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Selection method modelling and matching rule for rated power of prime motor used by Beam Pumping Units

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Abstract: The energy consumption of prime motors used in oilfields is the one-third of the total energy consumption of beam pumping unit wells. In order to keep initiating and operating the prime motor smoothly and safely, its actual rated poweris high much more than the needed. With the intention of improving the efficiency of the prime motor and decreasing the cost of rod-pumping, a set of rated power calculated methods and a set of matching templates was built up under the regarding conditions such as the changing rule of the system load, the heating of the prime motor andthe overload torque in the initiate processing. The tested data indicated that, after replacing the prime motor with lower power, the active power, the inactive power and the suspended polished-rod load were all decreased substantially.

Keywords: Rated Power; Prime Motor; Selection Method; Overload; Heating

1. Introduction

Oil and gas are one of the main energy resources that are difficultly replaced in the modern society. They are called black gold to economic and are the main materials for the petrochemical industry. With the development of economy, the target of energy-saving, emission-reduction, green and low-carbon production are our goal [1, 2]. Oilfields are great customers for power consumption, and had the responsibility to design the beam pumping units in order to improve their performance. The total consumed power of the Daqing oilfield is 99 hundred million kilowatt-hours, where the artificial lift occupied one-third . The "big motor drive small rod-pumping" always existed in the past, which was constantly denounced [3, 4]. Power-reducing of the beam pumping units is a big issue needed to be solved.

In 1993, Tang S. W.. et al [5] considered the oversize rated power of the prime motor wasone of the main reasons for the low efficiency of rod-pumping systems. The authors regressed the grand efficiency function of the beam pumping unit by using tested data, and analyzed the reasonable selection methods for the rated power of the prime motor. In the end, the investigators drew the conclusion that the utilization ratio of the nominal rated power was not higher than 35%. The grand efficiency of rod-pumping units was in the scope of 65% ~ 75%, while the utilization ratio of the nominal rated power was in the scope of 20% ~ 35%.

In 2009, Duan B. H. et al [6] analyzed the running mechanical characteristic of the prime motor and the load characteristic of the beam pumping units, setting up a selection motor template though the stroke, the frequency of stroke and the polished-rod load ratio. Sixty-eight oil wells were optimized by this motor selection template. The tested results indicated that the power of motor decreased 2.3kW averagely, and the power consumption per day was decreased 4.2kWh on average. Actually, the current documents for selecting motor in oilfield are not enough.With all kinds of energy-saving motors had been applying in the oilfields, the guiding theory and method of optimized selection motor is needed urgently.

According to the calculated model of the prime motor output torque and the motor working pattern, a set of selecting method of the motor rated power was set up with the considering of polished-rod load change rule, heat of motor, initiate power and overload of torque. A set of motor matching template was also set up, which is suitable to be applied in the oilfields. The tested results indicated that application of this paper's motor selection method could decrease the rated power of the prime motor and could improve the efficiency of the prime motor.

2. Selection method of the prime motor of the beam pumping units

The prime motor of the beam pumping units undertakes the variable loads and continue period working manner.Therefore, the selection of the prime motor must be conducted in the follow principles:

1) The rated power of the prime motor must be utilized as substantially as possibly;
2) The maximum running temperature of the prime motor must not exceed the allowable value
3) The overload and the initiate capacities of the prime motor must be satisfied to the demand of load.

2.1 Selection program of the prime motor of the beam pumping units

The selection program of the prime motor of the beam pumping units in the oilfield is shown in the following:

