Adaptive power line communication for intelligent separate layer production with single-core cables

Liu Changzan¹, Dang Bo²*, Yang Ling², Xu Linkang², Dang Ruirong²

¹School of Marine Science and Technology, Northwestern Polytechnical University, Xi’an, 710072, Shaanxi, China
²Key Laboratory of Education Ministry for Photoelectric Logging and Detecting of Oil and Gas, Xi’an Shiyou University, Xi’an, 710065, Shaanxi, China

*Corresponding author’s e-mail: bodang521@126.com

Abstract. Power line communication (PLC) techniques have been proven to be efficient for the intelligent separate layer production (ISLP) system with single-core cables. However, the permanent mode of the ISLP may cause a continuous change of the resistance and capacitance of the single-core cables due to the long-term effect of high temperature, high pressure as well as the vibration of the bad downhole conditions, which will have great influence on the data transmission efficiency. In this paper, we present an adaptive PLC approach for the data transmission of ISLP with single-core cables. Instead of the precise slide rheostat, program-controlled potentiometer is used to achieve an adaptive decoding algorithm for fast initialization of the ISLP transmission. Moreover, a long-term adaptive method is also proposed to adjust the gain and filter coefficients in real time according to the bit error rate of data transmission systems. Finally, experiments were conducted and the results demonstrate the effectiveness of the proposed adaptive PLC data transmission for the improvement of the efficiency and stability of the ISLP system.

1. Introduction

By using the downhole permanent reservoir monitoring system, intelligent separate layered production (ISLP) techniques [1-3] can achieve adaptive adjustment of the oil production as well as water injection schemes for enhanced oil recovery and efficient development of the oilfield. In recent years, the test and control of ISLP systems have attracted lots of attentions and interests. However, in order to ensure the stability of the ISLP system, there still have many problems to be solved in the field of data transmission [4-6]. As one of the most popular data transmission techniques for downhole application, power line communication (PLC) with single-core steel pipe cables [7-9] offer several advantages over the acoustic and mud pulse wireless transmission technologies, such as higher reliability and transmission rate, better trafficability and lower cost. However, since the ISLP systems are placed in the well permanently, the cables are affected by the harsh environmental factors such as high temperature, high pressure and vibration, whose resistance and capacitance will fluctuate correspondingly and may result in unstable data transmission [10]. The traditional high-speed PLC data transmission with single-core cables relies on manual adjustment of the gain and filter coefficients of the ground decoding system to compensate for the change of resistance and capacitance of the single-core cables [11,12]. However, the manual adjustment requires high experienced operators, which is inefficient for the unpredictable change of the bad downhole conditions. Especially in the process of permanent underground monitoring, the manual adjustment method cannot solve the problem of data
transmission in time and effectively, which will have great influence on the performance of PLC data transmission. In order to solve this problem, this paper presents an adaptive PLC system for the data transmission of ISLP with single-core cables. The program-controlled potentiometer is used instead of the traditional precise sliding rheostat. Using the adaptive decoding algorithm, the gain and filter coefficients of the transmission system are adjusted in real time according to the bit error rate (BER) of the signal transmission, so as to realize the adaptive data transmission and improve the data transmission efficiency and stability of the cabled ISLP system.

2. Data transmission model of cabled ISLP system
The cabled ISLP system adopts the permanent downhole system to monitor the production status of each layer, and the monitored data such as temperature, pressure and the oil nozzle cone are transmitted to the ground processing system in real time through PLC with single-core steel pipe cables. After evaluating the production parameters of all layers, the ground system will send the configuration parameters to downhole system, so that a closed-loop automatic adjustment intelligent system can be formed. The model of the cabled ISLP system with PLC data transmission is shown in the Fig. 1. It should be noted that the uplink data transmission and the downlink command transmission of the cabled ISLP system have low requirements on the transmission rate, where the uplink 20 Kbps transmission rate can meet the actual demand generally, and the downlink command transmission rate only needs to ensure a fixed number of commands to be issued. By contrast, the key of PLC data transmission in the ISLP system is the guarantee of the long-term stable communication.

