Sensor Network based Oil Well Health Monitoring and Intelligent Control

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Abstract: ***Most oil pumping units (OPUs) have been using manual control in the oilfield. This existing oil-pumping system, a high power-consuming process, has the incapability of OPU's structural health monitoring. In this paper, a sensor network based intelligent control is proposed for power economy and efficient oil well health monitoring. The proposed sensor network consists of three-level sensors: 1) several types of basic sensors, such as load sensor, angular sensor, voltage sensor, current sensor and oil pressure sensor, which are the first level sensors (FLS), are used for oil well data sensing; 2) our developed intelligent sensors (IS), which belong to the second level sensor, are designed mainly for an oil well's data elementary processing, main fault alarm/indication, typical data storage/indication, data/status transmission up to the third level sensor (TLS), data/status transmission between IS, and command transmission down to the OPU motor; and 3) our developed software-defined (SD) control centers with an embedded database, i.e., the TLS, are designed for hundreds of oil wells data storage/management, data processing, malfunction detection, malfunction alarm/indication, stroke-adjustment command transmission down to a specific IS for power economy and the malfunction report to the maintenance staff via global system for mobile communications (GSM) short message service (SMS).***

Keywords: health monitoring, intelligent system, intelligent sensor, power economy, sensor network

1. Introduction

In this paper, a sensor network based intelligent system is proposed and applied for remote oil well health monitoring and automatic oil-pumping control. The motivation of developing this system is that due to the special nature of oil exploration and oil drilling, the majority of oil pumping units (OPU1) are spread over barren hills, mountains and deserts, and the existing oil-pumping systems still adopt manual control. Existing manual control systems have three evident drawbacks: 1) The OPU administrators have to frequently go to the oilfield to check the OPU status and collect its health analysis data. 2) Power consumption for OPU is huge during the oil-pumping process. 3), since an administrator has to take charge of a number of oil wells, an OPU malfunction is difficult to locate and repair in a reasonable time, which causes an oil production drop.

To overcome these three disadvantages of the existing manual control system, a sensor network based automatic control system is proposed for OPU management and oil well health monitoring. This proposed system consists of three-level sensors: the fist level sensors (FLS), the intelligent sensors (IS) and the third level sensors (TLS). A set of FLS, i.e., five sensors, are commonly used for an oil well's data sensing, which includes a load sensor, an angular sensor, a voltage sensor, a current sensor and an oil pressure sensor for one oil well. The IS is developed mainly for an oil well's data elementary processing, main fault alarm/indication, typical data storage/indication, data/status transmission up to the TLS, data/status transmission between IS, and command transmission down to the OPU motor. The software-defined (SD) TLS is designed for hundreds of oil well's data storage/management, data processing, malfunction diagnosis, malfunction alarm/indication; oil pumping stroke-adjustment command transmission down to a specific IS for power economy and the malfunction report to the maintenance staff via global system for mobile communications (GSM) short message service (SMS).

The remaining paper is organized as follows. Section II introduces the whole network topology and system description. The development of IS is given in Section III. And, the development of the SD TLS is provided in Section IV. Section V depicts the whole system assembly in the Chinese Petroleum's Changing Oilfield and reports the elementary experiment results with respect to remote pumping stroke adjustment and automatic oil well malfunction diagnosis, followed by Conclusion in Section VI.

2. Network Topology and System Description

The proposed system is comprised of our developed SD TLS, each of which wirelessly communicates with hundreds of IS. Each IS is designed with the capability of data transferability with a set of FLS, its adjacent IS and its corresponding TLS as well as the capability of command transmission down to its OPU motor. Each group of FLS, including a load sensor, an angular sensor, a voltage sensor, a current sensor and an oil pressure sensor, are utilized for data sensing from an OPU, which convert all measurements into electrical signals and then transport them into its corresponding IS.

Wirelessly transmitting OPU static parameters (At the initial stage), significant malfunction reports (if necessary), sensing data and elementary processing data to other specific sensors using a developed communication protocol; Relay data/status transmission from another IS to FLS when there is a communication failure between another IS and FLS; Setting of oil well static parameters:

OPU addition, parameter manual input, update, deletion and interface indication.

