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Sectional Variable Frequency and Voltage Regulation Control Strategy for Energy Saving in Beam Pumping Motor Systems

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ABSTRACT Despite the fact that the energy losses in the beam pumping motor systems (BPMS) utilized in oil fields represent a monumental challenge industrially, very few studies discussed the feasibility and applicability of a universal energy saving technology for such industry. This study proposes a sectional control strategy integrating variable frequency (VF) with voltage regulation (VR) based on the mechanical load characteristics of the BPMS. Main merits of the proposed strategy are as follows: 1) controlling horse-head acceleration through VF, and indirectly weakening the inertia torque of polished rod load, thereby reducing the power consumption during the up-stroke; and 2) based on monitoring load conditions in real time, auto-tracking VR is adopted to optimize the online efficiency of the system. The proposed strategy utilized the adaptive fuzzy logic control to alternate between VF and VR modes. The proposed energy saving strategy was applied to a CYJ10 BPMS driven via a 37-kW induction motor in simulation and experimental environments. Results revealed that the effectiveness of the proposed strategy to improve the load balance effects through better utilization of the counterbalance during the heavy-loading conditions in up-stroke. Furthermore, the energy consumption is reduced via the auto-tracking of VR under light-loading conditions during the down-stroke. Moreover, the energy saving ratio is more than 10% under different dynamic liquid levels and counter weights. The effectiveness of the proposed strategy is verified through comparing the calculated results with the measured data for a standard oil rig, and the generality is verified as well.

INDEX TERMS Beam pumping motor system (BPMS), induction motor control, energy saving strategy, variable frequency (VF), voltage regulation (VR), adaptive fuzzy logic controller, oil field applications.

I. INTRODUCTION

Electric motors are the cornerstone in industrial systems. Being the main prime mover to industry, electric motors consume more than 60% of the total energy in industrial plants. Consequently, ample research efforts are excreted industrially and academically to enhance the operational efficiency, health and condition monitoring of electric motors. For instance, the online fault detection of induction motors windings fault was addressed in [1], while the optimal design and loss analysis of novel rotor structure for electric vehicle (EV) motors was investigated in [2], [3]. Moreover, the utilization of induction motor in EV application was highlighted in [4], and an energy saving technology for induction motor was investigated in [5].

Energy saving technologies are crucial in high energy-consuming industries, such as oil field, steel, power plant, etc. Developing a universal energy saving strategy for motor systems operation in oil production industries is still a vital area of investigation especially industrially. The difficulty of
finding such universal technique is owing to the dynamic load nature in the oil field. Therefore, this paper mainly focuses on this issue in oil field industry.

Being the backbone of the oil production industry, a typical beam pump motor systems (BPMS) consists of four parts: 1) driving motor, 2) pumping unit, 3) sucker rod, and 4) oil pump, as Figure 1 represents. A typical operational cycle of BPMS includes heavy loading, light loading conditions and generation mode [6]. Furthermore, to meet the high starting torque requirement, the rated power of the installed motors are usually higher than the load average power, which leads to significant waste of electric energy [7].

The aim of this study is to provide a general energy saving technology for BPMS in oil production industry. The load torque and magnitude of suspension point load in up- and down-stroke of BPMS are firstly analyzed in detail.

Afterwards, the relationship between the acceleration of horse head suspension and motor speed is deduced. On this basis, a general energy saving technology of VF and VR coordinated control is proposed. This technology indirectly improves the balancing effect of the counterweight on load through frequency conversion measures in specific crank position intervals. Whereas in other sectors, tracking VR technology is implemented, which makes the motor run under light load conditions with higher efficiency. Finally, the feasibility and benefit of the proposed technology is analyzed, and experimental validation is performed in field on a standard oil rig.