![Figure 1. Cabled ISLP system with PLC data transmission](image_url)

PLC data transmission system with single-core cables in the Fig.1 comprises two parts: power supply and data transmission. The data is transmitted by DC power line carrier, including borehole coupling transformer, single-core cables, ground coupling transformer, gain module, filter module and decoding module. The ground system supplies DC power to the downhole permanent reservoir monitoring system through the single-core cables to ensure the normal operation. The downhole data collected by the permanent reservoir monitoring system are coupled to the single-core cables through the borehole coupling transformer and uploaded to the ground system, and the ground system decouples the signal with the ground coupling transformer. Taking the uplink data transmission as an...
example, the transmission signal is amplified by the gain module, and the filter module filters out the low-frequency signal and compares it with the reference voltage. The processed signal is put into two JK flip-flops for hardware decoding. At last, the analog-to-digital convertor (ADC) module is used to sample the data to realize the final software decoding. It should be noted that the attenuation of the signal on the actual logging cables is influenced by resistance, capacitance, inductance as well as the insulation of the cables [13].

For the conventional logging system with single-core cable, since the cable of each logging winch is fixed, the gain and filter coefficients in Fig. 1 do not need to be adjusted after the initial setting. However, for the permanent ISLP system which needs to work underground for quite a long time, the parameters of cable, such as resistance and capacitance, will change with the underground temperature, pressure, vibration and other environmental factors. Thereby, the gain and filter coefficients must be adjusted in real time to ensure the stable transmission of the ISLP system.

2.1. Design of program-controlled decoding system

Both the gain and filter modules of the PLC decoding system is directly related to the values of the feedback resistances. The traditional manual operations that use two 20K ohm high-precision sliding rheostat for signal regulation is inefficient. As an alternative, the program-controlled potentiometer is utilized instead of the sliding potentiometer, so that the regulations can be controlled by software accurately to ensure the signal quality. Taking the program-controlled potentiometer AD5291 as an example, the ground software writes parameters to RDAC register through SPI communication, so as to adjust the output resistance between W and B ports, whose resistance value $R_{WB}$ can be written as

$$R_{WB} = \frac{D}{256} R_{AB}$$

where $R_{AB}$ is the value of the full range of the program-controlled potentiometer, $D$ is the integer value written into the RDAC register in AD5291, and the resolution of the resistance value is 78.125 Ω. However, there are still some problems in the manual software adjustment, such as the requirement of experienced operators, low efficiency and unable to adjust in time. Therefore, on the basis of the above model, this paper presents an adaptive fast decoding algorithm for the cabled ISLP system.

2.2. Adaptive fast decoding algorithm for PLC initialization

In the initialization of communication, the permanent downhole monitoring system circulates a fixed section of data, and the ground processing system decodes the received signal. In this paper, we employ the BER as the criterion to evaluate the appreciation of the gain and filter coefficients, where the BER is defined as the number of error data during a certain monitoring time. The BER $W_{i,j}$ of the current configuration of the two program-controlled resistors can be calculated by

$$W_{i,j} = \frac{C_{i,j}}{T}$$

where $i$ is the programable resistor of gain module, $j$ is the programable resistor of filter module, $T$ is the time duration, and $C$ is the total number of error bits. According to Equation (2), we can analyze the practicability of the current values of the program-controlled resistor. For inappropriate BER, the values of the programmable resistor should be changed correspondingly. We can repeat the above operations to realize the scanning of all possible combinations of two programmable resistors to achieve the best BER performance. However, this would be inconvenient for PLC data transmission. Assuming the total settable number of each program-controlled resistor is $E$, there will be $E^2$ possible combinations. If we follow the scheme above, the time required for full traverse is