3. Development of IS

A. System Description of IS

This subsection aims at clarifying the logic connection between the shown oil well in Fig. 1 and the developed IS. As shown in Fig. 2, a group of FLS in our proposed system consists of a load sensor, an angular sensor, a voltage sensor, a current sensor and an oil pressure sensor while the IS mainly contains two components: the designed control board and the frequency converter. Five kinds of sensing data from FLS are imported to its IS. The IS usually transmits oil well static parameters (At the initial stage), significant malfunction reports (if necessary), dynamic sensing data and elementary processing data directly to the TLS. As a special case, when the wireless communication between the IS and the TLS fails, the IS sends data to its adjacent IS for relay transmission up to the TLS.

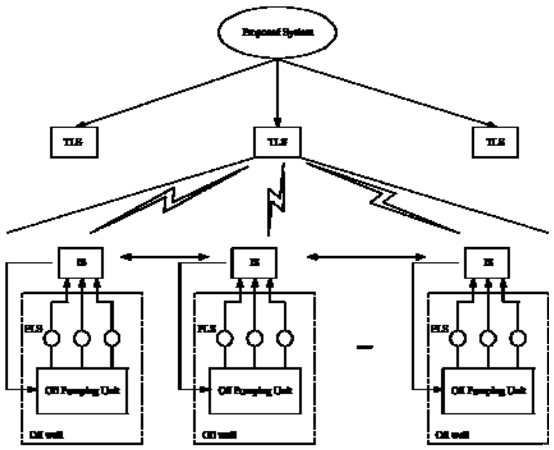


Figure 1: System topology for OPU health monitoring and intelligent control.

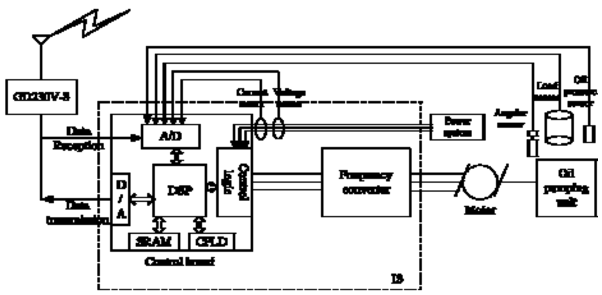


Figure 2: Information communication between FLSs and IS.

B. Design Diagram of IS

Fig. 3 shows the block diagram of our proposed IS. One can see that, the IS consists of the following six modules: a central processing unit(CPU) module, a sensing module, a relay protection module, a frequency converter module, a wireless communication module and a user interface module, which are given a detailed introduction in the following paragraph.

CPU Module: The CPU in our system is the Motorola DSP56F807; the CPU has 20 Inputs/Outputs (I/O).

