Analysis of Variable Frequency Energy-Saving Operation of Beam Pumping Unit

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Abstract. The frequency converter has been applied in the beam pumping unit, but the field application is still immature, and the energy saving effect is not ideal. This paper briefly analyzes the movement law of the beam pumping unit, and makes a proper simplification of the suspension point load. It derives the work done by the motor in one stroke of the steam head, and combines the oil recovery per unit time of the pumping unit. The operating law of the inverter when the ratio of motor energy consumption to oil production is the smallest. Finally, through simulation analysis, it is verified that the energy consumption of the slow and fast operation mode is lower than that of the constant speed operation mode.

1. Introduction

Because of its simple structure, high reliability, simple operation and low maintenance cost, the beam pumping unit is widely used in China's oil production industry and has a large number, accounting for 94% of the total pumping unit. However, this kind of oil production system is very inefficient. The average level in the domestic general region is only 12% to 23%, and the efficiency is not as high as 30%. The highest system efficiency in foreign countries can only reach about 46% [1]. At present, the number of pumping units in China is more than 100,000 units, and the installed capacity of electric motors is above 3,500 MW. The annual power consumption exceeds 10 billion kWh, and the potential for power saving is huge.

At present, there are three main ways to save energy in the pumping unit system: First, starting from the structure of the pumping unit: using energy-saving pumping units, including out-of-phase crank balance pumping unit, linear motor pumping unit, involute pumping Machine, etc. The literature [2] analyzes the power-saving principle and characteristics of the involute energy-saving pumping unit. The field test shows that the active power-saving rate of the involute energy-saving pumping unit reaches 26.51%. The literature [3] studied the working performance of the linear motor pumping unit and its impact on the pumping system, and compared with the beam pumping unit, the energy saving effect is more obvious. The second way to save energy is to achieve energy saving by using special motors, such as high slip motors, ultra-high slip motors, and permanent magnet synchronous motors. In [4], through a number of experiments, the energy consumption of the pumping unit system was theoretically analyzed, and the conditions that the high-gear rate motor-driven beam pumping unit can
save energy can be obtained. In [5], the quantitative analysis of the dynamic performance of the beam-type pumping unit with ultra-high-slip motor is theoretically analyzed. The results show that the use of ultra-high slip motor can not only save equipment power, but also save energy. Improve equipment life. The design process of the permanent magnet synchronous motor for pumping unit is detailed in the literature [6]. Compared with the ordinary asynchronous machine, the power saving effect is obvious. The third way to save energy is to control the motor speed through the inverter to achieve energy saving. Through the theoretical analysis and experimental verification, the literature [7-10] shows that after using the frequency converter, the beam pumping unit can adjust the upper and lower stroke speeds separately, adjust the strokes arbitrarily, achieve soft start, and greatly improve the power factor. Etc., achieved good practical application results.

To improve the power efficiency of the oil recovery machine, it is obviously uneconomical to replace the original pumping unit with an energy-saving pumping unit. High-slip motor has limited energy-saving effect and is only effective under certain conditions. Therefore, it is not economical to directly change ordinary asynchronous machine to high-slip motor. The rare earth permanent magnet motor will gradually demagnetize after a period of use and has to be replaced or recharged. If the inverter is used, there is no need to make too many changes to the original system. Only some devices are added on the input side. Compared with other energy-saving methods, it has many advantages and is the future development direction [11].

2. Motion analysis of beam pumping unit

The beam type pumping unit has a conventional type, a heterogeneous type, a front type, a gas balance type, a profiled type, a two-stage balance type and a slant straight well type beam pumping unit. The heterogeneous beam pumping unit is a well-performing pumping unit that has been successfully reformed in the past 30 years. This paper takes the heterogeneous type as an example to analyze its motion law [12]. Figure 1 shows a schematic diagram of the linkage mechanism of the heterogeneous beam pumping unit. The quantities are expressed as: r-crank rotation radius; \( \phi \) - crank rotation angle; l-link length; b-bridge beam rear arm length; a-bridge beam forearm length; J-fulcrum to gearbox output shaft; K - two fulcrum spacing; the horizontal distance between the I-fulcrum to the output shaft of the gearbox; (HG) - the vertical distance between the fulcrum and the output shaft of the gearbox; W-suspension load.

