# DYNAMIC FREQUENCY CONTROL STRATEGY FOR ENERGY CONSERVATION OF MOTOR SYSTEMS WITH DYNAMIC LOAD CONDITIONS

Wenle SONG[1], Lei WANG[1], Guidong ZHU[1], Zhijian ZHANG[2], Guangliang YANG[3]*

*Beam pumping units (BPUs) are widely used in the oil production industry. Due to the large number of mechanical transmission mechanisms in BPUs, the system's consumption is generally high, which accounts for about 40% of total consumption in the oil production industry. This paper analyzes the basic load torque characteristics of BPUs. To reduce the operation cost and improve the system's efficiency, a dynamic frequency control strategy is proposed. The strategy takes the minimum root mean square (RMS) of input power as the control object and minimizes load fluctuation effectively. Experiment validations are also performed with a 45-kW induction motor. The results indicate that power saving ratio increases 10% compared with traditional converter-fed control, and the peak input power of BPUs can be reduced by 20 %. The research results of the paper serve the energy saving and consumption reduction of the oilfield high-energy consumption industry and provide an effective approach reducing power fluctuation of driven motor system of BPUs.*

**Keywords:** Motor system, Variable frequency control, Dynamic and potential load, Energy conservation

## 1. Introduction

The oil production industry is one of the main energy-consuming industries around the world. Beam pumping units (BPUs) are widely used in the oil production industry due to the simple structure and high reliability in the field [1]. Generally, energy consumption accounts for about 40% of total consumption in oil production industry, but the average load ratio of BPUs is usually lower than the nominal power of installed driven motors. In addition, due to the existence of mechanical transmission mechanisms and a variety of energy conversion in operation, the system efficiency is low [2]. Therefore, to reduce the

[1] State Grid Cangzhou Electric Supply Company, Cangzhou District, Hebei, 061001, China
[2] Power Dispatching Control Center, State Grid Beijing Electric Power Company, Xicheng District, Beijing, 100031, China
[3] School of Electric and Electronic Engineering North China Electric Power University, Changping District, Beijing, 102206, China

operation cost and improve system's efficiency, the development of energy saving technologies of BPUs are still a hot topic in oil industry.

At present, there are two main types of energy saving methods for beam pumping motors: 1) Adopting variable frequency speed control and other energy-saving strategies [3-6]. 2) Improving the motor structure to achieve better mechanical characteristics [7-8]. Previous research has carried out a large number of studies on the above two aspects. For example, an intermittent power supply control method based on the automatic load tracking and power switching technology is proposed in [9]. Compared with traditional strategies, the impulse current is reduced considerably. Combined with the star angle switching and automatic reactive power compensation technology, the power saving rate reaches 10-25%, saving about 15120 kWh per year. A dual-pulse width modulation converter is applied to the oil pump in [10], which can smoothly adjust the frequency in the range of 5-75Hz, improving the system power factor. Compared with traditional strategies, the harmonic components can be reduced considerably, and the total power saving rate reaches 37.83%. In [11], the motor power factor is improved by compensating the capacitor to reduce the energy consumption, which is characterized by low cost and high energy saving efficiency. In addition, the efficiency and power factors of pumping units with seven control methods, such as maximum efficiency control and optimized speed control, are compared systematically [12], obtaining suitable control strategy for pumping units, which provides a reference for the reasonable selection of control methods. In terms of motor selection, a linear electromagnetic pumping motor is proposed in [13], which effectively overcomes disadvantages of large volume and high cost of traditional pumping units with long stroke. The motor has the virtue of simple structure, adjustable speed and small volume, which is suitable for special working environments such as offshore oil exploitation. A new two-speed motor is proposed, and its basic operating characteristics are analyzed in [14]. Unlike the traditional two-speed motor, which requires two windings in the stator, the motor only needs one winding, and the cost is further reduced. In [15] the dynamic performance of high-speed energy-saving motors using amorphous materials is studied, and the results show that such motors can significantly reduce copper consumption, which is conducive to the energy saving and consumption reduction of the system. In addition, the no-load iron consumption of energy-saving motors at power frequency is studied based on time-step finite element analysis [16], which provides an important reference for the refined analysis of energy saving for beam pumping motor systems (BPMS).

Although previous literature has studied energy saving method of BPMS, there are still limitations. For example, reducing the load torque fluctuation of the pumping motors with variable frequency control can effectively reduce additional loss. However, a few literature studies on reducing the load fluctuation range. In addition, the two-quadrant converter-fed devices are widely used in oil fields, while the traditional two-quadrant converter is not suitable when a driven motor operates with generator mode, which limits its wide application.