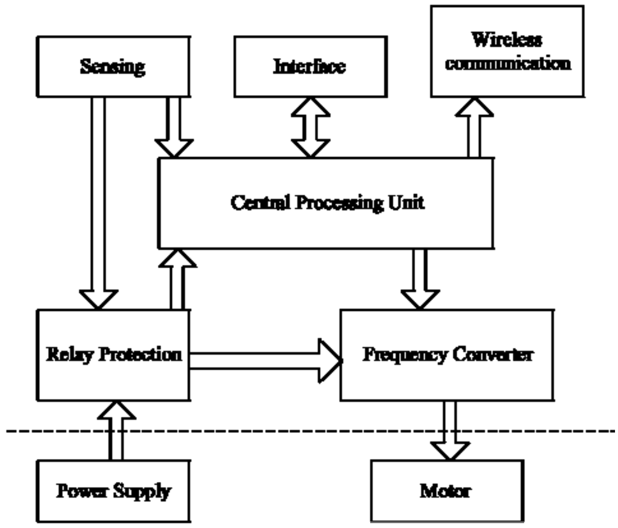


Figure 3: Block diagram of the designed IS

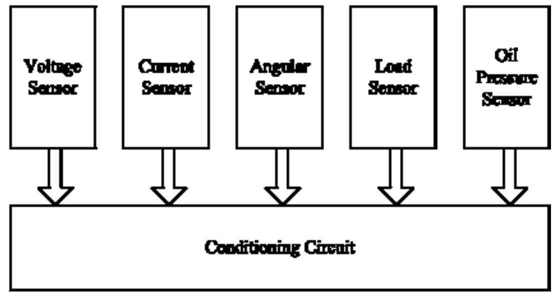


Figure 4: Sensing module

1. Sensing Module: Sensing module contains a load sensor, an angular sensor, a voltage sensor, a current sensor, an oil pressure sensor and a conditioning circuit.
2. Relay Protection Module: Relay protection module consists of a circuit breaker, a contactor and a connection circuit.
3. Interface Module: Interface module includes 4 ×4 keyboard, 128 ×64 LCD, indicator lights, a buzzer, power switch, start button and stop button.
4. Frequency Converter Module: Frequency converter module contains frequency converter, and a braking resistor.
5. Wireless Communication Module: Wireless communication module is made of a radio station and a Yagi antenna.

4. Development of TLS

System Description of TLS

This subsection aims at clarifying the connection between the TLS and its radio station, i.e., GD230V-8, as well as its GSM module, i.e., GSM Wireless Module TC35i. As shown in Fig. 8, the TLS includes three components: 1) a user interface for interaction; 2) some embedded algorithms for wireless communication between the TLS and the IS, a regular data request on all managed IS, a malfunction diagnosis, a pumping stroke adjustment and GSM SMS; and 3) a database for data storage.

The wireless data, usually including dynamic sensing data and significant malfunction reports for one specific OPU, is acquired via the communication protocol and is then stored in its database.

Design of User Interface

The user interface of the TLS has several sub-pages: 1) Dynamic indication of per OPU current typical data, current LPD, current pump diagram and current malfunction-diagnosis results; 2) Query of per OPU historical data, historical typical data, historical LPD, historical pump diagram and historical malfunction-diagnosis reports; 3) Forms for reporting statistics.

Malfunction Diagnosis

This project considers the 9 most important oil well malfunctions , , including (1) underground oil shortage, (2) gas effect, (3) oil pump on the touch, (4) oil pump under the touch, (5) wax deposition, (6) pumping rod broken off, (7) plunger stuck, (8) oil pump serious leakage and (9) no malfunction. Different malfunctions have quite different LPD. The typical LPD of these 9 malfunctions are illustrated in Fig. 12, where no malfunction corresponds to a quasi-parallelogram LPD; underground oil shortage corresponds to a 'gun'-shape LPD; a circular arc occurs in its LPD under a gas effect; a top-right longhorn occurs for an oil pump on the touch while a lower-left longhorn occurs for an oil pump under the touch; some irregular dog teeth occur for wax deposition; the quasi-parallelogram LPD becomes much narrower if the pumping rod breaks off; the LPD becomes a cucumber-shaped tilt if the plunger is stuck; and the top-right corner is gone under the condition of oil pump serious leakage. Evidently, the oil well malfunction diagnosis can be executed based on LPD classification. BP neural network () is used for malfunction classification, since it is a global approximation method and