Structure and equivalent model of excitation system based on full controlled device (FCDES) in [6-9] has a detailed analysis, its single infinite system shown in Figure 1:

![Figure 1. Linkage mechanism of the heterogeneous beam pumping unit](image)

For the convenience of analysis, the movement of the hoe is simplified to the up and down linear motion, and the movement of the pumping unit can be simplified to the movement of the crank slider mechanism [13]. The displacement of the hoe can be expressed by the formula (1):

\[
S = r[(1 - \cos \phi) + \frac{1}{\lambda}(1 - \sqrt{1 - \lambda^2 \sin^2 \phi})] \frac{a}{b}
\] (1)
$S$ indicates the distance from the top of the hoe to the highest point of the hoe, and $\lambda = \frac{r}{l}$. When $\lambda$ is small, that is, the crank radius is much smaller than the link length, for $\sqrt{1 - \lambda^2 \sin^2 \varphi} = 1 - \frac{\lambda^2 \sin^2 \varphi}{2}$. Then the head displacement can be approximated as

$$S = r(1 - \cos \varphi + \frac{1}{2} \lambda \sin^2 \varphi) \frac{a}{b}$$

(2)

The derivation of $S$ is the suspension speed:

$$V = \omega r (\sin \varphi + \frac{\lambda}{2} \sin 2 \varphi) \frac{a}{b}$$

(3)

The derivation of $V$ is the suspension speed Acceleration:

$$\alpha = \omega^2 r (\cos \varphi + \lambda \cos 2 \varphi) \frac{a}{b}$$

(4)

When the hammer moves to the lowest point, the upper end of the connecting rod is at the highest point, and the crank and the connecting rod are in a straight line. At this time, the corresponding crank angle $\phi_u$ can be expressed as:

$$\phi_u = \arccos\left(\frac{k^2 + (l + r)^2 - b^2}{2k(l + r)}\right)$$

(5)

When the hammer moves to the highest point, the upper end of the connecting rod is at the lowest point, and the crank and the connecting rod coincide. The corresponding crank angle $\phi_d$ can be expressed as:

$$\phi_d = \pi + \arccos\left(\frac{k^2 + (l - r)^2 - b^2}{2k(l - r)}\right)$$

(6)

On the upstroke, the hammer moves from the lowest point to the highest point, and the crank angle varies from

$$\varphi = (\phi_u, \phi_d)$$

(7)

When the stroke is down, the hammer moves from the highest point to the lowest point, and the crank angle varies from

$$\varphi = (\phi_d, 2\pi) \cup (0, \phi_u)$$

(8)

3. Analysis of minimum energy consumption ratio of variable frequency operation

In the process of oil recovery, the pump head must bear a variety of loads, and the head load can be expressed by equations (9) and (10) [14].
\[ W_{up} = W_{ju} + W_{du} + W_v + F_u \quad (9) \]
\[ W_{down} = W_{jd} - W_{dd} - W_v - F_d \quad (10) \]

\( W_{up} \) - Upstroke hammer load, \( W_{ju} \) - Upper stroke static load, \( W_{du} \) - Upstroke inertia load, \( W_v \) - Vibration load, \( F_u \) - Upstroke friction load, \( W_{down} \) - Downstroke hammer load, \( W_{jd} \) - Downstroke static load, \( W_{dd} \) - Downstroke inertial load, \( F_d \) - Downstroke friction load.

