Research on Precise Damping Matching for Transient Electromagnetic Transmitter

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Abstract. A method is introduced to precisely match the damping resistor of different transmitting coils via the output port of the transient electromagnetic transmitter. Theoretical analysis of the distributed parameter model of the transmitting coil are described. Equations calculating the critical damping resistor are derived from the self-inductance, internal resistance, and the distributed capacitance of the transmitting coil, accordingly. Extensive experiments demonstrate that the proposed method can rectify the overshoot and oscillation phenomenon of the emission current during the late period of the turn-off.

Introduction

Transient electromagnetic method (TEM) is a geophysical exploration method, which also known as time domain electromagnetic method [1]. Transient electromagnetic system consists of transmitter, receiver and data processing software. The principle of the system is transmitter sends a constant amplitude current pulse to ground periodically through ungrounded transmitting coil, which can create a primary pulse magnetic field under the ground. Then, primary pulse magnetic field can induce eddy current if there has a conductive medium under the ground. When turn off the pulse, receiving coil can receive the secondary magnetic field generated by the eddy current. The underground geological structure can be obtained after secondary magnetic field data analyzed and processed by data processing software [2-3].

The ideal emission current waveform send by transient electromagnetic transmitter is bipolarity constant amplitude rectangular wave [4]. In practice, however, emission current falling edge is exponentially because of the load is an inductor, which has self-inductance and parasitic capacitance. Therefore, the actual response is second order underdamped response, which can lead to overshoot and oscillation phenomenon of the emission current during the late period of the turn-off [5]. It will affect early signal of secondary magnetic field seriously. One method widely used to accelerate the emission current decrease and reduce oscillation, is to use a damped resistor in parallel with the coil to ensure system to be critical damping response, and the resistor value varies according to the coil parameters, and cooperating with the voltage stabilizing clamp technique for increasing the emission current falling edge slope [5].

Voltage Stabilizing Clamp Fast turn-off Principle

Literature [5] pointed out that using voltage stabilizing clamp fast turn-off transmitting circuit, as shown in Figure 1, can adjust the emission current falling edge. In Figure 1, the dotted line frame 1 is clamp circuit, and the dotted line frame 2 is adjustable constant pressure source. When turn off the forward power supply, emission current \( i(t) \) begins to drop, current forms a continuous loop through
load $L$, $D_7$, $C_1$ and $D_2$. If the voltage value $u_{c_1}$ remains constant during current turn-off, the emission current will decrease linearly, and the pace of decline is proportional to voltage value.

In Figure 1, resistor $r$ is damping resistor that match with the transmitting coil. It is necessary to adjust the resistor value to rematch after changing coil or coil turns. Therefore, it is difficult to achieve the best match in practical applications. In this paper, a method and device for automatically and precisely match the damping resistor is introduced to cope with this disadvantages.

**Matching Damping Resistor**

**The Basic Principle of Damping Absorption**

Transient electromagnetic transmitter transmitting coil divided by size can be into two types: big loop and small coil with multiple turns. The equivalent circuit model of small coil with multiple turns not only includes the coil inductance and the internal resistance, but also the distributed capacitance between the turns, this will lead to a typical second order response [6]. If connecting the constant voltage clamp circuit but without the absorption circuit, then the overshoot and oscillation phenomenon of the emission current usually occur during the late period of the turn-off [7]. The equivalent circuit of transmitter coil is shown in Figure 2.

In Figure 2, $u_c(t)$ is clamp voltage of the transmitting coil, $R$ is internal resistance, $L$ is the coil inductance, $C$ is parasitic capacitance, $r$ is damping resistor and $u$ is voltage source.

It can be knew from Figure 2 that the equivalent circuit is second order circuit, and formula (1) can be obtained by the circuit structure and Kirchhoff’s law.

$$\begin{align*}
C \frac{du(t)}{dt} + \frac{u(t)}{r} &= i(t) \\
L \frac{di(t)}{dt} + i(t)R + u &= 0
\end{align*}$$

$$
\begin{cases}
    C \frac{du(t)}{dt} + \frac{u(t)}{r} = i(t) \\
    L \frac{di(t)}{dt} + i(t)R + u = 0
\end{cases}
$$
According to formula (1), the time domain expression of this model can be expressed as:

$$\frac{d^2 u(t)}{dt^2} + \left(\frac{R}{L} + \frac{1}{rC}\right) \frac{du(t)}{dt} + \frac{1}{LC} \left(\frac{R}{r} + 1\right) u(t) = 0$$  