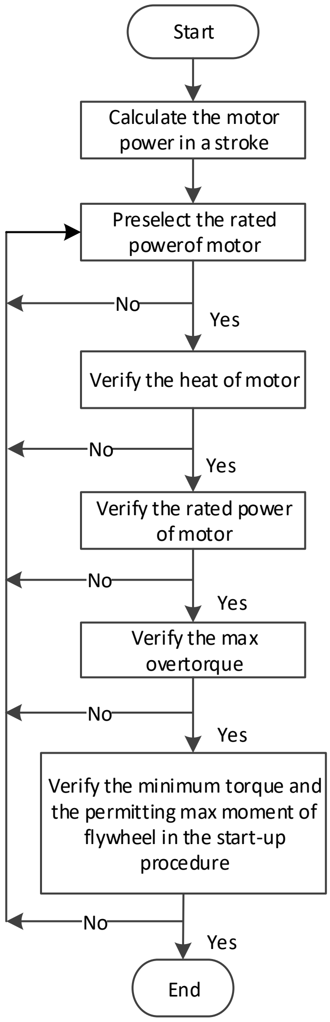

Figure. 1 Selection process of rated power of motor

2.2 Predictive selection of the rated power of the prime motor of the beam pumping units

The motor load of the beam pumping units is changing continually and belongs to continua period working pattern. Therefore, the prime motor must be predictively selected at first. Then, the heating and overload of the predictive motor must be verified. If the verified results indicate that the rated power of the prime motor is not enough for the corresponding working conditions, the predictive selection of the prime motor must be remade.

The formulas for the predictive selection of the prime motor are expressed as follows:

$$p_e = k \cdot \overline{p} \tag{1}$$

p_e —the rated power of the prime motor using in the oil well;

$\overline{p}$ —the equivalent averaged output power of the prime motor using in the oil well, kW;

k —the heat growing coefficient of the prime motor, in general, it is in the scope of 1.1-1.6.

$$p = \frac{n \cdot T}{9549} \tag{2}$$

p —the transient power of the prime motor, kW;

T —the output torque of the prime motor, kN.m;

$$\overline{p} = \frac{\int pdt}{t} \tag{3}$$

t —a stroke time of beam pumping units, s;

$\bar{p}$ —the equivalent averaged power of the prime motor，Kw.

Within a given condition of construction parameters of the beam pumping units and the swabbing parameters of the oil well, the transient output torque of the prime motor could be calculated by the follow formula (4):

$$T=\frac{1}{i\eta_m^m}\left[\eta_b^m\left[W-B+\frac{J_b}{A}\varepsilon_b\right]\overline{TF}-M\sin(\theta+\tau)+J_p\varepsilon\right] \qquad (4)$$

i —the total transmission ratio from the motor axis to the output axis of gearbox;
η_m —the transmission efficiency from the motor axis to the crank axis;
η_b —the transmission efficiency of four-bar linkage, non-dimension;
m—exponent, $T>0,\ m=1;\ T<0,\ m=-1$;

W —the suspended polished-rod load, kg;

B —the unbalance weight of walking beam, kg;

J_p —equivalent rotate inertia of crank axis, kg.m^2;

A —the forearm length of walking beam, m;
ε_b —the angular acceleration of walking beam, rad/t^2;
$\overline{TF}$ —the torque factor, non-dimension;
τ—crank polarization angle, degree;
θ—crank angle, degree;
ε —crank acceleration，rad/t^2, it is solved numerically by the movement difference equation, and also be solved by the tested angular velocity expanded to Fourier series and then differential

2.3 Verifying the rated power of the prime motor

2.3.1 Heat verifying of the prime motor

In the running period with load, the motor's inner consumption will be turned into heat quantity, which causesthe increasing of the temperature of the prime motor. The insulating material of winding is the worst part of the motor.Consequently , the highest temperature allowed by the insulating material is the highest temperature allowed by the prime motor. In another word, the lifetime of insulating material is the lifetime of the prime motor.

The working pattern of the prime motor of the beam pumping units is variable load and continuous. Under this working pattern, the rated power of the prime motor can be selected through the equivalent torque. At first, the equivalent torque $\bar{T}$ is calculated in a period.After that, the rated torque T_e of the prime motor can be selected.

The equivalent torque of the prime motor is calculated as the follow formula (5):

$$\bar{T}=\frac{\int Tdt}{t} \qquad (5)$$

Under the condition of the standard environment temperature, the requirement of heat verifying, which is adopted by the equivalent torque method, is displayed in the follow formula (6):

$$\bar{T}\le T_e \qquad (6)$$

$\bar{T}$ —equivalent average power of the prime motor, kN.m;

T_e —rated torque of the prime motor, kN.m。

When the environment temperature is not equal to standard value, the heating should be verified by the revised value of rated torque.

2.3.2 Verify the maximum overload torque

$$M_N \geq \frac{M_{L\max}}{0.9K_u \cdot \lambda_T} \qquad (7)$$

In the equation:

$M_{L\max}$——the maximum negative torque, N.m;

K_U——the fluctuation coefficient of power grid voltage, here is 0.72;

λ_T——the overload times of the motor torque, here is 2.0;

0.9——the safe coefficient regarding the calculate error and parameter fluctuation.