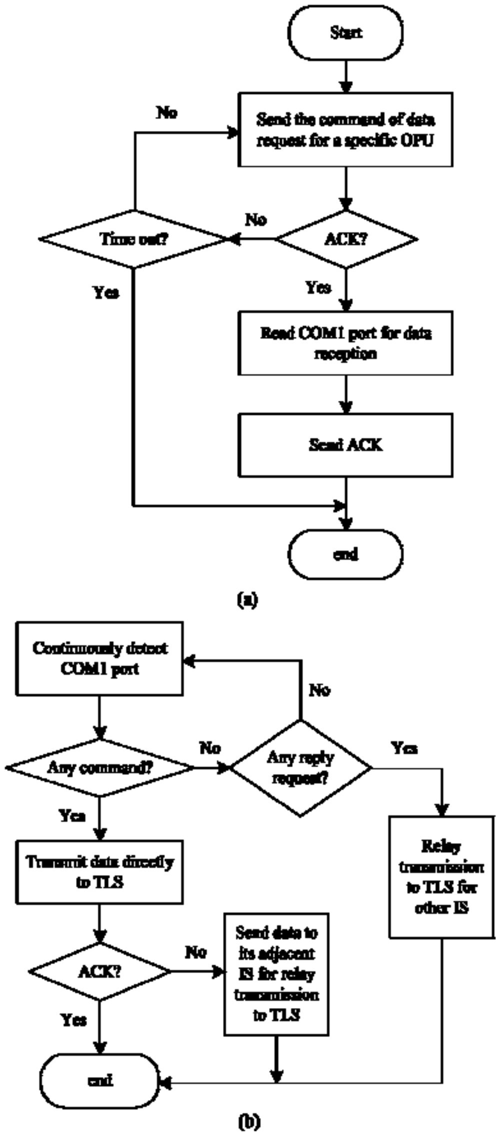
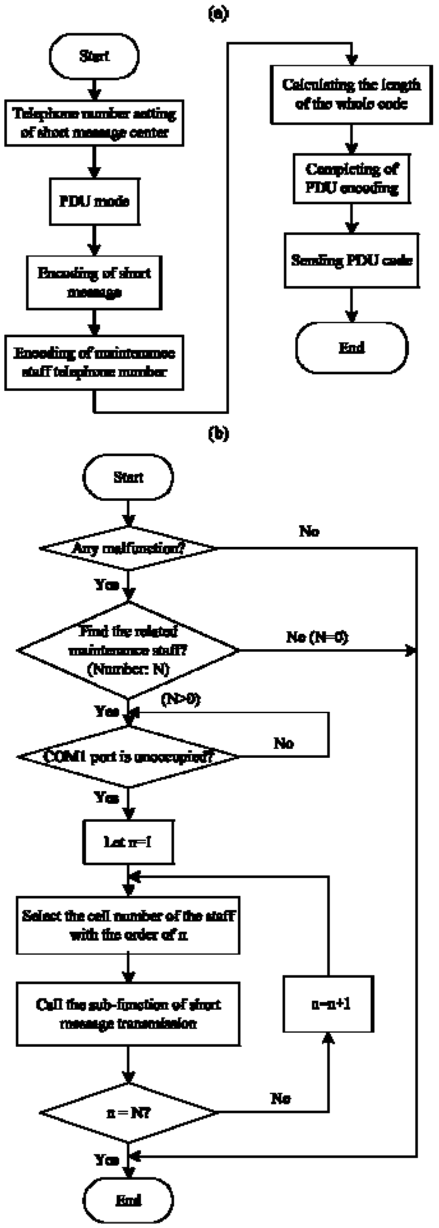


Figure 5: TLS data request on a specific OPU, (b) a specific IS data transmission.

Thus has a good generalization capability although its convergence is slow. Three-layer neural network is sufficient for oil well malfunction diagnosis. In our design, the input layer has 70 neurons.

GSM SMS

Short Message Transmission Using AT Commands: There are two modes for short message transmission of the Siemens GSM module TC35i: TEXT mode and PDU mode. TEXT mode is for English SMS while PDU mode has capability of both English SMS and Chinese SMS. Both modes utilize the AT commands for short message communication. The PDU mode is selected for our application. The entire short message transmission consists of four steps: 1) setting the telephone/cell phone number of the short message center using the command: 2) changing to the PDU mode using the command: 3) encoding the short.



GSM short message transmission using commands, (b) informing malfunctions to the related maintenance staff using GSM SMS, where is assumed to be the number of the related maintenance staff. Message to PDU code; and 4) sending the whole PDU code using the command:$\boldsymbol{AT + CMGS}$

Malfunction Transmission Via GSM SMS: The malfunction transmission to the related maintenance staff is accomplished using GSM SMS), which calls the sub function of GSM short message transmission using $\boldsymbol{AT}$ commands. Once the OPU malfunction is identified, the COM1 port is then continuously checked2until it is idle. Furthermore, calling the sub function of GSM short message transmission sends the OPU malfunction name to all maintenance staffs one by one.