When the lower part of the oil pipe is anchored, the vibration of the pipe string is suppressed, and the load generated by the vibration of the pipe string can be neglected, then equations (9) and (11) can be expressed as:

\[ W_{up} = W_{r'} + W_L' + (W_r + \varepsilon W_L) \frac{\alpha}{g} + F_v \quad (11) \]
\[ W_{down} = W_{r'} - W_r \frac{\alpha}{g} - F_d \quad (12) \]

That is, \( W_{r'} \) - Gravity of sucker rod in well fluid, \( W_L' \) - Liquid column load on the full plunger area, \( W_r \) - Sucker rod weight, \( W_L \) - Liquid column weight, \( \varepsilon \) - Acceleration correction factor, \( \alpha \) - Sucker rod acceleration, \( g \) - Gravity acceleration.

In a stroke, if the function of the hanging point is expressed, then

\[ W = \int_0^{T_1} W_{up} V dt + \int_0^{T_2} W_{down} V dt \quad (13) \]

That is, \( T_1 \) indicates the upstroke time, \( T_2 \) indicates the down stroke time. \( \omega_1 \) indicates upper stroke crank angular velocity, \( \omega_2 \) indicates down stroke crank angular velocity, for \( d\phi = \omega dt \), then

\[ dt = \frac{d\phi}{\omega} \quad (14) \]

Bring equation (14) into equation (13):

\[ W = \int_0^{\omega_1} W_{up} \frac{V}{\omega_1} d\phi + \int_0^{\omega_2} W_{down} \frac{V}{\omega_2} d\phi \quad (15) \]

The worst-case situation is used to analyze the energy consumed by the pumping unit during one stroke cycle, that is, all inertial loads consume only electrical energy, regardless of the regenerative energy generated by its reverse acceleration. In addition, to simplify the analysis, it is considered that half of the time of each up-and-down stroke is in the reverse acceleration state (reducing the suspension load), and the other half is in the forward acceleration state (increasing the suspension load), then the work of the suspension point can be expressed as

\[ W = \int_0^{\omega_1} W_{up} \frac{1}{\omega_1} d\phi + \int_0^{\omega_2} W_{down} \frac{1}{\omega_2} d\phi \]

Bring the equations (3), (4), (5), (6), (11), (12) into the above equation to get the work done by the suspension point in one stroke:
\[ W = k_1 m_1 \omega_1^2 + k_2 m_2 \omega_2^2 + k_3 \] (16)

Where

\[ m_1 = (cW' + W'), \frac{a^2 r^2}{b^g} \] (17)

\[ m_2 = W', \frac{a^2 r^2}{b^g} \] (18)

\[ k_1 = \frac{1}{2} \cos 2 \delta_1 - \frac{1}{4} \lambda (\sin 3 \delta_1 + \sin \delta_1 - \cos 3 \delta_1 + \cos \delta_1) \] (19)

\[ \delta_1 = \phi_1 - \phi_0 \] (20)

\[ k_2 = \frac{1}{2} \cos 2 \delta_2 + \frac{1}{4} \lambda (\sin 3 \delta_2 + \sin \delta_2 + \cos 3 \delta_2 - \cos \delta_2) \] (21)

\[ \delta_2 = \phi_2 - \pi - \phi_0 \] (22)

\[ k_3 = (W' + \overline{W}_j + C) \frac{d^2 r}{b} \] (23)

In addition, the theoretical displacement of the deep well pump can be expressed by the formula (24):

\[ Q = KSn \] (24)

Where, \( Q \) - Deep well pump theoretical displacement per day, \( K \) - Displacement coefficient /m², \( S \) - Polished rod stroke / meter, \( n \) - Rush times /min.

\[ n = \frac{60}{\frac{\pi}{\omega_1} + \frac{\pi}{\omega_2}} \] (25)

Then the theoretical stroke of the deep well pump can be expressed as:

\[ Q' = \frac{KS}{24\pi} \frac{\omega_0 \omega_1}{\omega_1 + \omega_2} \] (26)

Let \( F = \frac{W}{Q'} \), \( T = \frac{1}{n} \). In order to obtain the upper and lower stroke angular velocities when the energy consumption ratio is the smallest, according to the actual operation of the boring machine, it can be discussed in three cases:

1. \( \omega_1 = \omega_2 = \omega \), \( T \) is variable, then

\[ F = \left( (k_1 m_1 + k_2 m_2) \omega + \frac{k_3}{\omega} \right) \frac{KS}{48\pi} \] (27)

When
Energy consumption ratio is lowest.

