Modeling and Design of a Wideband Electromagnetic Logging Detector

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Abstract. Due to the increasing complexity of oil and gas exploration objects, it is necessary to study the electrical properties of rocks in different frequency bands. At present, electrical properties of formation such as resistivity and phase change of electromagnetic propagation have attracted great attention in petroleum industry. In this paper, the influence of working frequency for tools, coil distance, mud in borehole, formation conductivity and other measuring conditions on detector signal is studied through numerical modeling, and the key circuit design technology of data acquisition of detector for wideband electromagnetic logging is preliminarily discussed. The modeling results can provide theoretical analysis for the design of parameters and data acquisition circuit of the detector, and lay a foundation for the accurate study of oil saturation of rock and the determination of reservoir fluid properties.

1. Introduction

Electric logging is one of the earliest major logging methods used to evaluate oil and gas properties in petroleum industry. Electromagnetic (EM) logging technology can be used to determine the water saturation of the formation to judge the oil-water layer. The methods commonly are used to measure the electrical properties of rocks including the electrode method and the coil method. Electromagnetic wave is transmitted to the formation through transmitting coil or transmitting electrode, and then the phase difference and amplitude ratio of electromagnetic wave from the formation are measured. The formation resistivity and dielectric constant can be obtained, according to the functional relationship between them. Since the coil method eliminates the frequency component of the signal source, the measurement results of the coil method can reflect the electrical parameters and dispersion characteristics of the rock more accurately than the electrode method\cite{1}. Xinjiang oilfield logging company added a high frequency current of about 10kHz on the basis of double laterality, and used the modulus difference between the measured real resistivity at low frequency and resistivity at high frequency as the oil and gas indication standard, so as to evaluate the oil and gas bearing characteristics of the formation\cite{2}. In 2005, Liaohe petroleum exploration bureau obtained the patent CN2680855, "a frequency domain complex resistivity tool". In 2008, a combined measurement method of the phase difference and the amplitude ratio for the electromagnetic propagation resistivity logging was put forward by defining a new mathematical expression about the amplitude ratio\cite{3}. In 2010, a high-frequency electromagnetic-wave logging tool has been developed to detect the dielectric constant and resistivity of the sedimentary formation by measuring the phase difference and amplitude.
ratio synchronously[4]. In 2014, the logging response of the layered media to the LFMCWs under the noise environment has been numerically modeled using numerical mode matching (NMM) and inverse fast Fourier transform (IFFT)[5]. Xiao fei et al. simplified the electromagnetic wave model by using the properties of Lambert W and obtained the analytical expression of the nonlinear equation, also they studied the working parameters of dielectric logging tool by using the numerical method[6]. Jin Mat et al. proposed an effective non-conformal finite element domain decomposition method to solve the problem of complex sensor array included in electromagnetic logging model[7]. In 2018, Decheng Hong et al. presented a set of compact formulations to model the response of the electromagnetic well-logging tools in eccentric multilayered medium. Numerical results show that the effect of insulating protection layer gradually appears with the increase of the eccentric distance[8]. In 2011, Schlumberger obtained the invention patent "Applications of wideband EM measurements for determining reservoir formation properties" authorized by US Patent Office's. The invention uses electromagnetic field to stimulate the reservoir to measure the electromagnetic signal in the formation, extract the spectral complex resistivity changing with frequency, and finally obtains the electrical characteristics of the formation by using the induced polarization model. Baker hughes inc. obtained a U.S. license to determine formation characteristics, including resistivity or conductivity of formation fluids, dielectric constant of dry rock matrix, and water-bearing porosity of formations, using real and imaginary parts of propagating resistivity measurements.

At present, wideband electromagnetic logging has been paid more and more attention by oilfield companies and engineering service companies for its ability to measure dielectric constants and conductivity at different depths. Yang zhenwei et al. introduced the research progress of the complex resistivity method in recent years from the aspects of tools, equipment and mathematical models of the complex resistivity method, and proposed that the forward modeling of complex resistivity based on Maxwell equation is the forefront and hotspot of the research[9]. Liu Sixin et al. introduced a multi-frequency electromagnetic wave logging system for experimental purposes. The test and data simulation show that the multi-frequency electromagnetic wave oil well program is feasible[10]. In this paper, the basic theory of the broadband electromagnetic logging is introduced firstly. Then the influence of borehole, formation, working parameters on the detector characteristics is discussed using Ansoft Maxwell software, forming detector response rule, which lays the theoretical and methodological foundation for the realization of broadband electromagnetic logging tools and the correction of influencing factors. Furthermore, the design for function module of the detector is preliminary discussed.