II. MECHANIC LOAD CHARACTERISTICS OF BPMS
A typical load curve of BPMS is displayed in Figure 2(a). The horse head torque, \( M_{hh} \), is the equivalent negative torque that is suspension point load, \( PRL \), acts on the crank through four-bar linkage mechanism; and the balance torque, \( M_{bb} \), produced by the counter balance may offsets the horse head torque, and the total load torque are integrated by those two torques. Based on the classical mechanical dynamics theory, the differential equation of crank motion can be obtained according to (1) [7]

\[
\begin{align*}
J_e \ddot{\theta}_1 + \frac{1}{2} \dot{\theta}_1 \frac{dJ_e}{d\theta_1} &= M_{ed} - M_{ef} \\
M_{ef} &= (PRL - B_w) \cdot TF - M_c \cdot \sin(\theta - \tau)
\end{align*}
\]

FIGURE 2. Mechanic load characteristics of BPMS. (a) Torque components of crank. (b) Speed and acceleration of horse-head.

where \( J_e \) is the inertia of BPMS; \( M_{ed} \) is the driving torque, \( M_{ef} \) is integrated equivalent load torque, \( B_w \) is the unbalanced weight of system; \( TF \) is the torque factor which reflects the negative torque of per unit suspension load acting on the
crank, PRL is suspension point load; $M_c$ is the maximum balance torque of counter balance, and $\tau$ is the offset angle of counter balance.

Based on the previous analysis, the load characteristics of BPMS is different from the constant torque or constant power load. During a running cycle, the velocity $v_c$ and acceleration $a_c$ of the horse head varies with the oil pump conditions underground, as Figure 2(b) depicts. After ignoring the fluctuating load of sucker rod, the motion law of sucker rod and oil pump can be simplified to the vertical motion model of mass “$m$,” and the force relationship is given in (2)

$$PRL = m \times (g + a_c)$$  (2)

where the first term is related to gravity acceleration constant $g$ is called static load, while the second term related to acceleration $a_c$ is dynamic load. It is noteworthy to mention that acceleration $a_c$ varies abruptly near the lower dead point (the initial stage of the upper stroke). The suspension load PRL inertial load torque cannot be neglected, and the dynamic load ratio can reach 10%-30%. Furthermore, due to the submergence degree of the tubing, the mass of static and dynamic loads generated during the up- and down-stroke operation are unequal. Consequently, the previous formula is modified as in (3). The calculation methods of $m_1$ and $m_2$ are illustrated in Figure 3.

$$PRL = m_1 \times g + m_2 \times a_c$$  (3)

$\theta_4$ are all $O-O_1$ references, and counter clockwise direction is positive; 3) Direction of the horse head suspension is positive vertically. The output power of the motor is determined by the total load torque $M_{ef}$, which is defined by the balance moment and the horse head torque under the different crank positions stated in Section II. However, the horse head torque $M_{hh} = (PRL - B_w)$.

$\overline{TF}$ is related to the spatial position angle and it is constant. It can be seen that the load torque $M_{ef}$ is related to PRL when the weight of the counter balance and the length of the beam arm are given, and the relationship is shown in Figure 5. If the acceleration $a_c$ can be controlled by VF according to the mechanical characteristics of four-bar linkages between the connecting crank and the oil pumps, especially near the lower dead point (the initial stage of the up-stroke), the inertia load torque in PRL can be effectively reduced. Therefore, the output power of the motor can be reduced and energy saving can be achieved.

III. VF CONTROL STRATEGY BASED ON THE MOTION OF FOUR-BAR LINKAGE

A. CHARACTERISTICS OF FOUR-BAR LINKAGE STRUCTURE

The four-bar linkage is a vital component in the BPMS, which can transfer the circular motion of the crank into the linear reciprocating motion of the suspension point on the horse head. The mechanics perspective illustration is presented in Figure 4. The prescribed positive directions are as follows: 1) the crank angular displacement $\theta_1$ is calculated from 12 o’clock position (vertical upwards position), and the clockwise direction is positive; 2) Crank reference angle $\theta_2$, connecting rod reference angle $\theta_3$ and beam reference angle $\theta_4$ are all $O-O_1$ references, and counter clockwise direction is positive; 3) Direction of the horse head suspension is positive vertically. The output power of the motor is determined by the total load torque $M_{ef}$, which is defined by the balance moment and the horse head torque under the different crank positions stated in Section II. However, the horse head torque $M_{hh} = (PRL - B_w)$.