5. System Assembly and Experiment Results

System Assembly in the Oilfield

In our proposed system, one OPU is connected to one IS and a set of FLS: a load sensor, an angular sensor, a voltage sensor, a current sensor and an oil pressure sensor as shown in Fig. 16(a), where the load sensor and the angular sensor are visible while other three sensors are inside the box and thus not visible in this figure. Specifically, each FLS is installed at a proper spot for sensing the oil well's data, which is connected to the developed IS by a cable. Additionally, the IS is also connected to a radio station (connected to an antenna), to the OPU's motor and to the power supply.

Oil well Malfunction Diagnosis

Automatic oil well malfunction diagnosis is one of the main features of our proposed system. In this section, we conduct a practical experiment of the malfunction diagnosis on 25 HUACHI oil wells. However, as these oil wells all belong to three catalogues: Class 9—no malfunction, Class 1—underground oil shortage and Class 2—gas effect, plenty of oil well's historical LPD record of the whole Changing Oilfield are also utilized for testing our BP neural network based malfunction classification. By considering both current data and historical LPD records, there are more than 40,000 oil well LPDs used for malfunction classification, where about 26,600 records, two thirds of the dataset, are used as training data for our proposed neural network while other 13,300 records, one third of the dataset, are used as testing data. In this application, the three-layer BP neural network consists of 70 input neurons, 12 hidden neurons and 9 output neurons.

Even though the corresponding training output is binary as shown in Table I, the testing output is actually a decimal fraction not exactly 0 or 1, where the catalogue corresponding to the maximal output is regarded as the true one. According to this principle, an overall 90.3% classification accuracy is achieved for testing-data malfunction diagnosis using our proposed neural network. Table III illustrates the corresponding classification accuracy for each malfunction for testing data. It is noticed that there are several malfunctions that are difficult to classify, such as Class 3, Class 4 and Class 5, so that they have a relatively lower classification accuracy compared to other classes. This result is intuitive when you examine their corresponding LPD in Fig. 12 because their LPD are more or less similarity difficult to be classified. Another observation to point out is that the classification error mainly comes from 1) the confusion between Class 1 and Class 2, 2) the confusion between Class 3, Class 4 and Class 5, and 3) the confusion between Class 8 and Class 9. Another essential point is the misclassification of Class 9—no malfunction. Since the most frequent status of an oil well is no malfunction, its misclassification may result in a large amount of inconveniences. Seen from the classification performance given in Table III, to avoid this misclassification: Class 9—no malfunction is misclassified to Class 8—Oil pump leakage, some mild leakage cases are thus ignored and only severe oil pump leakage is reported as a malfunction to be fixed.

6. Conclusion

In this paper, a sensor network based oil well remote health monitoring and intelligent control system was proposed for OPU management in the oilfield. This proposed system consists of three-level sensors: the FLS, the IS and the TLS. The FLS have been used for an oil well's data sensing, including a load sensor, an angular sensor, a voltage sensor, a current sensor and an oil pressure sensor for each oil well. The IS was designed mainly for an oil well's data elementary processing, main fault alarm/indication, typical data storage/indication, data/status transmission up to the TLS, data/status transmission between IS, command transmission down to the OPU motor. And the SD TLS was designed for hundreds of oil wells' data storage/management, data processing malfunction detection, malfunction alarm/indication; stroke-adjustment command transmission down to a specific IS for power economy and malfunction reporting to maintenance staff via GSM SMS. The design of the IS and the TLS was given in details.

Appendix

TLS Data Processing

The flow path of all parameter calculations is provided as follows:

1) Using load sensor and angular sensor, the most important parameter, i.e., LPD is obtained. Next, based on LPD, both the pumping diagram and oil well malfunction diagnosis can be achieved.
2) Using current sensor and voltage sensor, the motor input power is acquired. Based on this parameter as well as LPD, ground efficiency and balance adjustment can be calculated.
3) Using oil pressure sensor and sound wave generator, the underground efficiency is obtained. Based on underground efficiency and ground efficiency, the system efficiency can be calculated.
4) Using the parameters of pumping diagram, oil level and pumping stroke, the oil production can be obtained.

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