CONSIDERATIONS ON THE NECESSITY TO COMPENSATE REACTIVE POWER OF PUMPING UNITS DRIVING MOTORS

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REZUMAT : Datorită particularităților de lucru, motoarele asincrone cu rotorul în scurtcircuit utilizate în schelele de producție petrolieră la acționarea unităților de pompare lucrează la parametri energetici foarte scăzuți. Este sarcina specialiştilor de a determina cauzele şi a adopta măsurile necesare creşterii performanțelor energetice ale acestora. În prezenta lucrare sunt analizate cauzele care determină lucrul cu un factor de putere scăzut, metodele şi mijloacele de îmbunatățire a factorului de putere cât şi impactul compensării puterii reactive asupra unor indicatori energetici locali sau globali.

Cuvinte cheie: pompaj de adâncime, factor de putere, putere reactivă, cădere de tensiune, pierderi de putere.

ABSTRACT. Due to their working characteristics, induction motors with short circuit rotor used in oil fields to drive pumping units work at very low energy factors. The specialists' task is to determine the causes and to take the necessary measures to increase their energy performance. In this work we analyze the causes that determine operation with a low power factor, methods and means of improving the power factor as well as the impact of reactive power compensation on some local or global energy indicators.

Keywords: beam pumping, induction motor, power factor, reactive power, voltage drop, power loss

1. INTRODUCTION

It is well known that the most widespread oil extraction method is beam pumping. Three phase high slip induction motors with short circuit rotor, encased (anti-explosive construction), with powers between 5.5 and 75 kW, with supply voltages from 380 V to 1 KV and with synchronism velocities of 750, 1000 or 1500 r/min are used to drive pumping units. These motors are generally oversized, with considerably higher power than the required ones because:

- start-up conditions are heavy (resistant torque at start-up is maximum);
- motors supply voltages are lower than the nominal voltages because of the voltage drop from the supply networks with significant lengths.

The power of electric driving motors is chosen based on some empirical calculations proposed in the literature by various authors[3], calculations that lead to noticeable errors, in the sense that these calculations lead to powers up to 80 ÷ 90 % higher than the necessary actual power.

It is obvious, though, that on choosing the electric motor pump unit operational factors are taken into account:

- charge of the polished rod (ranges between 0.9 and 19.3 t-f);
- spin velocity on reducer gear exit (4 ÷ 20 r/min);
- length of stroke (ranges between 0.4 and 5 m);
- number of up-and-down strokes /min (4 ÷ 20).

For low output wells, the motor load factor is considerably reducing itself along with the drop of the reservoir pressure and the liquid level in the well's column.

Pumping units driving motors supply is made through CMPA cabin - 0.5 kV, the circuit diagram is shown in fig.1 and it ensures:

- supply voltage and sink current measurement;
- pumping unit local start-up and shutdown (U.P.);
- automatic delayed restart on voltage fading and reappearance;

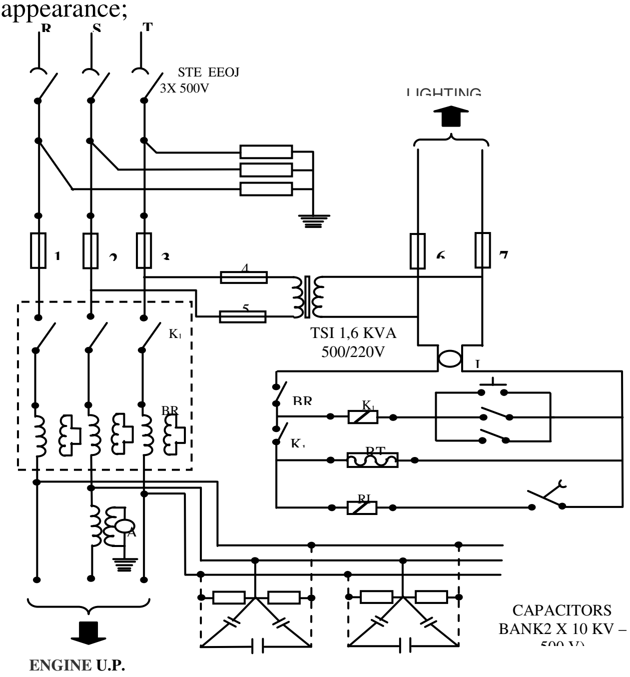


Fig.1 Circuit diagram from CMPA cabin - 0.5KV

- driving motor short circuit, overload and two-phase operation protection;
- protection against atmospheric discharges;
- local artificial lighting needs;
- power factor (cosφ) improvement using static capacitors;

Unfortunately, these cabins do not contain power measure systems, which makes extremely difficult to perform rigorous energy analyses regarding the effective estimation of energy indicators of driving motors. Under these conditions, the power of electric driving motors is chosen based on some empirical calculations set by various authors and presented in the literature.