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B. VF CONTROL STRATEGY FOR BPMS

A detailed derivation of the geometric relationship between the reference angles of the four-bar linkages during operation was given in [8]. The angular acceleration $\ddot{\theta}_4$ expression of the forearm of the beam is according to (4).

$$\ddot{\theta}_4 = \dot{\theta}_4 \left[ \frac{\dot{\theta}_2}{\dot{\theta}_2} + \left( \dot{\theta}_2 - \dot{\theta}_3 \right) \cot (\theta_2 - \theta_3) - \left( \dot{\theta}_3 - \dot{\theta}_4 \right) \cot (\theta_3 - \theta_4) \right]$$  (4)
where crank angular speed is \( \dot{\theta}_2 = \Omega_1/k \), \( \Omega_1 \) is rotation angular speed of motor, \( k \) is transmission ratio between belt and gear box; \( \dot{\theta}_2 \) is crank angular acceleration, which is the first derivative of \( \dot{\theta}_2 \); \( \dot{\theta}_3, \dot{\theta}_4 \) are the first derivative of reference angles of connecting link \( \theta_3 \) and reference angle of beam \( \theta_4 \), respectively.

\[
\begin{align*}
\dot{\theta}_3 &= \frac{R}{P} \cdot \sin (\theta_4 - \theta_2) \\
\dot{\theta}_4 &= \frac{R}{C} \cdot \sin (\theta_3 - \theta_2)
\end{align*}
\]

(5)

As shown in Figure 4, it can be observed that under different crank position angle \( \theta_2 \in (0 \sim 360^\circ) \), \( \theta_3 \) and \( \theta_4 \) are uniquely determined in space position, and both of them have no relationship with \( \dot{\theta}_2 \); therefore, \( \dot{\theta}_3 \) and \( \dot{\theta}_4 \) are one-to-one correspondence relationship with \( \theta_2 \). Substitute (5) into (4), \( \dot{\theta}_4 \) can be uniquely expressed as in (6) and (7)

\[
\begin{align*}
\dot{\theta}_4 &= K_2 \cdot [\dot{\theta}_2 - (K_1 - K_2) \cdot \dot{\theta}_2^2] - K_3(1 - K_1) \cdot \dot{\theta}_2^2 \\
K_1 &= \frac{R}{P} \cdot \sin (\theta_4 - \theta_2) \\
K_2 &= \frac{R}{C} \cdot \sin (\theta_3 - \theta_2) \\
K_3 &= \frac{R}{C} \cdot \cos (\theta_2 - \theta_3) \\
K_4 &= \cot (\theta_3 - \theta_4)
\end{align*}
\]

(6)

(7)

Since the running cycle of BPMS is generally more than 6s, the crank angular acceleration \( \dot{\theta}_2 \) changes relatively slow [7]. From an engineering perspective, \( \dot{\theta}_2 \) in (4) can be neglected and it does not affect the calculation accuracy of \( \dot{\theta}_4 \), which can also be verified by following simulations. Therefore, it can be rewritten as follows:

\[
\dot{\theta}_4 = K_5 \cdot \dot{\theta}_2^2
\]

(8)

where, \( K_5 = -K_2K_4(K_1 - K_2) - K_3(1 - K_1) \).

Considering that the slip of induction motors is usually between 0.02 and 0.05, the range of speed variation after loading is very confined. In (6), \( \dot{\theta}_2 \approx \Omega_2/k \) is approximately constant. Therefore, the variation trend of angular acceleration of horse head polished rod is basically consistent with the parameter \( K_5 \). Therefore, after calculating the parameter \( K_5 \) at different crank positions according to the structure of BPMS, the crank angular velocity can be obtained according to the set acceleration \( a_c \) value, and the target frequency can be obtained by further reverse approximation calculation. The calculation formula is displayed in (9):

\[
f_1 = \sqrt{\frac{a_c}{A \cdot K_5}} \cdot \frac{60k \cdot f_N}{2\pi \cdot n_N}
\]

(9)

where \( A \) is the length of the forearm of the beam (m); \( f_N = 50Hz \) is the rated frequency of the power supply; \( n_N \) is the rated speed of the motor (r/min).