In the case of variable frequency operation, if the angular velocity of the up and down strokes is equal, then the above values \( \omega_1 \) and \( \omega_2 \) are taken, the energy consumption ratio is the smallest, and the pumping unit operates most economically.

(2) \( \omega_1 \neq \omega_2 \), \( T \) is constant

At this time, the displacement \( Q \) is fixed, under the condition of \( \frac{\pi}{\omega_1} + \frac{\pi}{\omega_2} = T \), \( W \) is smallest.

When

\[
\omega_1 = \frac{\pi}{T} \left(1 + \frac{k_1 m_1}{\sqrt{k_1 m_1} + k_2 m_2}\right), \quad \omega_2 = \frac{\pi}{T} \left(1 + \frac{k_2 m_2}{\sqrt{k_1 m_1} + k_2 m_2}\right)
\]  

The energy consumption ratio is the smallest, and the pumping unit operates most economically.

Since \( \delta_1 \) and \( \delta_2 \) is generally small, \( k_1 \) and \( k_2 \) can be taken as 0.5. It can be seen from equations (17) and (18) that \( m_1 > m_2 \) when \( \omega_1 < \omega_2 \), the upper stroke angular velocity is lower than the lower stroke angular velocity, which is often used by the inverter to drive the pumping unit. Mode of operation, this mode of operation can achieve a smaller energy consumption ratio.

(3) \( \omega_1 \neq \omega_2 \), \( T \) is variable, then

This situation is similar to condition (2), \( \omega_1 \) and \( \omega_2 \) are determined by equation (29). At this time, the minimum energy consumption ratio can be expressed as

\[
F = \frac{1440}{KS} \left[ \frac{1}{T} \left( \frac{k_1 m_1}{\sqrt{k_1 m_1} + k_2 m_2} \right)^2 + k_1 T \right]
\]  

The minimum energy consumption ratio is determined by equation (30) and there is a minimum value. However, in order to ensure a certain amount of oil recovery, the pumping unit does not change much, so it is actually difficult to select \( T \) according to formula (30) to obtain the minimum energy consumption ratio. The actual practice is to ensure a certain condition according to condition 2. After the punching, adjust the up and down running speed appropriately to obtain a smaller energy consumption ratio.

4. Simulation at the lowest energy consumption ratio

Taking the CYJY6-2.5-13HB pumping unit as an example, it can be calculated according to its size.

\( \varphi_0 = 27.7^\circ, \phi_i = 11.7^\circ, \phi_d = 188.5^\circ, k_1 = 0.38, k_2 = 0.11, k_3 = 8.45 \) kNcm.

The diameter of the sucker rod is 22mm, the area of the plunger is 11.34cm², the displacement coefficient is 1.5m, the pump depth is set to 1000m, the moving surface is 800m, the liquid column load caused by the liquid level pressure difference is ignored, and the friction load is static. 1% of the load, according to the empirical formula [14],

\[
W_\varphi = 40.2 + 3.89\varphi^2 (\cos \varphi + 0.178 \cos 2\varphi) \\
\varphi = (11.7^\circ, 188.5^\circ)
\]

\[
W_{\varphi_{max}} = 30.5 - 3.05\varphi^2 (\cos \varphi + 0.178 \cos 2\varphi) \\
\varphi = (188.5^\circ, 371.7^\circ)
\]
From equations (31) and (32), an up and down stroke indicator diagram at different angular velocities can be drawn as shown in Fig. 2.