This paper analyzes the basic load torque characteristics of BPUs. Based on two-quadrant frequency conversion technology, a dynamic frequency control strategy is proposed, which minimizes load fluctuation. Compared with traditional two-quadrant frequency conversion technology, this method can also have a better energy saving effect with generator mode. Finally, with a 45kW induction motor, the proposed control strategy is compared with the traditional two-quadrant control. The results show that the presented control strategy outperforms traditional strategy in reducing the peak input power and the average input power, and the peak power is about 20% lower than traditional two-quadrant converters, by which the system efficiency can be improved significantly. The research results of the paper serve the energy saving and consumption reduction of the oilfield high-energy consumption industry and provide an effective approach reducing power fluctuation of driven motor system of BPUs.

## 2. Characteristics of variable frequency control for high energy-consuming potential load system

### *Application characteristics of typical high energy consuming BPMS*

According to the mechanical structure of BPUs in Fig. 1, there are many components in the system, which leads to low system efficiency. In particular, the horsehead and other mechanical structures lead to the change of working conditions, which further reduces the system efficiency.

Variable frequency control is widely used in oil production of BPUs in oil field. The main feature is that frequency adjustment can conveniently change the operating parameters of pumping units, which meets the production requirements, and improves the underground efficiency to achieve energy saving. When the frequency is reduced, the power change in unit time is reduced. At the same time, the fullness of the oil pump is improved, the closing time of the down-stroke pump is increased, and the pump efficiency is improved, which increases the liquid production. Furthermore, frequency adjustment can also reduce the mechanical impact and extend the system’s operating life effectively. In practice, to reduce the control complexity, the fixed frequency regulation method is widely adopted in engineering applications. However, it cannot achieve the optimal frequency control for variable load, which limits the improvement of efficiency.

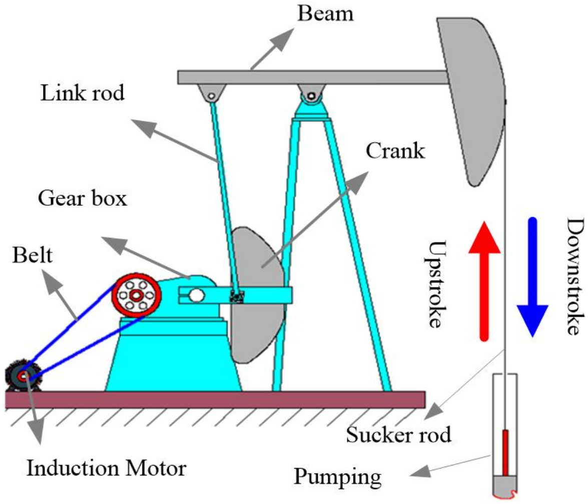



Fig. 1. Beam pumping units

***Dynamic frequency control strategy***

The purpose of this study is to propose a way to improve the system's efficiency by frequency control approach but not increase the cost. Based on analysis of the mechanical structure and working conditions of BPUs, a dynamic frequency control strategy for motor systems with dynamic loads.

The above-mentioned energy-saving control approach fully considers the structure of four-bar linkage and horsehead. Firstly, this paper reveals the influence of variable frequency control on load torque performance. The real-time frequency of the power supply is adjusted under the conditions of operating cycle and rotating speed. The presented strategy can adjust the rotating speed of the motor at different working conditions and realize smooth and optimal control of the operating power of BPUs. Furthermore, the proposed control strategy can improve power fluctuation range and reduce additional losses caused by large torque fluctuation. Moreover, the proposed control strategy meets the requirement that the operation cycle of the down-stroke power generation area is longer than that of the up-stroke, which improves productivity.

## 3. Load torque performance of BPUs with variable frequency control

***Composition of the load torque***

It can be seen from Fig.1 that the horsehead load acts on the crankshaft through the beam and the connecting rod mechanism. Combined with the balance weight that moves in a circular motion, horsehead load constitutes the equivalent resistance torque, which acts on the crankshaft. The diagram of the crank is shown in Fig. 2. The torque $M_{ef}$ on the rotating shaft can be expressed as in (1) [17].

$$M_{ef} = M_p + M_b \tag{1}$$

where: $M_p$ - the torque of horsehead, $M_b$ - the torque of balance blocks.

