Study on Energy Analysis of Drilling Rig and Energy Storage Supercapacitor Configuration

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Abstract. It is an effective approach for recycling the energy during the process of lowering drill string and casing to reduce the cost of the oil drilling rig lifting system. In the present work, for the multi-model drilling rig, the total energy recovery and energy-saving ratio are calculated with considering the effect of hook without loading. The total energy recovery and energy-saving ratio is significantly increased when hook without loading is considered. Employing the supercapacitor, an automatic energy storage system is designed, and the control strategy of this system is discussed. The energy of lowering drill string and hook without loading is recycled for the energy replenish of lifting drill string and hook without loading. The selection and analysis of the supercapacitor in the system configuration must take into consideration the quantity, volume, quality, and the utilization of the supercapacitor at the same time, selecting the suitable capacity of the supercapacitor for reducing the cost of drilling effectively.

1. Introduction

In the process of oil drilling, the drill string or casing should be placed in the well when replacing the drill bit or cementing the casing into the well. It means that tens or hundreds of tons of columns need to be put down, and large potential energy can be recycled. The usual method used currently is to connect the energy to the braking resistor and to dissipate it into heat energy. If this part of energy is stored in energy storage elements and used to assist lifting drill string, the energy can be recycled. Supercapacitors have the advantages of fast charge and discharge, long life, and high power density. These characteristics are well-suited for drilling conditions, which promotes the supercapacitors have been widely applied in the field of drilling.

During the process of pulling out of hole, the weight of the column becomes lighter and lighter. Accordingly, the weight of the column becomes heavier and heavier in the process of running in hole. The automatic energy storage system and control strategy of the supercapacitor need to be optimized in order to make best use of the energy recovered during running in hole and reduce the impact of the winch to the power system. Chen Jian [1] employed the DC-DC converter control the charging or discharging of the supercapacitor by judging the rise or fall of the DC bus voltage, and analyzed the control strategy for charging and discharging of supercapacitors under four conditions of pulling out of hole, running in hole, casing and drilling. Dong Xinghua [2] designed a frequency control strategy for the composite energy storage system of supercapacitors and batteries, and employed PLC control the charge and discharge operations by detecting the frequency of the inverter. In the present work, the
total energy recovery and energy saving ratio of various types of drilling rigs when taking into account
the hook without loading are calculated, and the calculation with considering the recycling the energy
of the hook without loading is also conducted in the control strategy, so that the total energy recovery
and the energy saving ratio are further improved. Finally, the selection and analysis of the
supercapacitor in the system configuration are carried out.

2. Energy characteristics
In the process of tripping, there are four procedures: lifting drill string, lowering hook without loading,
lowering drill string in hole, and lifting hook without loading. By analyzing the kinetic energy and
potential energy of these four stages, the total energy of lifting drill string and the recycled energy of
lowering drill string can be calculated to obtain the energy saving ratio. The drilling rig lifting or
lowering system is simplified as shown in Fig. 1. \( m \) is the weight of the drill string, and the system is
lifted or lowered by the wire rope tension \( f \) and the drill string gravity \( G \).

![Figure 1. The model of the drilling rig during lifting and lowering](image)

Single weight:

\[ m_1 = qh \] (1)

Lifting weight:

\[ m_1 = m_1 K_1 \] (2)

Lowering weight:

\[ m_2 = m_1 K_2 \] (3)

The number of times for Lifting or lowering:

\[ n = \frac{H}{h} \] (4)

Where \( q \) is the average weight of drill string per meter in the air, \( H \) is the depth of the well, \( h \) is the
length of the drill string, and \( K_1 \) is the process of lifting drill string static load correction coefficient, \( K_2 \)
is the static load correction coefficient when lowering drill string.

2.1. Kinetic energy
During the lifting or lowering of drilling rig, the total energy is composed of the potential energy \( E_p \)
and the kinetic energy \( E_k \). The velocity \( v \) is changing in the process of acceleration - constant speed -
deceleration, and the acceleration \( a \) is also changing, thus the calculation of kinetic energy is divided
into two stages, acceleration and deceleration:

Acceleration stage:

\[ G - f = ma \] (5)

\[ h_a = \frac{v^2 - v_i^2}{2a} \] (6)
\[ \Delta E_{1m} = G h_n - f h_n \]  
(7)

Deceleration stage:
\[ f - G = ma \]  
(8)

\[ h_n = \frac{v_n^2 - v_{n-1}^2}{2a} \]  
(9)

\[ \Delta E_{2m} = f h_n - G h_n \]  
(10)

Lifting drill string:
\[ \Delta E_k = \frac{\sum (\Delta E_{1m} + \Delta E_{2m})}{\eta} \]  
(11)

Lowering drill string:
\[ \Delta E_k = \sum \Delta E_{1m} \times \eta \]  
(12)

2.2. Potential energy
\[ \Delta E_p = mgh_n \]  
(13)

Lifting drill string:
\[ \Delta E_p = \frac{\sum \Delta E_{pw}}{\eta} \]  
(14)

