Real-time Monitoring System of Leakage Current for Electric Submersible Pump

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Abstract. With the increasing exploitation of marine gas, electric submersible pump technology has attracted more and more attention. Under the influence of the bad underground environment, the insulation performance of the electric submersible pump will gradually deteriorate during its operation, resulting in current leakage, causing dangerous phenomena such as phase-to-phase open circuit, fire or electric leakage to ground, which brings destructive damage to the electric submersible pump equipment. In order to solve this problem, this paper designs a real-time monitoring system of the leakage current for the electric submersible pump based on the principle of current mutual inductance and transducing, and constructs the indoor well condition simulation experiment. The experimental data shows that the system can monitor and display the current leakage of the electric submersible pump in real time to ensure the safe operation of the electric submersible pump.

1. Introduction
In recent years, with the decrease of easy-to-produce crude oil reserves, the well condition of oil well is more and more complicated. As an important artificial lifting equipment, electric submersible pump plays an irreplaceable role in the secondary and tertiary oil recovery, which puts forward higher requirements for the application reliability of electric submersible pump[1]. However, the insulation of the electric submersible pump is affected by various factors such as electricity, heat, machinery and bad environment during its operation. Its performance will gradually deteriorate[2], resulting in current leakage, causing dangerous phenomena such as phase-to-phase open circuit, fire or electric leakage to ground, which brings destructive damage to the electric submersible pump equipment. At present, in order to ensure the safe use of the electric submersible pump[3], the insulation test of the electric submersible pump system is carried out by megger before going downhole according to the regulations. If the insulation performance is to be tested after going downhole, the whole electric
submersible pump well must be powered off and stop operating. It is impossible to monitor the insulation damage of electric submersible pump in real time. In order to solve these problems, a real-time monitoring system of leakage current for electric submersible pump is designed based on the existing monitoring system of electric submersible pump and downhole condition. Finally, the well simulation experiment shows that the system can accurately monitor the current leakage of the electric submersible pump in real time, evaluate the insulation damage of the electric submersible pump well correctly, and ensure the safe operation of the electric submersible pump unit.

2. Monitoring system of electric submersible pump and downhole condition

Schematic diagram of monitoring system of electric submersible pump and downhole condition is shown in Figure 1.

The ground system is mainly composed of ground artificial star point, combination unit, ground control circuit, etc. The artificial star point is constructed by a three-phase electric reactor with the same three-phase winding parameters as the downhole motor, which supplies power for the downhole monitoring circuit based on the principle of star point equipotential. The underground part is mainly composed of submersible motor part, metal armored cable, frequency conversion and pressure suppression system, and downhole monitoring circuit. The metal armored cable is used as the power supply channel. The three-phase power supply on the ground with variable frequency supplies power to the downhole motor through the three-phase power line of the metal armored cable. The motor is responsible for driving the whole set of electric submersible pump equipment to start operation[3]. The outer side of the three-phase power line is wrapped with an insulating layer to isolate the power and protect the cable. The outermost layer of armored cable is cable armor, which is used as the
information carrier to transmit the DC signal corresponding to each measured parameter, such as downhole temperature, pressure, vibration, etc. monitored by the downhole monitoring circuit to the ground.

Due to the harsh underground environment, the insulation performance of the electric submersible pump will gradually deteriorate during its operation\cite{3}, which is a potential threat to the operation of the electric submersible pump. In view of this, the armor shown in Figure 1 is used as the transmission channel of measurement information to monitor the leakage current that may be generated during the operation of the electric submersible pump in real time on the ground\cite{4}.

3. The principle of real-time monitoring for leakage current of electric submersible pump

3.1. Working principle of current mutual inductance transducer

The current transformer is an instrument which converts the large primary current into the small secondary current according to the electromagnetic induction principle to measure the current. Current transformer is generally used in power system, which plays an important role in current transformation and electrical isolation. It is composed of a closed iron core and two windings of the primary and secondary sides\cite{5}. As shown in Figure 2, when the circuit-under-test passes through the core ring, a magnetic field will be generated around the circuit-under-test, which will generate alternating magnetic flux through electromagnetic induction, and the secondary winding will generate a current decreased by the ratio of turns.