2.3.3 Verify the minimum initiate torque and the allowable maximum flywheel torque of the prime motor

The minimum initiate torque of the prime motor:

$$M_{M\min} \geq \frac{M_{L\max} \cdot K_s}{K_u} \qquad (5\text{-}15)$$

The allowable maximum flywheel torque of the prime motor GD_{xm}^2;

$$GD_{xm}^2 = GD_0^2(1 - \frac{T_{L\max}}{T_{sav}K_u^2}) - GD_M^2 \qquad (5\text{-}16)$$

Demanded: $GD_{xm}^2 \geq GD_{mec}^2$

In the equation:

$M_{M\min}$——the minimum initiate torque of the prime motor, N.m;

$M_{L\max}$——the potential maximum negative torque in the initiate process, N.m;

K_s——the accelerated torque coefficient to be enough to ensure the initiate process, in general it is 1.15～1.25;

K_U——the fluctuation coefficient of the voltage that is the rate between the axis voltage and the rated voltage in the initiate process, here is 0.85;

GD_M^2——the flywheel torque of the motor rotor, N.m^2;

GD_{mec}^2——the maximum flywheel torque of transmission machinery that converted on the motor axis, N.m^2;

GD_0^2——the allowable maximum flywheel torque in the total transmitted system including the prime motor, N.m^2;

T_{sav}——the averaged initiate torque of the prime motor, N.m;

3. Beam pumping units and the prime motor matching method templates

In order to simplify the usage of the methods in the oilfield, the computation process of Fig.2 is shown to calculate the rated power of motors at all kinds of work conditions. A serial of the motor selection templates were also designed in Table.1. General engineers could select the reasonable rated power of the prime motor in term of the style of beam pumping units, the stroke and the frequency of stroke as shown in Table.1.