IV. NEW ENERGY SAVING TECHNOLOGY FOR BPMS

A. APPROACH BASED ON MECHANICAL CHARACTERISTICS OF BPMS

Taking the center of crank rotation as the origin, a space polar coordinate system is established as shown in Figure 6. The polar angle \( \theta_1 \) is the position angle of crank and is clockwise positive. The length of polar diameter represents the rotating moment of crank. For better illustration, each torque is treated as absolute value. As Figure 6 depicts, the balance torque \( M_{bh} \) is fixed, while the horse head torque \( M_{hh} \) is affected by the several factors including the balance weight, dynamic liquid level, oil viscosity, ... etc. However, the overall imbalance of the comprehensive negative torque \( M_{ef} \) at different crank positions is the same, such as: 1) the A-B sector \( M_{hh} > M_{bh} \) is mostly in motor mode, and the balance effect of \( M_{bh} \) on \( M_{hh} \) becomes weak with the decrease of \( \theta_1 \); the C-D sector \( M_{bh} < M_{hh} \), at this time, the motor transfers the mechanical energy into electric energy to the power grid, and the partial potential energy is wasted in the process of potential energy conversion to electric energy. 3) The counter balance weight of BPMS in the lower stroke sector is either motor or generator modes, but the load ratio of the down-stroke is generally low.

![FIGURE 6. Operation conditions of BPMS in different crank position.](image-url)
B. PRACTICAL VR TECHNOLOGY BASED ON MINIMUM LOSS OBJECTIVE

As to an induction motor, stator copper loss \( P_{cu} \) can be divided into two parts \( P'_{cu} \) and \( P''_{cu} \), which are caused by excitation current \( I_0 \) and load current \( I_s' \), respectively.

Moreover, stray losses \( P_s \) can also be assumed based on the motor power rating, according to the IEEE standard [16]. The summation of \( P_{fe}, P'_{cu} \) and \( P_s \) is defined to be constant losses \( P'_S \). This part is independent of load condition and can be computed according to (10).

\[
P'_S = (P_0 - p_m) \cdot k_u^2
\]

where \( P_0 \) is no-load loss under rated voltage; \( p_m \) is no-load mechanical loss under rated voltage, and the voltage ratio is expressed as \( k_u = \frac{U_0}{U_N} \).

Stator copper loss \( P'_{cu} \) and rotor copper loss \( P_{cu2} \) is related to the load condition, which can be defined as \( P'_{K} \), when VR are carried out, \( P'_{K} \) increases in a ratio of \( 1/k_u^2 \). It can be calculated based on (11):

\[
P'_{cu} = \left[ P_N \left( \frac{1}{\eta_N} - 1 \right) - P_0 \right] \cdot \left( \frac{\beta}{k_u} \right)^2
\]

where \( P_N \) is rated power; \( \eta_N \) is rated efficiency; \( \beta \) is load ratio, can be calculated by \( \beta = P_0/P_N \).

When the load ratio \( \beta \) is constant, \( P'_S \) can be reduced while \( P'_K \) can be increased by regulating the input voltage to the motor terminals, and there must be an optimal voltage to minimize the motor losses. The VR benefit coefficient \( k_p \) can be defined in (12):

\[
k_p = \frac{\sum P_u}{\sum P} = \frac{P'_S + p_m + P'_K}{P_0 + [P_N(\frac{1}{\eta_N} - 1) - P_0] \cdot \beta^2}
\]

where \( \sum P_u \) is the total motor losses with random voltage, and \( \sum P \) is the total motor loss under rated voltage condition.

By substituting (10) and (11) into (12), and making \( \frac{dk_p}{dk_u} = 0 \), the optimal voltage ratio under arbitrary load coefficient \( \beta \) can be obtained.

\[
k_{uai} = \sqrt{\alpha \beta^2}, \quad \alpha = [P_N(1/\eta_N - 1) - P_0]/(P_0 - p_m)
\]

Based on (13), it can be concluded that only load ratio \( \beta < 1/\sqrt{\alpha} \), energy saving can be achieved by VR method. Considering the motor manufacturing factors, this study does not configure step-up treatment when \( k_{uai} > 1 \).