2. Broadband electromagnetic logging principles

2.1. Wave equation for electromagnetic logging [11-12]

\[ \varepsilon \nabla \times e^{-1} \nabla \times \mathbf{H} - \omega^2 \mu \varepsilon \mathbf{H} = i \omega \varepsilon \mathbf{J}_m \]  
\[ \mu \nabla \times \mu^{-1} \nabla \times \mathbf{E} - \omega^2 \mu \varepsilon \mathbf{E} = i \omega \mu \mathbf{J}_e \]

Under the condition of axial symmetry, the axial Z component can be used to characterize the tangential component of the field in any locally uniform and passive region:

\[ H_z = \frac{1}{k^2 - k_z^2} \left[ \frac{\partial}{\partial z} \nabla, H_z + i \omega \varepsilon \hat{z} \times \nabla, E_z \right] \]

\[ E_z = \frac{1}{k^2 - k_z^2} \left[ \frac{\partial}{\partial z} \nabla, E_z - i \omega \mu \hat{z} \times \nabla, H_z \right] \]

Meanwhile, the axial field component satisfies the following two-dimensional wave equation in any locally homogeneous and passive region:

\[ \left( \nabla_n^2 + k_n^2 \right) H_z = 0 \]
This transforms a three dimensional problem into a two dimensional eigenproblem. The eigenmode of the field can be calculated by semi-numerical and semi-analytical methods. Finally, the recombined solution will be determined by the shape of the excitation source. The borehole formation boundary meets the following conditions:

\[
\frac{\partial \varphi}{\partial n} = 0 \quad r \in \pi \\
\varphi \to 0 \quad r \to \infty \\
\varphi_+ = \varphi_- \\
\sigma_+ \frac{\partial \varphi^+}{\partial n} = \sigma_- \frac{\partial \varphi^-}{\partial n}
\]  

The potential at any point on the well axis is \( \varphi \). Actually the \( \varphi \) at any point of well axis should be solved. That is, we're going to solve for \( \varphi \) at every point in the well. The Poisson equation with boundary value above needs to be solved, and different potential can be obtained under different boundary conditions.

### 2.2. Response signal calculation

1. Phase difference (\( \text{ang}_d \))
   
   \[ \text{ang}_d = \text{ang}_\text{deg}(\text{Matrix1.Z(Current1,Current_1)})) - \text{ang}_\text{deg}(\text{Matrix1.Z(Current1,Current_2))} \]

2. Amplitude ratio (\( \text{mag}_r \))

   \[ \text{mag}_r = \text{mag}(\text{Matrix1.Z(Current1,Current_1)})/\text{mag}(\text{Matrix1.Z(Current1,Current_2)}) \]

3. Induced voltage (\( V_{\text{mag}} \))

   \[ \sqrt{\text{re}(\text{Matrix1.L(Current1,Current_1))}^* + \text{im}(\text{Matrix1.L(Current1,Current_1))}^*} \]

### 3. Borehole response

#### 3.1. Mud conductivity

| mud_con (S/m) | V_mag (V) | ang_d (°) |
|--------------|-----------|-----------|
| 0.01         | 7.6107815762e-6 | 1.08717739278321e-8 |
| 0.017783     | 7.6107815499e-6 | 1.08717739045560e-8 |
| 0.031623     | 7.6107815032e-6 | 1.08717738625879e-8 |
| 0.056234     | 7.6107814199e-6 | 1.08717738321218e-8 |
| 0.1          | 7.6107812715e-6 | 1.08717736562755e-8 |
| 0.177828     | 7.6107812715e-6 | 1.0871389921594e-8 |
| 0.316228     | 7.6107812715e-6 | 1.0871389511035e-8 |
| 0.562341     | 7.6107812715e-6 | 1.08713887702324e-8 |
| 1            | 7.6107812715e-6 | 1.08713874516423e-8 |

Fig. 1 Relationship between mud conductivity and induced signals

The change of detector response characteristics is observed when the default value of rock conductivity is 1S/m, and the mud conductivity changes from 0.01S/m to 1S/m. Table 1 shows the induced voltage and phase difference data measured at different mud conductivity at 2MHz transmitter frequency. From figure 1, under a certain formation conductivity, when the mud conductivity
(mud_con) is between 0.01S/m and 0.1S/m, the mud conductivity has little influence on the induced voltage, which is conductive to measure response characteristics. When the conductivity of mud in well is greater than 0.1S/m, the induced voltage attenuation of the electromagnetic wave is very fast, which is not conductive to measurement. Namely electromagnetic logging is not suitable for low-resistivity mud.