$$T_b = E^2 T$$

Taking AD5291 with $E = 256$ and $T = 100ms$ as an example, it will cost $T_b = 1.82$ hours to go through all possible combinations, which is substantially unacceptable for practical application. In this paper, we present an adaptive fast decoding algorithm to reduce the time consuming. In the
initialization of the PLC data transmission, we use a training set to realize the BER evaluation, where the resistance of two programmed rheostats is scanned by applying the dichotomy to find the appropriate gain and filter coefficients. The scanning is divided into $M$ stages, in which the step length of the $m$-th stage scanning is $La_m$ and $Lb_m$ for gain and filter resistors with the number of steps of $Na_m$ and $Nb_m$, respectively. Then we have

\begin{align}
La_m &= Na_{m+1} \times La_{m+1} \\
Lb_m &= Nb_{m+1} \times Lb_{m+1}
\end{align}

The structure of the adaptive fast decoding algorithm is shown in Figure 2, where the $m$-th stage scanning can be divided into two parts as follows:

1. Scan with step length of $La_m$ and $Lb_m$, respectively, and then find two groups of values corresponding to the best two BERs, with which the scanning can be terminated as long as the BER satisfies the threshold.

2. If $m < M$, two $(m+1)$-th stage scannings should be carried out by taking the two groups of values above as the scanning center, with the range and step of $La_m$ and $Lb_m$, and $La_{m+1}$ and $Lb_{m+1}$, respectively. Note that the ranges of the current stage are just the step lengths of the last stage.

![Figure 2. Adaptive fast decoding algorithm structure](image-url)

Specifically, the procedure of adaptive fast decoding algorithm is shown in Figure 3. Taking the first row with $M$ stages as an example, the first stage scanning is carried out to obtain two groups of values corresponding to the best two BERs within all possible combinations of the gain and filter resistance with the steps of $La_1$ and $Lb_1$, respectively. And if the BER of the best two groups reaches the threshold, the scanning will be terminated. Otherwise, the second stage scanning should be conducted with the range of $La_1$ and $Lb_1$, respectively. Similarly, the fast scanning of the $m$-th stage can be divided into two parts (steps). If the BER still cannot satisfy the threshold after all scannings, the coefficients corresponding to the minimum BER obtained should be adopted.
The scanning time of the proposed adaptive fast decoding algorithm shall not be larger than:

$$T_b = \sum_{m=1}^{M} 2^{m-1} N_{a_m} N_{b_m} T_s$$

(6)

Taking the program-controlled resistor AD5291 ($E = 256$), $T = 100$ ms as an example, if $M = 4$ and steps $N_{a_m} = N_{b_m} = 4$ ($m=1,2,3,4$), the longest time to complete such a scan will be 24 seconds, which is far less than the time of a full traverse.

3. Long-term adaptive PLC for ISLP systems

Through the adaptive fast decoding algorithm, we can get the appropriate combination of gain and filter coefficients for the initialization of the PLC data transmission. However, the permanent mode of the ISLP may cause a continuous change of the resistance and capacitance of the single-core cables due to the long-term effect of high temperature, high pressure as well as the vibration of the bad downhole conditions, which will have great influence on the data transmission efficiency. And the combination of gain and filter coefficients needs to be adjusted with the continuous change. Unfortunately, the traditional manual adjustment method cannot handle the problem of data transmission in time and effectively. To solve this problem, a long-term adaptive data transmission method is proposed in this paper.

During the long-term monitoring, intermittent transmission of training set will occupy transmission resources. Moreover, since little change of cable parameters in a short time, it is unnecessary to adjust the gain and filter coefficients in a too large range. In this paper, we take the number of frames successfully transmitted in a certain time as the standard of the BER to evaluate the stability of data transmission in the long-term monitoring for the cabled ISLP system. The real-time BER can be expressed as:

$$\bar{W}_{i,j} = 1 - \frac{V_i P}{V_{t,j} T_s}$$

(7)