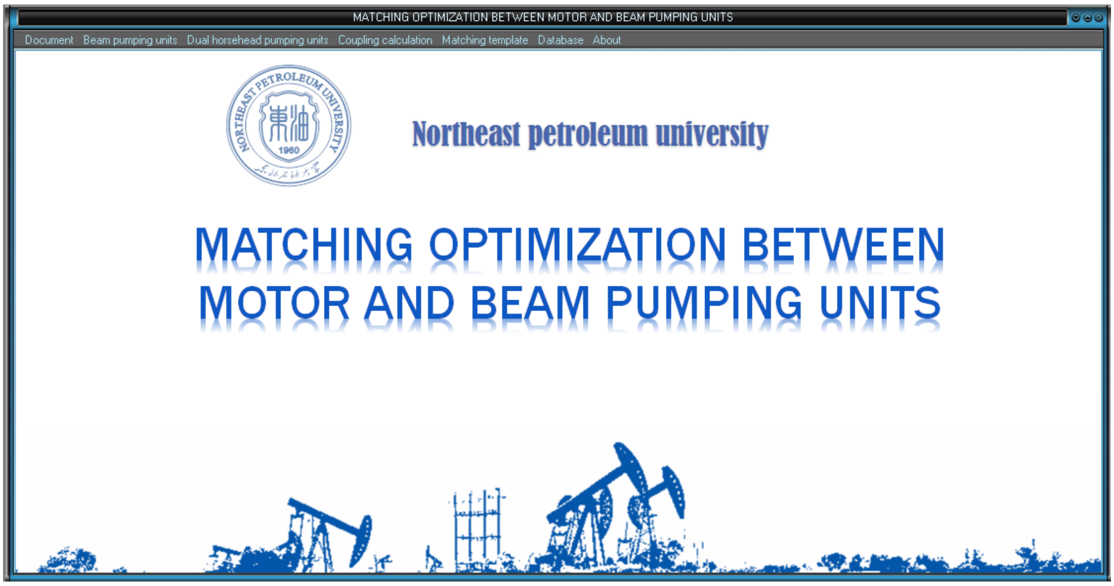

Figure. 2 Interface of the reasonable matching optimize program

Table.1 Motor selecting template for CYJ10-3-37HB

--- Stroke（3m）---

Frequency of stroke (min^{-1}) / load rate (%)	1	2	3	4	5	6	7	8	9	10	11	12
10	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
20	7.5	7.5	7.5	7.5	7.5	7.5	7.5	11	11	11	15	15
30	7.5	7.5	7.5	7.5	11	11	11	15	15	18.5	18.5	22
40	7.5	7.5	7.5	11	11	15	15	18.5	22	22	30	30
50	7.5	7.5	11	11	15	18.5	18.5	22	30	30	30	37
60	7.5	7.5	11	15	18.5	22	22	30	30	37	37	45
70	7.5	7.5	11	15	18.5	22	30	30	37	37	45	45
80	7.5	11	15	18.5	22	30	30	37	45	45	55	55
90	7.5	11	15	22	30	30	37	45	45	55	55	75
100	7.5	11	18.5	22	30	37	37	45	55	55	75	75

Note: In Table.1, the first row is frequency of stroke; the first column is the rate of polished rod load; the color areas are the required rated power of motor (kW).

1) The Table.1 is the criteria for selecting the rated power of Y-type motor;
2) All the permanent magnet synchronous motors and high slip motors could been selected by the Table.1;
3) The permanent magnet synchronous motors are not suitable for middle and high frequency of stroke (more than 6 min^{-1}) condition;
4) The high slip motors are not suitable for middle and low frequency of stroke (less than 6 min^{-1}) condition.

4. Test in the simulation tested well

A test was conducted on a simulation well. The length of its plunger was 1000m. The circle medium was water. The tested data included all kind of the input electric parameters of the prime motor (the tested node 1 in Fig.3), the net torque of gearbox (the tested node 2 in Fig.3) and the suspended polished-rod dynamometer card (the tested node 3 in Fig.3).

The basic designed parameters of beam pumping units were shown in the Table.2. Base on the compute process of motor selection (Fig.1) and the selection optimize program, the style and the rated power of the prime motor can be designed.

The current parameters were tested by the 3169 type Electric Parameters Tester. The net torque of gearbox was tested by the Torque Tester. The polished-rod dynamometer card was tested by the Indicator Diagram of Instrument named Qian-Li-Ma. The analysis, post processing and plot of the tested data can be handled by the ORIGIN® and the EXCEL®.

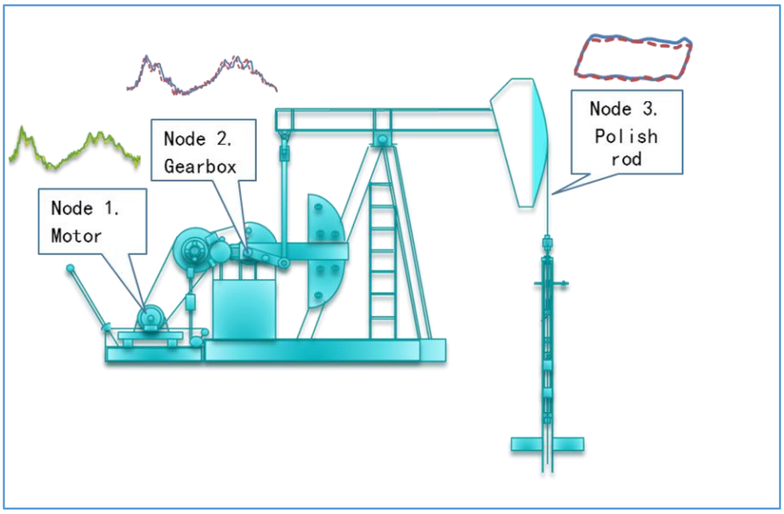

Figure.3 tested nodes of field well

Table.2 Basic parameters of the motor and the field well

Beam pumping unit	CYJ10-3-37HB		
Original motor	Y280S-8	Rated power of original motor（kW）	37
Replaced motor	Y225M-8	Rated power of replaced motor（kW）	22
Depth of plunger（m）	1000	Diameter of pump（mm）	57
Working fluid level（m）	600	Diameter of tube（mm）	76
Diameter of rod（mm）	22	Water cut（%）	100
Stroke（m）	2	Frequency of stroke（1/min）	6