C. SECTIONAL VF AND VR COORDINATE CONTROL STRATEGY

It is pointed out that the four-quadrant power electronics converter not only has the advantages of fast dynamic response and high control accuracy, but also can work in two or four quadrants for energy feedback, and it has no harmonic pollution to power grid due to the filtering function [17].

In recent years, it has been widely applied in various industrial fields. This paper chooses four-quadrant converter to meet the demand of decoupling control of supply voltage \( U_1 \) and frequency \( f_1 \). Firstly, the loss parameters of the motor are obtained by means of testing or information from the manufacturer, and operator “\( \alpha \)” in formula (13) is obtained. Then, the acceleration \( a_c \) of the horse head is obtained by simulation of the four-bar structure of BPMS, and the A-B sector section is scaled and adjusted properly. Finally, the VF and VR scheme is implemented according to the crank position angle \( \theta_1 \), and the control flow is shown in Figure 7, it shows that the proposed strategy mainly contains three parts, VR control, VF control and adaptive fuzzy control, furthermore, the subgraph at top right shows how to inquire acceleration \( a_c \).

Owing to the fact that the VF stage aims to control the suspension acceleration \( a_c \) to reduce the inertia load torque in PRL, while the VR stage aims to minimize the motor losses, those two objective functions are different. It may lead to the jump phenomenon of voltage and frequency instructions in the interface processing during the alternation of VF and VR, and numerical oscillation also occurs in both simulation and field application. Therefore, it is necessary to adopt a practical control method to avoid the abnormal running in field. There are several control methods for motor systems, for instance, neural network and internal model control [18], sliding model [19] etc. However, due to the complex and occasional operation condition of BPMS, such as vibration and skidding phenomena of the connecting parts, it is difficult to establish an accurate mathematic model from the aspect of practical application. To overcome this problem, this study adopts adaptive fuzzy control algorithm [9] to achieve smooth transition when VF and VR, by which the fuzzy variables can be determined and controlled by expert system.
and experience. In addition, the soft rapid re-switching control strategy [20] is also adopted to avoid the inrush current in transient process. The actuator is given in Figure 7, and the algorithm is in (14)

\[ m_{k+1} = m_k + k_p \cdot e_k = m_k + k_p \cdot (X_{\text{order}} - X_{\text{real-test}}) \]  

(14)

where \( X \) means \( U_1 \) or \( f_1 \); \( k_p \) is the gain coefficient, and the system stability must satisfy \( k_p < 1 \); \( m \) is the final instruction value after the CPU processing.

V. ENERGY SAVING EFFECT AND BENEFIT ANALYSIS

A. SIMULATION RESULT AND ENERGY SAVING EFFECT

Simulation was performed on a BPMS CYJ10 driven by a 37-kW induction motor. The parameters are as follows: crank \( R = 1.15 \text{m} \), link rod \( P = 3.35 \text{m} \), beam rear arm \( C = 2.4 \text{m} \), forearm \( A = 3.0 \text{m} \), base rod projection \( I = 2.3 \text{m} \), beam support point \( H = 3.28 \text{m} \), structure unbalanced weight \( B_w = 0 \); pump depth \( L = 940 \text{m} \), sucker rod diameter \( D = 30 \text{mm} \); belt and gear box parameters: \( k = 149.33 \), \( \eta_1 = 0.88 \); four link rods: \( \eta_2 = 0.95 \). Rated motor’s efficiency \( \eta_N \) is 91.2%, no-load loss \( P_0 \) is 1.42kW, mechanical loss \( p_m \) is 493W, operator \( a = 2.32 \), time step \( dt = 1 \times 10^3 \text{s} \), and frequency response is about 10Hz/s, that is, the output limit of the actuator is 0.01Hz/dt. A comparison of indicator diagram and torque characteristics, with 600m dynamic liquid level, before and after the application of the aforementioned technology is shown in Figure 8.