The moment of balance weight can be expressed as in (2).

$$M_b = M_g \sin(\theta - \varphi) \tag{2}$$

where: $\theta$ - crank angle, $M_g$ - gravity of the balance blocks, $\varphi$ - the lag angle of balance blocks.

Horsehead load includes weight of rod, underground liquid oil and the acceleration load. The horsehead load $M_p$ can be expressed as in (3).

$$M_p = MT_F H_{CL} \left(g + a_1 K_\theta \theta'^2\right) \tag{3}$$

where: $M$ - equivalent mass, $T_F$ - torque factor, $K_\theta$ - structure factor, $\theta'$ - rank angular velocity, $H_{CL}$ - the transmission efficiency.

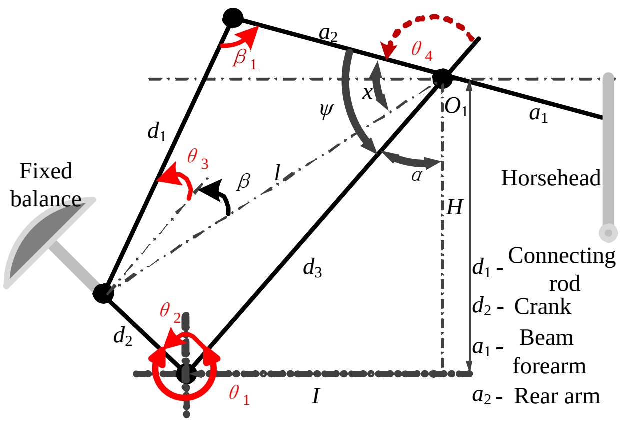



Fig. 2. Movement of crank

***Mechanism of load torque change with variable frequency control***

The motor is connected with the crankshaft through the belt deceleration mechanism, and these two parts can be regarded as mechanically rigid connection, so the relationship between motor angular velocity and crank rotation angle can be give as in (4).

$$\theta' = k\Omega \tag{4}$$

where: $k$ - the speed coefficient, $\Omega$ - the angular velocity of the motor.

The relationship between angular velocity of motor $\Omega$ and power frequency $f$ can be expressed as in (5).

$$\Omega = \frac{(1-s)2\pi f}{p} \tag{5}$$

where: $s$ - the slip ration, $f$ - the frequency of power supply, $p$ - pole pairs of the motor.

## 4. Frequency control method for power optimization

***Analysis of dynamic frequency control***

Although constant frequency control can reduce the peak power, the required input power is still constant, which cannot improve the system efficiency to the greatest extent. Therefore, taking the minimum root mean square (RMS) of input power as the object, the real-time dynamic frequency control can effectively improve the above problems.

According to the mechanism of the motor, the torque relationship can be given in (6) and (7).

$$J\frac{d\Omega}{dt} = T_2 - T_{\mathrm{dp}} \tag{6}$$

$$T_{\mathrm{dp}} = kM_{\mathrm{ef}} \tag{7}$$

where: $T_2$ - the output torque of the driven motor, $J$ - the system's inertia, $T_{\mathrm{dp}}$ - the load torque applying on the motor shaft torque.

Since BPUs runs slowly, almost 10s per cycle, the motor speed changes a little. In order to simplify the control process and improve the engineering practicability, the change of slip ratio can be ignored. Therefore, relation in (8) can be obtained.

$$T_2 - T_{\mathrm{dp}} = 0 \tag{8}$$

Based on (1) - (8), the relationship between output power of driven motors and operating frequency of power supply can be obtained as in (9) and (10) [18].

$$P_{\mathrm{2f}} = 2\pi\left[M_{\mathrm{g}} f\sin(\theta-\varphi) + MT_{\mathrm{F}}H_{\mathrm{CL}}\left(gf + D_0 f^3\right)\right]/k \tag{9}$$

$$D_0 = 4\pi^2 a_1 k^2 k_{\theta} \tag{10}$$

According to the principle of constant V/F control in converter, the relationship between voltage in motor terminal and frequency of power supply can be obtained as in (11).

$$\frac{U_1}{U_0} = v_0\frac{f}{f_0} \tag{11}$$

where: $v_0$ - the corrected factor, $f_0$ - the rated frequency of the power supply, $U_0$ - the rated voltage.

