journal of Applied Geophysics*, **136**, 211-218(2017)
4. K. Schoeman, P. Meyer, D. I. L. D..Villiers, *Africon*, 1-5(2013)
5. Y. Moursy, R. Iskander, M. M. Louërat, *Mixed-Signal Testing Workshop*, 1-6(2015)
6. B. Niklas, H. Garbe, M. Schaarschmidt, *International Symposium on Electromagnetic Compatibility-Emc Europe*. 1-6(2017)
7. H. S. Saini, J. M. Martinez, L. A. C. Lopes, *Iet International Conference on Power Electronics, Machines and Drives IET*, 1-6(2014)
8. J. A. Ferreira, Kane, I. J. Klinkert, *IEEE Transactions on Industry Applications*, **40**, 213-219(2017)
9. M. Stork, *Radioelektronika. IEEE*, 1-4(2017)