where $i$ is the programable resistor of gain module, $j$ is the programable resistor of filter module, $T_s$ is the observation time, $V_i$ is the transmission cycle of each frame, and $P$ is the number of frames successfully transmitted in $T_s$ time.
To ensure the stability of the PLC data transmission, the scanning procedure of the long-term adaptive transmission should be made with in a suitable range. The scheme of the adaptive method as shown in Figure 4 can be decomposed to several individual procedures of adaptive fast decoding in Section 2.2. As long as the BER is larger than the threshold during the monitoring, the fast-adaptive decoding scanning with $M=1$ in Section 2 should be carried out. Furthermore, if the BER satisfies the threshold, the coefficients can be set as the values corresponding to the minimum BER. Otherwise, if the appropriate value is not found during the $M=1$ scanning, the fast-adaptive decoding scanning with $M=2$ will be carried out within a larger range. Similarly, we can repeat the above procedures with an increasing $M$ in larger range for scanning until an appropriate BER can be obtained or all the scanning is completed, and then the coefficients values corresponding to the lowest BER will be adopted.

By adaptive adjusting the gain and filter coefficients to maintain the BER in a proper range, the long-term and stable data transmission of the cabled ISLP system can be realized. It is noted that although a small scanning range of each stage may have little impact on the current data transmission, the probability of obtaining appropriate coefficients are also reduced. Thereby, suitable range and step length still need to be optimized according to the current conditions of well and single-core steel pipe cables.

4. Experimental analysis
In order to verify the efficiency and accuracy of the proposed adaptive fast decoding algorithm and the long-term adaptive transmission method, five different parameters of single-core cables for the ISLP system are utilized, and the equivalent resistance and capacitance are shown in Table 1:

| Number | 1    | 2    | 3    | 4    | 5    |
|--------|------|------|------|------|------|
| Resistance ($\Omega$) | 96.3 | 103.5 | 107.5 | 113.6 | 121.3 |
| Capacitance ($\mu$F) | 1.08 | 1.11 | 1.16 | 1.24 | 1.27 |
The manual adjustment and adaptive fast decoding algorithm are applied to the initialization of the PLC data transmission of the ISLP with the cable parameters of each case in Table 1 for 10 times, respectively. The BER versus adjustment time of the two methods are shown in the Figure 5. It can be seen that the manual adjustment method scatters out for different cable conditions. By contrast, the proposed adaptive fast decoding algorithm performs well, where the experiment results are centralized. It can be seen from the comparison that both the speed and accuracy of the adaptive fast decoding algorithm are better than that of the manual adjustment for efficient ISLP system.

![Figure 5. Comparison of the manual adjustment and adaptive algorithm for PLC initialization](image)

In order to verify the performance of the long-term adaptive transmission method, the BER of the PLC data transmission is experimented for a long time, and the BER with fixed coefficients, manual adjustment and long-term adaptive transmission method are compared in the Figure 6. The experimental time is set to be 350 minutes, and the parameters with respect to the resistance and capacitance of the single-core cables are set to be changed from the first case in Table 1 to the fifth case at a uniform speed. It can be seen from Figure 6 that the BER using fixed coefficients increases gradually versus the monitoring time, where the BER performance cannot meet the normal data transmission requirement for a long-term monitoring. Using the manual adjustment, it is obvious that the decrease of the BER performance can be corrected only when the manual operations were conducted (90 minutes approximately in the experiments). Although the performance decrease can be corrected, the manual adjustment method requires a long-time concerning, which would be inefficient and may cause data transmission interruption. The proposed long-term adaptive transmission method in this paper can adjust the coefficients according to the current BER in real time, and the BER can be maintained in a suitable range so that the stable PLC data transmission can be ensured.
5. Summary
In this paper, an adaptive PLC approach for the data transmission of ISLP with single-core cables is proposed to improve the stability of the permanent downhole monitoring system. On the basis of the program-controlled potentiometer, an adaptive decoding algorithm for fast initialization of the PLC data transmission is first introduced. Additionally, a long-term adaptive method is also proposed to adjust the gain and filter coefficients in real time according to the BER of data transmission systems. Experiments were conducted and the results demonstrate the effectiveness of the proposed methods for the improvement of the data transmission efficiency and stability of the ISLP system.

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