5. Results analysis of the simulation test well

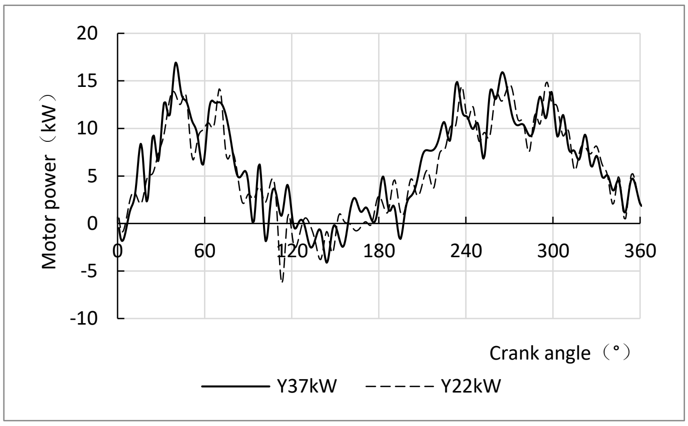

Figure. 4 Contrast to Input power curves

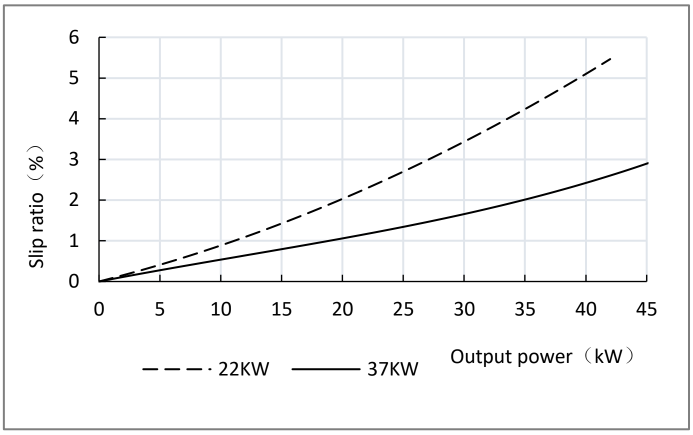

Figure. 5 Contrast to the slip rate curves of three phase asynchronous motor

Table.3 Contrast to the tested parameters after replaced motor

Prime motor		Peak value	Average value				
Type	Rated power	Active power		Reactive power	Apparent power	Power factor	Current
Y280S-8	37kW	16.08	5.86	22.74	24.00	0.25	35.98
Y225M-8	22kW	13.70	5.50	16.03	17.55	0.32	26.00
Rate of change		14.80%↓	6.18%↓	29.53%↓	26.88%↓	7.00%↑	18.03%↓

As can be seen in Fig.4, the power curve of 22kW motor had the same periodicity like the 37kW motor, but the peak power of the former was smaller than the later. The Fig.5 depicted two slip rate curves of 22kW motor and 37 kW motor, respectively. At the same output power condition, the slip rate of 22kW motor ware bigger than the 37kW. The bigger slip rate decreased more peak torque and the fluctuation ratio of power curve. For the motor with 22kW, the peak active power, the averaged active power, the inactive power, the apparent power andthe averaged current were decreased 14.80%，6.18%，29.53%，26.88% and18.03%, respectively, but the power factor was increased by 7%, whichindicated the prime motor’s overall performance was improved highly after the replacement of 22kW motor,.

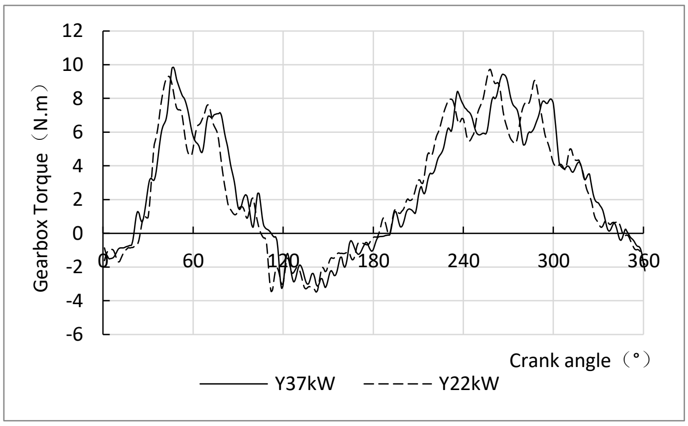

Figure. 6 Contrast to the net torque curves of gearbox

The Fig.6 presented the torque curves of the 22kW motor and the 37kW motor, respectively. The two torque curves had nearly the same trend. As can be seen in Table.4, after replaced the

37kW motor with the 22kW motor, the peak torque of gearbox was decreased from 9.79kN.m to 9.3kN.m by 5.01%. Because of the crank balance, the 22kW motor provided a bigger inertia torque than the 37kW motor. The high slip rate of the 22kW motor caused the change of balance degree from 0.94 to 1.05.