Current transformer is based on the principle of electromagnetic induction, that is, only when the measured current is alternating current, the corresponding current value can be measured. Therefore, the current transformer can only measure the AC current value, which will not be affected by the DC signal transmitted from the downhole by the cable armor. In order to solve the influence of field interference of industrial control\cite{6}, this paper selects two-wire current transformer chip XTR115 to transform the current signal received by current transformer into 4 ~ 20mA standard current signal.

In this paper, the selection of the standard rated value of the current mutual inductance transducer refers to the measurement index of leakage current\cite{3} of Phoenix xt150, the electric submersible pump monitoring equipment of Schlumberger, an oilfield technology company, as shown in Table 1.
### Table 1. Measurement parameters and indexes of Phoenix xt150

| Measurement parameters       | Measuring range | Accuracy | Resolution | Drift          | Rate |
|------------------------------|-----------------|----------|------------|----------------|------|
| Inlet pressure               | 0~5800psi       | ±5psi    | 0.1psi     | 5psi/year      | 4s   |
| Outlet pressure              | 0~5800psi       | ±5psi    | 0.1psi     | 5psi/year      | 4s   |
| Inlet temperature            | 0~150℃          | 1.33%    | 0.1℃       | --             | 4s   |
| Winding temperature          | 0~409℃          | 1%       | 0.1℃       | --             | 36s  |
| Vibration                    | 0~30g            | 3.33%    | 0.1        | --             | Variable |
| Leakage current              | 0~25mA           | 0.20%    | 0.001mA    | --             | Variable |

### 3.2. Calibration experiment of current mutual inductance transducer

Construct a DC circuit (Loop 1) powered by 5V constant current source and an AC circuit (Loop 2) powered by 12.78V AC source, as shown in Figure 3. Loop 2 includes adjustable load, precision ammeter 1 and precision ammeter 2. Loop 2 can get multiple sets of measurement data by adjusting the adjustable load resistance, precision ammeter 1 can measure current value of Loop 2 in real time, and precision ammeter 2 can measure 4 ~ 20mA standard current signal output by current mutual inductance transducer in real time.

Pass the two circuits through the air core in the middle of the current mutual inductance transducer. At this time, there are both DC current and AC current flowing through the air core of the current mutual inductance transducer. The current data of double circuit experiment under different loads are measured by precision ammeter 1 and 2. If the constant current source is turned off, at this time, only AC current flows through the core of current mutual inductance transducer. The experimental platform is as shown in Figure 3 (b). The current data of AC circuit experimental under different loads is measured by precision ammeter 1 and 2.

Under different loads, the experimental data of double circuit and AC circuit are shown in Table 2. The load of Loop 1 is 510, and the current is always 9.891mA.
Table 2. Experimental data of current mutual inductance transducer under different loads

| Loop 2 resistance/Ω | Loop 2 current/mA | Transmission current of loop 2/mA | Double circuit transmission current/mA | relative error/% |
|---------------------|-------------------|----------------------------------|---------------------------------------|-----------------|
| ∞                   | 0                 | 4.046                            | 4.041                                 | 0.12            |
| 935                 | 13.766            | 8.478                            | 8.440                                 | 0.45            |
| 795                 | 16.179            | 9.251                            | 9.205                                 | 0.49            |
| 634                 | 20.300            | 10.615                           | 10.545                                | 0.66            |
| 539                 | 23.847            | 11.726                           | 11.676                                | 0.42            |
| 491                 | 26.181            | 12.987                           | 12.427                                | 0.45            |
| 415                 | 30.988            | 14.024                           | 14.008                                | 0.11            |
| 356                 | 36.090            | 15.659                           | 15.658                                | 0.006           |
| 327                 | 39.288            | 16.740                           | 16.664                                | 0.45            |
| 303                 | 42.441            | 17.799                           | 17.894                                | -0.53           |
| 271                 | 47.384            | 19.429                           | 19.453                                | -0.12           |
| 264                 | 48.695            | 19.802                           | 19.903                                | -0.05           |

Figure 4. Comparison of current transducing value of AC circuit and double circuit

It can be seen from Figure 4 that the output current value of the current transducer has almost no change when the AC current and the AC&DC current pass through its core. Therefore, the current mutual inductance transducer can only measure the AC current, and the presence of DC in the loop does not affect the measurement results.