Lowering drill string:
\[ \Delta E_p = \sum \Delta E_{pw} \times \eta \]  
(15)

Where

Taking multi-model drilling rigs as an example, the total energy recovery and energy saving ratio are analyzed under different conditions of well depth. The weight is calculated by using the drill string of 5.5 × 2.54 cm; and the length of drill string \( h = 27 \) m. The average weight of each drill string in the air \( q = 36 \) kg/m; the weight of the hook without loading is shown in the Table 1; the static load correction coefficient when the drill string is running in hole \( K_1 \) and putting out of hole \( K_2 \) is shown in Table 2 [3]; the system efficiency is \( \eta = 0.72 \) [4-5].

| Table 1. The weight of hook |
|-----------------------------|
| The depth of well (km) | 1 | 1.5 | 2 | 3 | 4 |
| Weight (t)              | 4 | 5   | 6 | 8 | 10 |
| The depth of well (km) | 5 | 7   | 9 | 12 |
| Weight (t)              | 15| 18  | 20| 25 |

| Table 2. The static load correction coefficient |
|-----------------------------------------------|
| The depth of well (km) | 1 | 1.5 | 2 | 3 | 4 |
| \( K_1 \)            | 0.94 | 0.96 | 0.98 | 1.04 | 1.09 |
| \( K_2 \)            | 0.75 | 0.74 | 0.73 | 0.69 | 0.67 |
| The depth of well (km) | 5 | 7   | 9 | 12 |
| \( K_1 \)            | 1.16 | 1.29 | 1.50 | 1.81 |
| \( K_2 \)            | 0.65 | 0.61 | 0.59 | 0.57 |
Energy Saving Ratio $Q$:

$$Q = \frac{\eta \left[ 2am + qhK_{1} (1 + n) \right]}{2m + qhK_{1} (1 + n)}$$

$a=0$ —— $Q$ does not consider hook energy recovery;

$a=1$ —— $Q$ is considering energy recovery.

After calculation, the energy characteristics of the four processes of lifting drill string, lowering hook without loading, lowering drill string, and lifting hook without loading are shown in Fig. 1. Based on the calculation, the total energy and energy saving ratio of the hook without loading recovery are obtained, as shown in the Fig. 2. Since the kinetic energy consumption only accounts for less than 0.2%, the effect of kinetic energy is omitted.

![Figure 2. Energy Characteristics during Lifting or Lowering](image)

![Figure 3. Total energy characteristics](image)

It can be seen in Fig. 2 that the energy characteristics of lifting drill string or lowering drill string and the energy characteristics of lifting or lowering the hook without loading are linearly with the increase of well depth. The energy that can be recovered from the drill string is relatively considerable.
compared to the energy consumed by the drill string, while the energy recovered from the hook without loading is equal to the energy required to lift the hook. If the energy recovered from the hook without loading is recycled, the drilling costs can be effectively reduced.

According to Fig. 3, it can be seen that the deeper the well is, the more total energy recovery, but the energy saving ratio gradually decreases. However, even at a depth of 12,000 m, the energy saving ratio can reach to 16.5%, which is very valuable for recovery. If the energy of the hook without loading is recovered, the total net energy recovery increases, and the different depth of wells will increase the energy-saving ratio to varying degrees. When the well depth is 1000m, the energy-saving ratio increases 10%. When the well depth is 12000m, the energy-saving ratio increases 3.3%, indicating that it is necessary to recover the energy of hook without loading.

3. Energy storage system and control

3.1. Energy Storage System

![Figure 4. Winch regenerative braking energy storage system](image)

The system in Fig. 4 consists of 1-grid, 2-rectifier, 3-inverter, 4-operating motor, 5-control unit, 6-supercapacitor group, and 7-braking resistor. The working principle is: AC power is supplied from the grid 1, and the AC power is transmitted to the rectifier 2. The rectifier converts the AC power into DC power, and the DC power passes through the inverter 3 to become alternating current with controllable frequency and voltage, which drives the working motor 4 to work. When the working motor is reversed to generate alternating current, the alternating current is converted into direct current through the inverter, and the voltage of the direct current bus increases, and the control unit 5 controls the supercapacitor group 6 to charge, and the rest energy is consumed by the braking resistor 7 after being fullfilled [6].

3.2. System Control Strategy

The energy is controlled by detecting the voltage on the DC bus. As lifting drill string, the working motor is in the motoring state, and the DC bus voltage is maintained as the voltage after the grid voltage is rectified. When lowering drill string, the motor is in braking state. Meanwhile, the DC bus voltage rises, and the working state is judged by detecting the voltage on the DC bus. The DC bus voltage thresholds $U_L$, $U_H$ and $U_m$ are set. When the bus voltage is between $U_L$ and $U_H$, the motor operates in the motor state. When the bus voltage is between $U_H$ and $U_m$, the motor operates in the braking state [7]. The two states are described in detail as following.