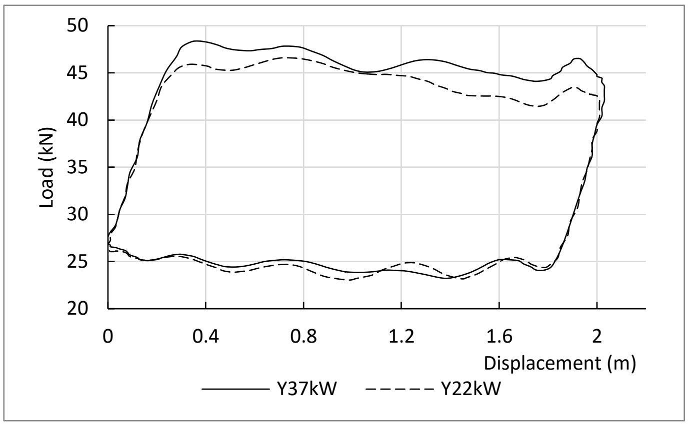

Figure. 7 Contrast to the polished-rod dynamometer diagrams

The Fig.7 showed two polished-rod dynamometer cards driving by 22kW motor and 37kW motor, respectively. As can be seen, the slip rate of the motor somehow influenced the peak polished-rod load and the polished-rod dynamometer card. In general, the curve fluctuation of the polished-rod dynamometer card of 22kW motor was clearly milder than that of the 37 kW motor, because of the rotational inertia of the rotate parts of the beam pumping units. After replacing the 37kW motor with 22kW motor, the maximum polished-rod load was decreased by 3.66%and the minimum polished-rod load was also decreased by 0.76%., which indicated that the 22kW motor with higher slip rate had the effect of decreasing the polished-rod load.

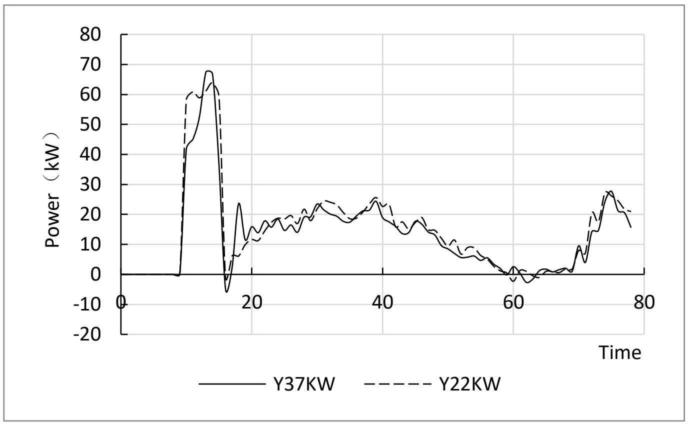

Figure. 8 Contrast to the starting powers

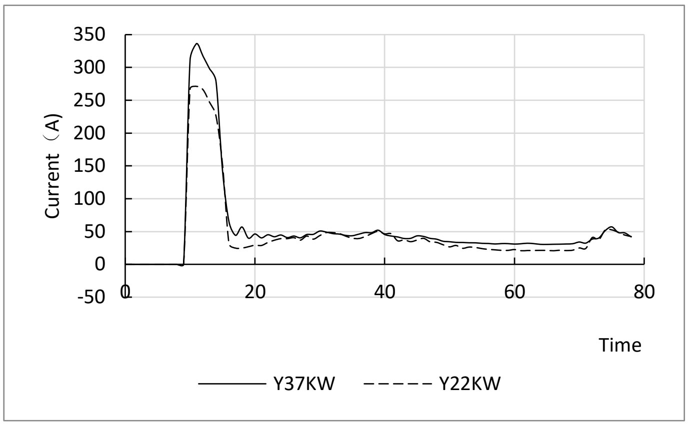

Figure. 9 Contrast to the starting current

The Fig.8 and Fig.9 presented the initiate power and initiate current curves of the 37kW and the 22kW prime motors, respectively. The initiate times of the two motors were nearly the same. The initiate peak powers of the 22kW and the 37kW prime motors were 63.85kW and 67.49kW, respectively. The initiate peak currents of the 22kW and the 7kW prime motors were 271.13A and 336.41A, respectively.