The copper consumption $P_{\mathrm{b}}$ of the motor is related to the load condition, it can be calculated as in (12) [18].

$$P_{\mathrm{b}} = \left(P_{\Sigma\mathrm{N}} - P_0\right)\left(\frac{f_0 P_{2f}}{P_{\mathrm{N}} f}\right)^2 \tag{12}$$

where: $P_{\Sigma N}$ - the rated losses of the driven motor, $P_N$ - the rated power of the driven motor, $P_0$ - the no-load loss of the driven motor, $P_{2f}$ - actual power of the driven motor.

Input power of the driven motor $P_1$ can be expressed as in (13).

$$P_1 = P_{2f} + P_0 + P_b \tag{13}$$

***Objective function***

The pumping unit is a periodic potential energy load system, and the power change trends in adjacent periods are basically the same. The above periodic power can be regarded as a periodic function. According to the mathematical principle, when the RMS value of this periodic function is the smallest, the variation range of this function is the smallest. Therefore, the power fluctuation of BPUs can be reduced by frequency control. The formula can be expressed as in (14):

$$P_g = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} P_1^2 d\theta_1} \tag{14}$$

where: $P_g$ - the RMS value of input power.

It can be seen that the objective function is:

$$F(x) = \min(P_g) \tag{15}$$

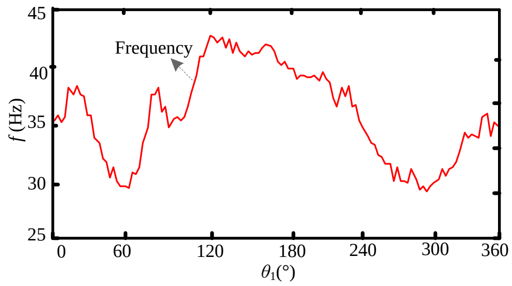
## 5. Simulation analysis

Taking a 45kW induction motor as an example, the proposed variable frequency control method is simulated and verified, and the results are compared to typical variable frequency control methods. The main parameters are as follows: the running cycle is 10 seconds, the input power is 14.3kW, and the adjusted frequencies are 15 seconds (30Hz), 20 seconds (25Hz) for different cases.

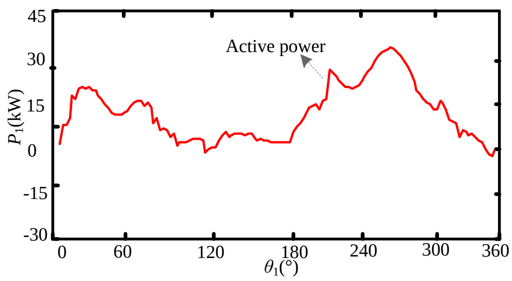
Fig. 3 shows the frequency curve using self-tracking control mode when the period is 15 seconds. In a cycle, the frequency is lowest at 29 Hz in the heavy-load region, and the adjusted frequency in power generation region is 35Hz. The frequency rises as generated power increases, and the highest value is 43.5 Hz. The average frequency of one cycle is 34 Hz, which can also meet the requirements in the field.

Fig. 4 shows the input power comparison under different frequency control methods when the period of BPUs is 15 seconds. The peak power of the resistance braking type frequency conversion is 44.6 kW and the power saving ratio is 20.9%. While the load peak power of the four-quadrant frequency conversion is 41.7kW and power saving ratio is 27.6%. When using the proposed method, the maximum power is 32.1 kW and power saving ratio is 33.2%.

Compared with typical control method, the proposed method has a prominent effect in reducing the motor power changing range and improving the energy efficiency of the system. Moreover, the cost of hardware has not increased, which plays a positive role in the promotion of the project and improves the applicability in the project.




(a)




(b)

Fig. 3. Adjusted frequency and input power curve when period is 15 s. (a) Frequency. (b) Input power.

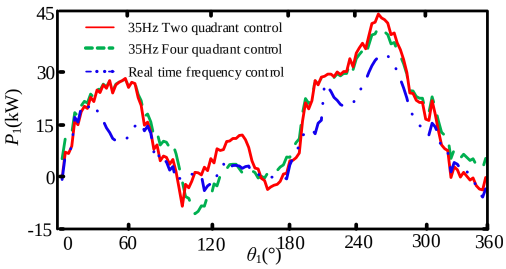



Fig. 4 Comparison of input power with different frequency control strategies

## 6. Experimental validation

***Control board design***

The proposed dynamic frequency control strategy realizes controllable energy conversion. The frequency control signal is required in the frequency converter to realize energy-saving control. Most of the existing frequency converters have external interfaces for frequency adjustment. Therefore, for the traditional converters, the proposed control strategy can be performed by using an external control module, and the cost can be considerably reduced in practice.