(2)

The simplified form is:

$$\frac{d^2 u}{dt^2} + 2\delta \frac{du}{dt} + \omega^2 u = 0$$  

(3)

Where:

$$\delta = \frac{1}{2} \left(\frac{R}{L} + \frac{1}{rC}\right)$$

$$\omega^2 = \frac{1}{LC} \left(\frac{R}{r} + 1\right) = \omega_0^2 \sqrt{\frac{R}{r} + 1}$$  

(4)

Where, $\omega_0$ is transmitting coil resonant frequency, and $\omega_0$ is natural resonant frequency.

From this, it can be seen that the emission current turn off process is a second order response. It can be divided into three states: over damping, under damping and critical damping [8]. Among this, both over and under damping are transient processes with oscillations. Besides the two states, the critical damping state can avoid concussion [9].

The damping coefficient can be defined as:

$$\zeta = \frac{\delta}{\omega_p} = \frac{RrC + L}{2\sqrt{rLC} \left(\frac{R}{r} + 1\right)}$$  

(5)

When $\zeta > 1$, the response is over damping. When $\zeta < 1$, the response is under damping. When $\zeta = 1$, the response is critical damping.

From formula (5), it can be seen that the damping coefficient is related to the coil internal resistance, self-inductance, parasitic capacitance and damping resistor. If we want to get the critical damping state, the damping resistor value should be changed with the coil parameters. In order to reduce interference and increase exploration depth during using small coil with multiple turns, usually necessary to increase the number of turns to improve the magnetic moment. But the coil self-inductance, internal resistance and parasitic capacitance changes with the number of turns, therefore, the previous matched damping resistor cannot match the new coil. And the response will no longer be critical damping response if damping resistor is not changed, which still can lead to overshoot and oscillation phenomenon of the emission current during the late period of the turn-off.

**Calculating of the Coil Equivalent Circuit Parameters**

Different transmitting coils parameters must be solved in advance and results should be stored in order to achieve precisely match the damping resistance. It can be queried as raw data when adjusting the damping resistance in the later period.

The formula for calculating the resistance value

$$R = \frac{\rho l}{S}$$  

(6)

Where $\rho$ is coil wire resistivity, $l$ is wire length and $S$ is wire cross-sectional area.

Calculating the transmitting coil self-inductance is based on the formula proposed by Kalantarov and Tseytlin in the 1955s.

$$L = \frac{\mu_0}{4\pi} N^2 d\Phi$$  

(7)
Where \( d \) is the transmitting coil diameter, \( N \) is the number of turns, \( \mu_0 \) is the magnetic permeability in vacuum, and \( \Phi \) calculating formula can refer to coil model of the short spiral tube when the value of \( k (k = \frac{\mu_0}{\Phi}) \) is small.

\[
\Phi = 2\pi \left[ \frac{k^2}{8} - \frac{k^4}{64} + \cdots \right] \ln \left( \frac{k}{4} + \frac{k^2}{32} \right) + \frac{k^4}{96} + \cdots
\]

(8)

The distributed capacitance between multiple turns is an important factor cause to overshoot and oscillation phenomenon of the emission current during the late period of the turn-off. And the value is related to the coil wire cross-sectional area, the insulation layer thickness and the distance between coil turns. Especially for transmitting coil with tight structure between turns, the insulation layer thickness will be the turns distance affecting the distributed capacitance.

\( N \)-turns coil distribution capacitance equivalent network structure is shown in Figure 3. Literature [10] pointed out that each coil can be equivalent to one node, and the node-to-node capacitance is calculated by a finite element model using the Maxwell 2-D electrostatic axisymmetric solver. The equivalent lumped distributed capacitance \( C \) between two terminal nodes can be calculated by calculating the parasitic capacitance of each turn and using Matlab software proper matrix operation to eliminate the intermediate nodes.

![Figure 3. Node-to-node lumped capacitance network.](image)

Different transmitting coils distributed capacitance value can be calculated in advance, and storing the result in computer to be used as raw data in field application.