3.2. Well hole radius

The logging response can be observed in table 2, when mud conductivity (mud_con) is 1S/m and formation conductivity (rock_con) is 0.1S/m, the hole radius (X mud) value is changed from 0.8mm to 8mm. Figure 2 shows that the induced voltage decreases with the increase of borehole in a certain range.

| Xmud (mm) | V_mag (V) | ang_d (°) |
|-----------|-----------|-----------|
| 0.8       | 7.6107812715e-6 | 1.0871736562755e-8 |
| 1.4226325803114 | 7.3586689696e-6 | 7.2823569939965e-9 |
| 2.5298221281347 | 7.0334049513e-6 | 4.8819011934453e-9 |
| 4.49873060152279 | 6.6834516458e-6 | 3.6424730653864e-9 |
| 8.0       | 6.3116611386e-6 | 3.17492023431829e-9 |

3.3. Formation conductivity

| rock_con (S/m) | V_mag (V) | ang_d (°) |
|----------------|-----------|-----------|
| 0.1            | 1.0366303965e-7 | 1.0857145695963e-11 |
| 0.0177828      | 1.0366305992e-7 | 1.08571456672171e-11 |
| 0.0316228      | 1.0366304046e-7 | 1.08571456145231e-11 |
| 0.0562341      | 1.0366304026e-7 | 1.08571455211409e-11 |
| 1              | 1.0366304056e-7 | 1.08571453465911e-11 |
| 0.1778279      | 1.0366304013e-7 | 1.08571454162558e-11 |
| 3.162278       | 1.0366304255e-7 | 1.08571454354071e-11 |
| 5.623413       | 1.0366304469e-7 | 1.08571429611714e-11 |
| 10             | 1.0366304841e-7 | 1.08571397919821e-11 |

Fig.4 Influence of rock conductivity on phase difference

![Fig.4 Influence of rock conductivity on phase difference](image-url)
As the default mud conductivity value is 0.1S/m and the rock conductivity is changed from 0.1S/m to 10S/m, the response data of electromagnetic logging are shown in table 3.

From figure 3, it can be found that the increase of formation conductivity will lead to a slight increase of induced voltage at the mud conductivity 0.1S/m and the uniform geological body as a single formation. When the ratio of rock resistivity and mud resistivity is greater than 0.01, that is, the mud resistivity is greater than 100 times the formation resistivity, and the measured value response is relatively obvious. From figure 4, it can be found that the phase difference slightly decreases with the increase of formation conductivity. Similarly, the effect of rock conductivity on amplitude ratio remains almost unchanged.

4. Working parameters response

4.1. Coil current

As shown in table 4, electromagnetic logging response characteristics is observed with the single variable current (I) changed from 10A to 500A. From figure 5, when the current is increased, the induced voltage shows a significant upward trend. From figure 6, the phase difference shows a very weak decreasing trend when the number of turns of the coil is increased. That is, the current is increased. When I is greater than 100A, the phase difference is extremely small.

4.2. Coil spacing

| Tab.5 Influence of antenna transmitting position on induced voltage | Tab.6 Influence of antenna transmitting position on phase difference |
|---|---|
| z_position (mm) | V_mag (V) | z_position(mm) | ang_d (°) |
| 1.650 | 8.40605195e-6 | 2.88 | 1.0941199261262e-8 |
| 1.298 | 8.642255952e-6 | 2.23 | 1.3348795829731e-8 |
| 1.311 | 8.63099817e-6 | 1.44 | 1.6640776144256e-8 |
| 0.993 | 8.87334858e-6 | 0.85 | 2.1029053257781e-8 |
| 0.7543 | 9.06378106e-6 | 0.36 | 4.0382615421166e-8 |
| 0.557 | 9.35602666e-6 | 0.30 | 4.0651277212975e-8 |
| 0.367 | 9.65386752e-6 | 0.23 | 2.8212058611362e-8 |
| 0.159 | 9.94448201e-6 | 0.15 | 1.3325199330072e-8 |

Figure 7 is a schematic diagram of the position of the detector transmitting source. Given the number of turns and the current unchanged, the radius of the coil and the distance between the two receiving coils fixed, and the position of the transmitting source on the z-axis changed, the response rules of the detector are analyzed.
Fig. 8 Relationship between coil spacing and induced voltage

The data of coil distance (z_position) and induced voltage are shown in table 5. From figure 8, if the coil distance is reduced, the induced voltage increases within a certain range. The data of coil distance and phase difference are shown in table 6. From figure 9, when the transmitting source TX is very close to re1, the phase difference decreases sharply. The study found that when L(Tx-re1)/L(re1-re2) is greater than 1.22, or L(coil distance)/L(source to well wall) greater than 2.75, the phase difference changes gradually.