After the replacement with a minor power motor, the initiate power and initiate current were all decreased by 5.39% and 19.4%, respectively. It indicated that the replaced 22kW prime motor had the capability of decreasing the initiate inertia load.

6. Field wells application

This selecting motor technology have been applied in the Daqing oilfield. The Table.4 showed the basic working conditions and the parameters of the tested wells. Relying on the selecting method, the replaced motor included two-speed dual power motor, high slip motor and permanent magnet synchronous motor. The average energy-saving rate of the ten oilfield wells has reached 13.24%.

Table. 4 Basic parameters of field wells

No.	Diameter of pump	Length of plunger	stroke	Frequency Of stroke	Working Fluid level	Beam pumping units	Up stroke load	Down stroke load
1	32	1760	2	4	1394	CYJ10	50.59	34.73
2	38	1708	1.7	3	1501	CYJ10	63.78	48.41
3	44	1403	3	6	1108	CYJY10	50.85	22.85
4	32	1659	2	4	1265	CYJY10	45.96	33.61
5	32	1509	2	7	1438	CYJY10	36.93	22.85
6	32	1203	2	5	1172	CYJY8	29.58	17.46
7	28	1168	2	5	1060	CYJY8	25.44	11.76
8	32	1599	2	3	1499	CYJS8	54.29	20.19
9	38	1617	3	4	1489	CYJY10	44.94	18.99
10	32	1396	2	4	1345	CYJY10	47.97	20.11

Table.5 Tested data of the field wells

No.	Original motor	Rated power	Consumed power	Length of Plunger (m)	Replaced motor	Rated power	Consumed Power (kW)	Length of Plunger (m)	power Saving Rate (%)
1	DFCJT-3.5	22	4.86	1490	YCHD225	15	4.21	1394	13.37
2	Y280S-8	37	2.87	1650	YCHD225	7.5	2.53	1637	11.85
3	DFCJT-3.5	31.4	8.82	1351	YCHD2258	15	7.56	1349	14.29
4	DFCJT-3.5	22	5.5	1540	TNM250M2	15	4.67	1504	15.09
5	DFCJT-3.5	22	6.2	1435	TNM225S	15	5.34	1459	13.87
6	DFCJT-3	18.5	2.25	1006	YCHD225	15	2.01	1105	10.67
7	DFCJT-3	18.5	3.05	717	YCHD225	15	2.76	1013	9.51
8	YCH200	22	3.96	1703	TNM250M2	15	3.45	1692	12.88
9	LP/CJT10D	22	5.048	1528	TNM225S	18.5	4.27	1527	15.41
10	YCCH250	37	6.1	1399	TNM250M2	15	5.18	1339	15.43
Averaged power saving rate（%）									13.24

CONCLUTIONS

With the intention of eliminating the high energy consumption caused by the prime motor with bigger rated power, we must reasonably decrease the rated power of motor, which can improve the working performance of the beam pumping unit.

The prime motor working pattern of the beam pumping units is the continuous period work pattern. Therefore, the heat output, ultra-torque, the minimum initiated torque and the maximum flywheel torque of the prime motor need to be verified the selection of the prime motor. A compute method of selecting motor was set up for beam pumping units. Meanwhile, the relative mathematics model has also been provided.

A program, named the reasonable matching method for the driving equipment and the beam pumping units, was coded with Visual Basic language. At the same time, selecting and matching templates were set up for the beam pumping units and the prime motor.

The tested results indicated that the rated power of motor was decreased from 37kW to 22kW;the active power of motor was decreased by 8.72%; the inactive power was decreased by 25.69%; the power actor was increased by 26.32%; the maximum polished rod load was decreased by 3.66%; the initiated power and the current of motor were decreased by 5.25% and 19.4%, respectively. These results also indicated the replaced prime motor in this paper's calculation method may effectively improve the running performance of beam pumping units system.

Ten oilfield wells were designed and tested by the reasonable matching method, where the tested average energy-saving rate reached 13.24%. It indicated the selecting method of the prime motor for beam pumping units had reached the objects of load-reducing and energy-saving.

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