**Matching Damping Resistor**

When \( \zeta = 1 \), the critical damping response can be obtained. And combine formula (5), the damping resistor formula associated with transmitting coil each parameter also can be obtained.

\[
r = \frac{L}{RC + 2\sqrt{LC}}
\]

(9)

From formula (9) can be knew, if the transmitting coil internal resistance, self-inductance, distributed capacitance and damping resistor value are calculated by previous formulas, the matching damping resistor value can be obtained. Table 1 presents the calculated self-inductance, parasitic capacitance and damping resistor of the equivalent transmitting coil circuit for various radii \( r \) and numbers of turns \( N \) when the effective area of the transmitting coil is 128\( \text{m}^2 \). We observe from table 1 that, as the number of turns increases and the radius of transmitting coil loop decreases, the equivalent internal resistance and self-inductance increase, whereas the capacitance decreases.

| \( N \) | 2  | 4  | 8  | 16 | 32   |
|-------|----|----|----|----|------|
| \( r \) [m] | 4.515 | 3.192 | 2.257 | 1.596 | 1.129 |
| \( R \) [\( \Omega \)] | 0.493 | 0.697 | 0.985 | 1.393 | 1.971 |
| \( L \) [\( \text{mH} \)] | 0.197 | 0.495 | 1.211 | 2.893 | 6.676 |
| \( C \) [\( \text{pF} \)] | 3822 | 992.2 | 346.8 | 140.6 | 62.53 |
Precisely Match and Adjust Damping Resistance Method

A method is introduced to precisely match and adjust the different transmitting coils damping resistor. This method through searching list of different transmitting coils parameters, and driving silicon-controlled to complete matching damping resistor automatically. Device circuit is shown in Figure 4, and components include photoelectric ($U_5$~$U_{12}$), bidirectional silicon-controlled ($Q_1$~$Q_4$), field-effect tube ($U_1$~$U_4$), filter capacitor ($C_1$~$C_4$), Matching resistor ($R_1$~$R_4$) and current limiting resistor ($R_9$).

Where, $R_1$~$R_4$ are damping resistors available to connected. The output port 1 and 2 connect transmitting coil, and all the control signal are provided by computer. If system does not detect an access signal, bidirectional silicon-controlled ($Q_1$~$Q_4$) are in turn off state. At this time, the damping resistor is in series with the filter capacitor ($C_1$~$C_4$) and resistor ($R_5$~$R_8$) branch, then parallel to the transmitting coil. Because the capacitor value of $C_1$~$C_4$ is small, the resistor value of $R_5$~$R_8$ is larger. Therefore, it’s equivalent to four RC high frequency filter circuits are connected to the transmitting coil, which will not affect the transmitting coil circuit model response nature. When the damping resistor is required, such as $R_1$, computer give a signal to field-effect tube $U_1$, and control the photoelectric $U_5$ and $U_6$, which drive the bidirectional silicon-controlled $Q_1$. Then the RC branch $C_1$ and $R_5$ are short-connected by $Q_1$, and the damping resistor $R_1$ can be connected to the transmitting coil. This device matching resistor can reach 16 combinations if all resistors value chose different from each other. In practical application, the device can call the transmitting coil parameters stored in computer, and the critical response damping resistor matching with the coil can be found. Then connecting the resistor to the coil by the above method.

Experiment

Two comparison experiments were conducted to verify the device feasibility. Transmitting coil unmatched damping resistor current waveform is shown in Figure 5. It can be seen that overshoot and oscillation phenomenon of the transmit current during the late period of the turn-off. Transmitting coil precisely matched damping resistor current waveform is shown in Figure 6. It can be seen that the transmit current is smooth and no overshoot during the late period of the turn-off. The experiment results show that the device is effective in improving the overshoot and oscillation phenomenon.

Figure 4. Automatic matching damping resistor device.

Figure 5. Unmatched damping resistor current waveform.  
Figure 6. Matched damping resistor current waveform.
Conclusion

A method is introduced to precisely match the damping resistor of different transmitting coils via the output port of the transient electromagnetic transmitter. The transmitting coil distributed parameters model had been researched and formula of those parameters are derived. The critical damping resistor value calculating formulas are derived from the self-inductance, internal resistance and the distributed capacitance of the transmitting coil. Experimental results show that the device can through searching list of different transmitting coils parameters, and driving silicon-controlled to complete matching damping resistor automatically. In general, this device can improving emission current overshoot and oscillation phenomenon during the late period of the turn-off, and remedy conventional transient electromagnetic transmitter defects, which only match one damping resistor for a specific transmitting coil, but cannot automatically and precisely match the damping resistor after adjusting the transmitting coil.

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