3.2.1. Motor state. During the process of pulling out of hole, the winch motor consumes a large amount of electric energy in the state of energy consumption. When the voltage of the DC bus is between $U_L$ and $U_H$, the control unit controls the discharge of the supercapacitor group. At this time, the power grid and the supercapacitor group discharge together. Main energy discharges by grid, and supercapacitor group assists discharge. When the DC bus voltage is lower than $U_L$, the grid alone supplies power. As lowering hook without loading after lifting a drill string, the winch motor is in regenerative braking state. When the DC bus voltage is between $U_H$ and $U_m$, the supercapacitor group is charged.
3.2.2. Braking state. During the process of running in hole, the winch motor switches to regenerative braking state. The motor reversal converts the regenerative braking energy into electrical energy, resulting in the increase of DC bus voltage. When the bus voltage is larger than \( U_m \), the control unit determines the supercapacitor group to charge, after that the braking resistor reduces the DC bus voltage below \( U_m \). When the bus voltage is between \( U_H \) and \( U_m \), the control unit controls supercapacitor group discharging. The power generated by the grid can also be charged to the supercapacitor group through the rectifier and the control unit. When the supercapacitor group is full, the remaining energy is consumed by the braking resistor. As lifting hook without loading, the winch motor is in the energy consumption state. When the DC bus voltage is between \( U_H \) and \( U_L \), the supercapacitor group discharges energy.

4. Supercapacitor configuration

Because the working voltage of single supercapacitor is not high, in order to fulfil the requirement in the practical application, multiple supercapacitor cells need to be connected in series, and a supercapacitor group is formed with a voltage equalization and charge-discharge stabilization system. When the rated voltage varies from \( U_1 \) to \( U_2 \), and the total energy released or stored by the supercapacitor group can be expressed as:

\[
E = \frac{1}{2} C \left( U_1^2 - U_2^2 \right)
\]  

(17)

**E**——The energy that supercapacitor can store, J;

\( C \)——Capacity of supercapacitor, F;

\( U_1 \)——Supercapacitor upper limit voltage, V;

\( U_2 \)——Supercapacitor lower limit voltage, V.

In order to fulfil the requirements, we select \( n \) series of supercapacitors with the same model and uniform characteristics, and then form \( m \) branches in parallel to make an \( n \times m \) supercapacitor group. The voltage relationship can be expressed as [8]:

\[
U = nU_m
\]  

(18)

The total capacitance can be expressed as:

\[
C = \frac{mC_m}{n}
\]  

(19)

**U**——The rated voltage of the supercapacitor;

\( U_m \)——Supercapacitor single rated voltage;

\( C \)——Total capacity of supercapacitor group;

\( C_m \)——Capacity of supercapacitor monomer.

On the basis of the maximum energy recovered during process running in hole, the effective energy storage of supercapacitor is calculated. The voltage variation range is 300V-600V, and a domestic company 2.7V, 3000F; 2.7V, 7500F; 2.7V, 9500F three kinds of supercapacitors are selected for comparison. By calculating the baseline capacity of the supercapacitors required for drilling rig of different well depths, three configurations are obtained, as shown in Table 3, Fig. 5 and Fig. 6.

**Table 3. Supercapacitor benchmark capacity**

| The depth of well (km) | 1   | 1.5 | 2   | 3   | 4   |
|------------------------|-----|-----|-----|-----|-----|
| Benchmark capacity (t)  | 39  | 58  | 77  | 109 | 140 |
| The depth of well (km)  | 5   | 7   | 9   | 12  |     |
| Benchmark capacity (t)  | 170 | 222 | 276 | 360 |     |
From Fig. 5 and Fig. 6, it is concluded that, with the same well depth, as the capacity of the supercapacitor becomes large, the required amount, quality and volume gets small. As the depth of well increases, the number, quality and volume of supercapacitors increases. It is seen that when the depth of the well is small, the utilization efficiency of the supercapacitor with a small capacity is high, and when the depth of the well is large, the utilization ratio of the supercapacitor with a large capacity also increases. Therefore, under the conditions of different well depths, we must pay attention to the quantity, volume, quality, and utilization of supercapacitors at the same time, in order to reduce the cost without affecting the energy storage.

5. Conclusion
Supercapacitor automatic energy storage system can be used to recover the energy generated as lowering drilling string and hook without loading, and the recycled energy can be used as lifting drilling string and hook without loading, which can increase the total net energy recovery, and improve the energy saving ratio of the energy recovery, and also reduce the cost of drilling.

Under different well depths, the deeper the well depth is, the larger the total net energy recovery is, but the energy saving ratio of lowering drill string recovery gets decrease. However, even at the depth of 12,000m, the energy saving ratio can reach 16.5%. If the energy of hook without loading is recovered, the maximum energy saving ratio can be increased 10% at well depth of 1000m and net
energy saving can reach 129MJ. When the well depth is 12000m, the energy saving ratio can also be increased 3.3%, and the net energy saving can reach 13620MJ, showing that it is necessary to recover the energy released from the hook without loading.

When the depth of well is small, the utilization efficiency of supercapacitor group with small capacity gets high. When the depth of the well is large, attention must be paid to the number, volume, quality, and the utilization of supercapacitor group, and also supercapacitor with appropriate capacities must be optimally selected.

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