This paper independently designs and develops the corresponding control board, as shown in Fig. 5. According to Fig. 5, the control board includes MCU CPU unit, 485 communication port, signal input port, AD conversion unit, etc. The basic process is that, after the signal is adjusted, it can be sent to the MCU. The MCU unit calculates and collates the data and gives relevant control variables to realize the control of frequency adjustment.

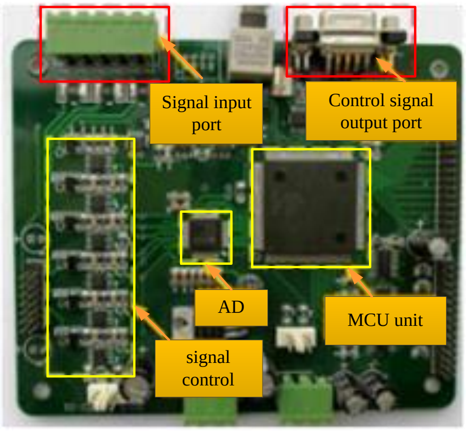



Fig. 5 Frequency control board

***Result analysis***

Through the standard test platform of BPU, the proposed method is performed. The running cycle of pumping unit is 10.5 seconds without dynamic frequency control and 17.5 seconds with dynamic frequency control. The results are shown in Fig. 6 to Fig. 8.

As shown in Fig. 6, with the dynamic control strategy, the maximum input power decreases from 43.7kW to 29.2kW, and the power saving ratio is 33.6%.

Fig. 7 shows the speed comparison of real-time dynamic frequency control and fixed frequency supply with two-quadrant converters. With the proposed dynamic frequency control, the motor speed with the proposed control strategy decreases from 536 rpm to 417 rpm; at the same time, the motor speed in the power generation region increases from 542 rpm to 587 rpm, which can effectively realize power smooth control.

According to the output torque curve in Fig. 8, it can be concluded that the peak torque decreases from 360Nm to 340Nm after the frequency decreases in the heavy load area. In the light load and power generation area, the torque increases, and the maximum is about 20Nm. The above test results are consistent with theoretical analysis.

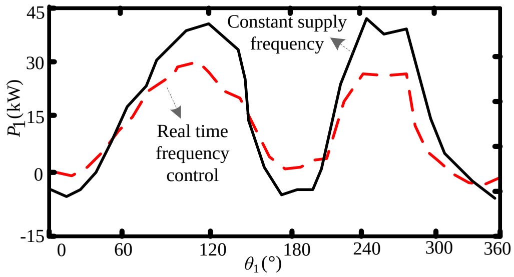



Fig. 6. Comparison of measured input power

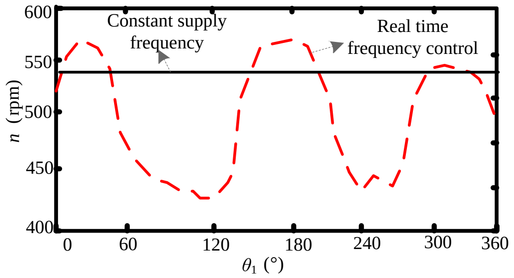



Fig. 7 Comparison of measured speed curve

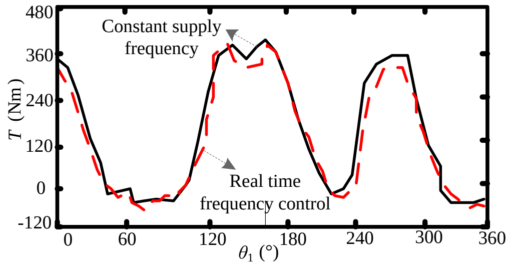



Fig. 8 Comparison of measured motor torque curve

## 7. Conclusions

This study proposes a dynamic frequency control for BPUs in oil production industry. The following results are obtained.

1) Based on the systematic analysis of the relationship between mechanical load torque, motor loss and frequency of potential energy load system, the relationship between motor energy consumption and frequency regulation in potential energy load system is summarized.

2) A dynamic frequency control strategy for reducing energy consumption of BPUs is proposed, which reduces power fluctuation under dynamic conditions.

Compared with traditional two-quadrant frequency control, the peak input power of BPUs can be reduced by 20 % and the energy-saving effect can increase by 10 % with the proposed control strategy.

3) Due to the above advantages, the proposed strategy can be widely used in oil-field production. This paper provides important reference for energy saving technology.

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