Tab. 7 Influence of frequency changes on the response

| Freq (MHz) | V_mag (V) | ang_d (°) |
|-----------|-----------|-----------|
| 0.01       | 7.59526208102e-6 | 0.06019626132e-9 |
| 0.11       | 7.59450224734e-6 | 0.66159238945e-9 |
| 0.21       | 7.59258196060e-6 | 1.26031050746e-9 |
| 0.31       | 7.58975331772e-6 | 1.85453941372e-9 |
| 0.41       | 7.5863370521e-6  | 2.4433464201e-9  |
| 0.51       | 7.58262136994e-6 | 3.02666436709e-9 |
| 0.61       | 7.57876886569e-6 | 3.60960516646e-9 |
| 0.71       | 7.5752471462e-6  | 4.17902201489e-9 |
| 0.81       | 7.5713354059e-6  | 4.74969956056e-9 |
| 0.91       | 7.5685870422e-6  | 5.31760581508e-9 |
| 1          | 7.54798624724e-6 | 11.4385761109e-9 |

Fig. 9 Influence of emission source position on phase difference

Fig. 10 Relationship between excitation source frequency and induced voltage

Tab. 7 Influence of frequency changes on the response

4.3. Working frequency of the detector

In modeling, the adaptive frequency range of the system is changed. At the range of working frequency from 0.01MHz to 2MHz, the induced voltage and phase difference is modeled. The results data are shown in table 7. From figure 10 and figure 11, when the conductivity of mud and rock layers
remains unchanged, only the working frequency of the detector is changed to observe the influence on the electromagnetic response. It is found that the response of the induced voltage and phase difference doesn’t change significantly within a certain frequency range (less than 0.1MHz). When the frequency is greater than 0.1MHz, the induced voltage decreases sharply and the phase difference increases sharply.

5. Detector function module design

According to the response modeling results of electromagnetic logging, Ansoft HFSS is used to model the electromagnetic logging transmitting and receiving. The depth of formation is calculated by wide Angle method and ray tracing method (RT) respectively. The formation depth obtained by RT inversion is taken as the standard to identify the lithology and oil-water content of formation by combining the real part signal of resistivity measured by electrode and the image part signal measured by high frequency.

The data acquisition and control circuit includes the acquisition of analog signals, digital filtering, algorithm processing, adaptive processing of control signals and controller area network (CAN) communication processing, which is completed by digital signal processor (DSP) chip and field-programmable gate array (FPGA) joint design. The DSP chip can be used to complete analogue digital (AD) acquisition and processing of related signals, as well as communication by CAN nodes. The FPGA can be used to realize the clock standard of the system and the logic control and implementation closely related to time.

The circuit design is shown in figure 12. The DSP chip is the high temperature digital signal controller sm320f28335-ht of TI company, which is the floating-point DSP for TI logging, with the working frequency up to 150MHz, and contains 16 independent high-speed AD converters, with the accuracy of 12bit. That can fully meet the needs of the system. High-speed AD chip can collect the signal waveform of the probe in real time, the maximum pulse width of the signal is 1us, and the sampling rate can reach 10MHz, that is, 0.1us to collect a group of data. The high-speed AD chip can acquire 10 points on the signal waveform of 1us-wide probe. The FPGA chip is the RT3PE600L of ACTEL company, which is an aerospace grade military device of ACTEL company. It has outstanding high temperature performance, and can acquire the conversion of data signals as well as the control and processing of signals. The downhole data can be sent by CAN bus. The bus rate on the large-diameter tool is 800Kbps, and that on the small-diameter is 300Kbps. The debugging of the equipment is carried out by USB-CAN converter, and the computer can directly communicate with the data acquisition control circuit, which can be used as a simple debugging method.

6. Conclusion

The response rule and induction signal of broadband electromagnetic logging are analyzed and summarized by discussing the influence of borehole, formation conductivity, coil current, coil distance and working frequency by numerical modeling method. On this basis, the key technology of data acquisition circuit design of broadband electromagnetic detector is preliminarily explored. The following conclusions can be drawn:

(1) Ansoft Maxwell software can be used for model response analysis.
(2) At the constant formation conductivity, and the mud conductivity between 0.01S/m and 0.1S/m, the mud conductivity has little influence on the induced voltage, which is conductive to measuring response characteristics. When the well mud conductivity is greater than 0.1S/m, the attenuation of induced voltage by electromagnetic wave is very fast, which is not conductive to measure.
(3) In a certain range, the induced voltage tends to decrease with the increasement of borehole radius. The phase difference decreases with the increasement of formation conductivity or the source spacing greater than 0.4mm. When the frequency is greater than 0.1MHz, the induced voltage decreases sharply, however the phase difference increases sharply. With the current increases, the induced voltage increases. The phase difference decreases sharply with current less than 50A.
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