When a BPMS driven by a 37-kW induction motor, the average power-saving ratio is \( E_{\text{save}} \approx 10\% \) after effectively implementing the proposed strategy. In addition, self-loss of the converter and the harmonic loss inside of the motor, \( E_{\text{loss}} \), is taken into account about 6% of the output power. Other parameters are as follows: the average load ratio is \( \beta_{av} \approx 33\% \), the price of industrial electricity \( C \) in China is 0.11 USD/(kWh), the price \( M_{\text{sev}} \) of converter is $150/kW, and the operating hours per year (HPY) is about 7200 h. The annual energy saving (AES) and cost recovery period (CRP) of BPMS can be calculated as in [21]:

\[
\begin{align*}
\text{AES} &= P_N \times \beta_{av} \times (E_{\text{save}} - E_{\text{loss}}) \times C \times \text{HPY} \\
\text{CRP} &= M_{\text{sev}} \times P_N / \text{AES}
\end{align*}
\]  

(15)

By substituting the above parameters into (15), the annual energy saving fee is $ 660 and the CRP is 14 months, which shows that the proposed strategy is an effective and practical technology for BPMS in oil field.
VI. EXPERIMENTAL VALIDATION

A. VALIDATION OF PROPOSED SIMULATION MODEL

Owing to the fact that the proposed strategy requires a decoupling between frequency and voltage, this study improves the model described in [22], and establishes a user-oriented practical model of rod production system. The three-layer nine-point finite difference method is used to solve the wave equation of the mechanical part; and the T-type equivalent circuit with variable parameters of excitation impedance is used to consider the saturation effect [6]. With 600m dynamic liquid level, the simulated speed and torque curves are compared with the measured one of the “standard oil well,” as shown in Figure 10 (a) and (b), which shows satisfactory alignment with the measured ones.

B. VALIDATION OF PROPOSED CONTROL TECHNOLOGY

The energy saving device based on the proposed strategy and oil field test platform are shown in Figure 11. The figure shows the field application of the developed device in Da Qing oil field, China. In this device, a programmable power electronic converter was used to realize the VF and VR control to the motor. The induction motor along with the converter and the proposed control strategy represents the electric drive system for the BPMS. In field test, a 37-kW motor which is same as that used for the simulation was selected and the soft re-switching control strategy proposed. Moreover, it was also used for avoiding the inrush current, the dynamic liquid level is 600 m and counter balance weight is 7.5 tons, respectively. In addition, output torque and rotor speed can also be measured directly by torque and speed sensors. As the operating cycle is close to 10 seconds, it is
difficult to compare the transient waveforms of voltage and current clearly.

In order to verify the effectiveness of proposed control strategy, the real measured RMS value of output torque and input power, with and without VR and VF control, are given in Figure 12 (a) and (b) for comparison proposes. It can be concluded that:

1) With the proposed control strategy, the output torque is obvious to be less than the one without proposed VR and VF control strategy, which is similar to the simulation result in Figure 8.

2) Means of input power without and with proposed VR and VF control are 4.81 kW and 4.44 kW, and the energy saving ratio is 9.02%. It is noteworthy to mention that due to the extra losses caused by power electronics converter, the power saving ratio is slightly less than the simulated one in Figure 9, especially for the light load condition. That is owing to the fact that the input power with proposed strategy is even larger than the original one, when crank angles are from 100 to 200 degrees in Figure 12(b).

VII. CONCLUSION
This study presented a practical sectional VF and VR universal control strategy for energy saving of BPMS in oil industry. The major contributions are as follows:

1) We showed that based on the mechanism of four-bar linkage, a control strategy integrated with VF and VR. The strategy indirectly weakened the inertia load torque and reduced the maximum load. This was achieved through the control of acceleration of the suspension point. The proposed strategy also reduced the motor’s output power with significant energy saving.

2) A four-quadrant power electronics converter was used to implement the proposed strategy. The energy savings was achieved by alternation of the supply mode at different crank positions. An adaptive fuzzy logic algorithm and soft re-switching strategy was used for smooth transition between VR and VF modes. The results showed that the power saving ratio of the system was more than 10%. The simulations and the effectiveness of the developed control strategy were experimentally verified.

An industrial four-quadrant power electronics converter was adopted in this study for sectional VF and VR control need to re-program and revise the original control code on the four-quadrant converter. For implementation in the oil field, it is necessary that the decoupling control of frequency and voltage should be further developed and embedded in future power electronic converters in industrial drives.

REFERENCES
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