2. OIL FIELDS ENERGY PERFORMANCE INCREASE BY POWER FACTOR IMPROVEMENT

Due to reasons from point 1, pumping units induction driving motors operate with a very low power factor. The operation with a low power factor has a series of negative effects with a final impact on the price per ton of extracted oil.

Thus, an induction motor that operates with a power factor cosφ < 0.7 will have a reactive power expenditure: $Q=\sqrt{3}\,U_lI_l\sin\varphi$ greater than the real power expenditure: $P=\sqrt{3}\,U_lI_l\cos\varphi$, and the power supplier require the payment of reactive power to those consumers who operate with a power factor lower than the neutral power factor ($\cos\varphi_n = 0.92$). And, as is known, reactive power is not a used power, but a fluctuant power which reduces power mains capacity.

On the other hand, at a constant real power (that implies a constant charge): $P=\sqrt{3}\,U_lI_l\cos\varphi$, operation with a low power factor entails the increase of the line current, increase that determines the increase of the loss in the supply network by Joule effect ($p_J=3R_lI_l^2$) as well as the increase of the voltage drops on the feed line ($\Delta U=U_1-U_2=R_lI_l$).

Due to the fact that the supply networks (aerial or in cable) of pumping units driving motors have significant lengths (hundreds or thousands of meters) both the power and energy loss and the voltage drop are not to be neglected.

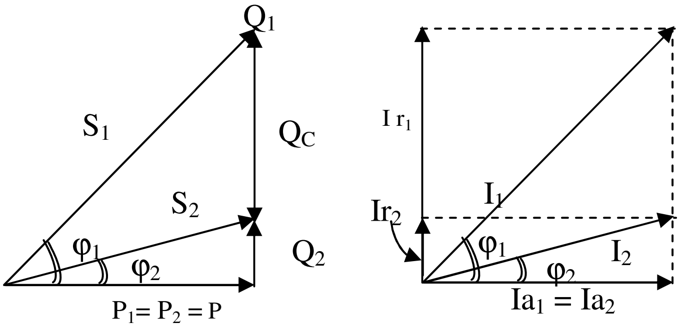
On these grounds it is a necessity to improve the pumping units driving motors power factor. This can be achieved by:

- more judicious choice of the driving motor power;
- elimination or reduction of no-load or low load operation times;
- use of static capacitor bank (with stepping control) placed in CMPA cabin;
- induction motors with short circuit rotor replacement with synchronous motors (that, as is known, can operate with a power factor unitary for all loads).

Further on we shall try to estimate the improvement of the energy performance of an induction motor that operates on constant load corresponding to a real incoming power P_1, by increasing the power factor from a value cosφ_1 to an index value cosφ_2. The power triangle is shown in fig. 2a and the vector diagram of currents for the two values of the power factor is shown in fig. 2b.

Index 1 is for electric variables corresponding to the angle of phase difference φ_1 and index 2 is for electric variables corresponding to the angle φ_2. At constant load, the real power taken from the network by the motor remains the same irrespective of the value of the power factor cosφ:

$$P_1=\sqrt{3}\,U_lI_1\cos\varphi_1=P_2=\sqrt{3}\,U_lI_2\cos\varphi_2.$$



a) ***b)***

Fig. 2 Power triangle (a) and vector diagram of currents (b)

The significances of the variables from the diagrams shown in fig.2 are the following:

-φ_1, φ_2 differences of phase between voltage and current corresponding to the two situations;

-P_1,P_2,P – real powers taken at constant load and constant voltage ($P_1=P_2=P$);

-S_1,S_2 – apparent powers corresponding to angles φ_1, φ_2 respectively;

-Q_1,Q_2 – reactive powers corresponding to angles φ_1, φ_2 respectively;

- Q_c – reactive power possibly delivered by a capacitor bank sized properly;

- I_{a1}, I_{a2} – real components of the currents $\underline{I}_1$, $\underline{I}_2$ respectively ($I_{a1} = I_{a2} = I_1\cos\varphi_1 = I_2\cos\varphi_2$);

- I_{r1},I_{r2} –reactive components of the currents $\underline{I}_1$, $\underline{I}_2$ respectively;

-$\underline{I}_1$, $\underline{I}_2$ – complex images of the currents I_1 and I_2.