4. Real-time monitoring system for leakage current of electric submersible pump based on the principle of current mutual inductance

4.1. System structure
The structure of the real-time monitoring system for the leakage current of the electric submersible pump is shown in Figure 5.
When the electric submersible pump and downhole multi-parameter monitoring system work normally, the downhole monitoring circuit transmits the DC current corresponding to the monitored multi-parameter to the multi-channel AD acquisition module in sequence along the cable armor. At the same time, the cable armor goes through the central hole of the current mutual inductance transducer, so as to monitor the leakage current of the electric submersible pump, then the current will be output as a 4 ~ 20mA standard current signal to the multi-channel AD acquisition module. After being processed by MCU, it will be displayed on LCD screen in real-time, and the corresponding insulation curve is drawn in the upper computer, and the historical data is stored as the basic data to evaluate the working condition of electric submersible pump.

![Figure 5. Structure of monitoring system](image)

### 4.2. Measurement circuit

The structure diagram of hardware circuit system is shown in Figure 6. STM32F103 is used as the main control chip. The system mainly includes current mutual inductance transducer, RS232 communication circuit, multi-channel AD acquisition module, LCD screen, SD memory card, alarm circuit, start button and upper computer.

After the system is powered on, press the start button to start the whole system. The main control chip controls the multi-channel AD acquisition module through the RS232 communication port to receive the current signal transmitted by the downhole equipment and current mutual inductance transducer. The multi-channel AD acquisition module sends the received current signal to the main control chip for processing and to calculate the insulation condition of the downhole electric submersible pump, which will be displayed on the LCD screen and sent to the upper computer at the same time, and the SD card stores the signal data processed by MCU.
When the monitoring system detects the insulation leakage of the electric submersible pump, the main control chip controls the alarm to ring and light the alarm indicator.

![Figure 6. Hardware circuit structure](image1)

5. Well condition simulation experiment and test results

The well condition simulation experiment is shown in Figure 7. The AC circuit representing the insulation leakage of the electric submersible pump and the DC circuit representing the working state of the downhole unit are respectively built, and the two circuits pass through the air core in the middle of the current mutual inductance transducer. Then connect the relevant hardware circuit and the upper computer, and adjust the AC circuit load to get multiple sets of measurement values.

Table 3. Monitoring data of real-time monitoring system for leakage current of electric submersible pump

| Ammeter reading/mA | Module acquisition current/mA | Relative error/% | LCD display/mA | Relative error/% | Upper computer interface/mA | Relative error/% |
|--------------------|-------------------------------|------------------|----------------|-----------------|-----------------------------|------------------|
| 8.154              | 8.152                         | -0.024           | 8.151          | -0.036          | 8.152                       | -0.024           |
| 9.772              | 9.771                         | -0.01            | 9.771          | -0.010          | 9.783                       | 0.112            |
| 10.586             | 10.585                        | -0.009           | 10.585         | -0.009          | 10.585                      | -0.009           |
| 11.624             | 11.628                        | 0.034            | 11.628         | 0.034           | 11.628                      | 0.034            |
| 12.724             | 12.722                        | -0.015           | 12.732         | 0.062           | 12.743                      | 0.149            |
| 13.735             | 13.732                        | -0.021           | 13.742         | 0.050           | 13.735                      | 0.000            |
| 14.589             | 14.578                        | -0.075           | 14.579         | -0.069          | 14.569                      | -0.137           |
| 15.258             | 15.265                        | 0.045            | 15.266         | 0.052           | 15.274                      | 0.103            |
| 16.302             | 16.299                        | -0.018           | 16.298         | -0.024          | 16.299                      | -0.018           |
| 17.669             | 17.672                        | 0.016            | 17.671         | 0.011           | 17.671                      | 0.011            |
From the measurement results in Table 3, it can be seen that the measurement error of the designed real-time monitoring system for leakage current of electric submersible pump is kept within 0.15%, which can accurately monitor the current leakage of electric submersible pump in real time.

6. Conclusion
Based on the real-time monitoring system of electric submersible pump and downhole state, this paper designs a real-time monitoring system for leakage current of electric submersible pump based on the principle of current mutual inductance. In addition, an indoor verification experiment for this real-time monitoring system is carried out. The results show that the system can accurately monitor the leakage current of the electric submersible pump in real time, and ensure the safe operation of the electric submersible pump unit.

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