Figure 2. Simulated digraph of one stroke

Taking the fixed stroke cycle as an example, and setting the stroke period to 10s (the stroke is 6), the angular velocity of the upper and lower running speeds is \( \omega_1 = \omega_2 = 0.628 \) and the upper and lower angular speeds of the shifting operation are \( \omega_1 = 0.462 \) and \( \omega_2 = 0.975 \) respectively. Set the ratio of the gearbox of the pumping unit to 322, the motor running frequency is 32.2 Hz when the speed is up and down, and the upstream frequency is 23.7 Hz and the downlink frequency is 50 Hz. The motor is a common 7.5kW asynchronous machine, and the voltage-to-frequency ratio control is used in the simulation.

Figure 3 shows the motor input torque waveform, motor stator current waveform, and motor input power waveform in one stroke when running up and down at the same speed.

Figure 3. Up and down speed single-stroke: (a) Motor torque (b) Stator current (c) Motor power

As shown in Fig. 3(a), the motor puts an upward load at 2 s, cuts the downward load at about 6.9 s, and reaches one stroke at 12 s. The load waveform has the same variation as the power diagram in...
Figure 2, which differs only in the value of one gearbox (not considering the transmission loss). Figure (b) shows the stator current waveform. The current frequency is constant, and the downlink load is smaller than the uplink load, so the current amplitude decreases. Figure (c) shows the input power waveform of the motor. When the motor is in the power generation state when going down, the power waveform area from 2s to 12s can be obtained. The electric energy consumed by the motor in one stroke is about 14,000 joules, and the average power of one stroke of the constant speed operation is 1.4kW.

![Motor Torque](image1.png) ![Stator Current](image2.png) ![Motor Power](image3.png)

**Figure 2.** Motor torque, stator current, and motor power waveforms.

**Figure 4.** Up and down shift single stroke: (a) motor torque (b) Stator current (c) Motor power

Figure 4 shows the operating conditions for one stroke time during up and down shifting operation. The motor's uplink load is cut in 2s. Because the uplink speed is slow, the downlink load is cut in about 8.7s and cut out in 12s. When the uplink is low, the stator current frequency is low, the input voltage is low, the motor input power is relatively small, but the time is long; when the downlink is high, the stator current frequency is high, the input voltage is high, the motor input power is large, but the running time is short. In Figure (c), the input power of the 2s to 12s motor is about 16100 joules, and the average power of one stroke of the variable speed operation is 1.22kW.

Comparing the electric energy consumed by one stroke motor under the two operating conditions, it indicates that the slow and fast shifting operation mode is more energy efficient than the constant speed operation mode, and the above theoretical analysis results are also verified. According to the simulation calculation results, the variable speed operation can save 4.32 kWh per day than the constant speed operation. A large oil field usually has tens of thousands of pumping units. In the case of using the same equipment, the economic effect of changing only the operation mode is considerable.

5. Conclusion
This paper briefly analyzes the operation law of the beam pumping unit, studies the energy consumed by the pumping unit in one stroke, and combines the sampling amount of the pumping unit per unit time to obtain the pumping unit with the lowest energy consumption ratio. The law of operation. Finally, through simulation, the energy consumed by the up and down speed operation and the up and
down speed operation in the same stroke time (the same oil recovery) is compared, and the theoretical analysis results are verified. It should be pointed out that the simulation and theoretical analysis consider the static load and inertia load of the suspension point, ignoring the loss of the transmission mechanism and the influence of the weight, and assume that the oil production amount is proportional to the stroke cycle, and the motor is in the braking state. The electric energy is stored on the DC bus, that is, the brake unit does not operate. In addition, the internal impedance of the motor also affects the energy consumption of the system. Therefore, the actual energy-saving effect is affected by many factors on the site, and it needs coordination in many aspects.

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