Analyzing the vector diagram of currents, we found that together with the power factor increase (angle φ reduction), the real value of the current taken from the network by the motor drops as a result of the current reactive component reduction.

Thus, from relation:

$$P_1=\sqrt{3}\,U_lI_1\cos\varphi_1=\sqrt{3}\,U_lI_2\cos\varphi_2,$$

it follows: $I_1\cos\varphi_1= I_2\cos\underline{\varphi_2}$ or $I_2=I_1\cos\varphi_1/\cos\varphi_2$.

Thus, if reactive power local compensation is achieved (at the motor), the current in the supply networks drops by cosφ_1/cosφ_2 times, which obviously leads to voltage drop and network power loss reduction.

If R_l is the line resistance, ΔU_1 – the voltage drop corresponding to the current I_1, ΔU_2 – the voltage drop corresponding to the current I_2 (after compensation) we can write:

$$\Delta U_1=R_lI_1$$

$$\Delta U_2=R_lI_2=R_lI_1\cos\varphi_1/\cos\varphi_2=\Delta U_1.\ \cos\varphi_1/\cos\varphi_2$$

which signifies a voltage drop reduction:

$\Delta U=\Delta U_1-\Delta U_2=\Delta U_1-\Delta U_1\cos\varphi_1/\cos\varphi_2=\Delta U_1(\cos\varphi_2-\cos\varphi_1)/\cos\varphi_2.$

Using p_{j1} to denote the network power loss corresponding to current I_1 (before compensation) and p_{j2} to denote the network power loss corresponding to current I_2 (after compensation), it follows:

$$p_{j1}=3R_lI_1^2$$

$$p_{j2}=3R_lI_2^2=3R_lI_1^2(\cos\varphi_1/\cos\varphi_2)^2$$

and a power loss reduction Δp_j:

$$\Delta p_j=p_{j1}-p_{j2}=3R_lI_1^2-3R_lI_1^2(\cos\varphi_1/\cos\varphi_2)^2$$

$$\Delta p_j=3R_lI_1^2(\cos^2\varphi_2-\cos^2\varphi_1)/\cos^2\varphi_2.$$

By considering cos φ_1=0.7 and cos φ_2=0.95, the voltage drop reduction is:

$$\Delta U=\Delta U\,\frac{0.95-0.70}{0.95}=0.26\,\Delta U_1$$

And power loss reduction:

$$\Delta p_j=R_lI_l^{\,2}\,\frac{0.9025-0.49}{0.95}=0.457\,p_{j1}$$

Since the length of the supply lines is significant (hundreds, even thousands meters) we can estimate that voltage drop and power loss reduction is considerable.

Network voltage drop reduction has benefic effects on pumping units driving motors and power loss reduction has direct effects on the electricity bill.

On the other hand, operation with a power factor lower than the neutral power factor ($\cos\varphi_n=0.92$) entails the payment of the reactive energy expenditure.

Thus, to an overall power factor, $\cos\varphi_m=0.7$, the real power expenditure is equal to the reactive power expenditure:

$$W_a=\sqrt{3}\,U_lI_l\cos\varphi_m\,t=\sqrt{3}\,U_lI_l\sin\varphi_m\,t=W_r$$

And if the reactive power unit price (1kVarh) is 20% from the real power unit price (1kWh), the reactive power compensation up to achieving a power factor greater than or equal to the neutral power factor leads to saving 20% from the electricity bill.

3. NUMERIC APPLICATION

A pumping unit is driven by an induction motor with a short circuit rotor having the following nominal parameters: P_{2n}=22 KW, U_{1n}=500 V, I_{1n}=35 A, $\cos\varphi_n$=0.85, n_{2n}=1440 r/min. the motor is loaded through a three phase cable CYAbY 1 kV, 4x16 with a length of 1.5 km. By measuring the following values were obtained: P_1=15.75 kW, I_l=26.8 A, U_l=485 V, where:

P_1 - real power taken;

I_l - real value of the current through a line un conductor;

U_l - real value of the line voltage.

3.1. Voltage drop calculus

The resistance of a supply network conductor is:

$$R_l=\rho\frac{l}{S}$$

ρ [Ω mm^2/m] – copper conductor resistivity (ρ_{Cu50}=0.020 Ω mm^2/m)

l – line length in meters;

S – conductor section in mm^2

$$R_l=0.020\,.\,\frac{1500}{16}=1.875\ \Omega.$$

We calculate the voltage drop ΔU_1 at the current taken I_1, corresponding to a power factor $\cos\varphi_1$ given by the relation:

$$\cos\varphi_1=\frac{P_1}{\sqrt{3}}\,\frac{1}{U_1I_1}=15750/\sqrt{3}\cdot 485\cdot 26.8\cong 0.7$$

$$\Delta U_1=RI_1=1.875\cdot 26.8=50.25\ \text{V}$$

Using a static capacitor bank properly sized, we increase the power factor to a value $\cos\varphi_2=0.95$. At the same load, the real power taken is conserving:

$$P_2=\sqrt{3}\,U_1I_2\cos\varphi_2=\sqrt{3}\,U_1I_1\cos\varphi_1=P_1$$

whence: $I_2=I_1\cos\varphi_1/\cos\varphi_2=26.8\,\dfrac{0.7}{0.95}=19.74$ A.

The voltage drop corresponding to the current I_2 is:

$$\Delta U_2=RI_2=RI_1\cos\varphi_1/\cos\varphi_2=1.875\cdot 19.74$$

$$\Delta U_2\cong 37\text{V}$$

Thus, it follows a voltage drop reduction:

$$\Delta U=\Delta U_1-\Delta U_2=50-37=13\text{V}$$

And a motor terminal $U_1`=U_1+\Delta U=485+13=498$ V

3.2Power loss calculus

Power loss in a three phase network by electrocaloric effect is given by the relation:

$$p_j=3R_lI_l^2$$

where: R_l – is the resistance of a line conductor;

I_l – real value of the line current.

Thus, for the two values of the line current, real power loss is:

$p_{j1}=3R_lI_1^2=3\cdot 1.875\cdot 26.8^2=4040.1\ \text{W}=4.04\ \text{kW}$

$p_{j2}=3R_lI_2^2=3\cdot 1.875\cdot 19.74^2=2191.88\ \text{W}=2.19\ \text{kW}$

Therefore, we shall have a power loss reduction:

$$\Delta p_j=p_{j1}-p_{j2}=1.85\ \text{kW}$$

Assuming that the motor is operating 24 h/day and 300 days/year, the result is a real power annual reduction:

$$W_a`=1.85\cdot 24\cdot 300\cong 13320\ \text{kWh}$$

If there are 100 such motors on an oil field, the annual reduction is:

$$W_a=100\ W_a`=1\ 332\ 000\ \text{kWh}$$

which, at a unit price of 0.25 lei/kWh, leads to saving

$$E_{Cl}=0.25\cdot 1\ 332\ 000=333\ 000\ \text{lei}$$

3.3Powers and energies calculus

For a power factor $\cos\varphi_1=0.7$, the result is $\sin\varphi_l=0.7$ and a reactive power:

$$Q=\sqrt{3}\,U_lI_l\sin\varphi_l=\sqrt{3}\cdot 485\cdot 26{,}8\cdot 0{,}7\cong 15.76\ \text{Kvar}$$

The reactive power consumed by the motor in one year in the above mentioned conditions is:

$$W_r` = 15.76 \cdot 24 \cdot 300 = 113\,472 \text{ kVarh}$$

And for 100 identical motors:

$$W_r = 100 \cdot W_r` = 11\,347\,200 \text{ kVarh.}$$

At a unit price of 0.053 lei/kVarh, it follows an expense C,

$$C = 0{,}053 \cdot 11\,347\,200 \cong 601\,400 \text{ lei}$$

Which resolves itself in saving E_{C2}, by compensating the reactive power so the power factor becomes greater than or equal to the neutral power factor ($\cos\varphi_n$=0.92).

Thus, it follows a total saving for the entire company:

$$E_C = E_{C1} + E_{C2} = 333\,000 + 601\,400 = 934\,400 \text{ lei.}$$

3.4Capacitor bank calculus

Using notations from fig.2a, we can write:

$$Q_C = Q_1 - Q_2 = 3X_C I_C^2$$

where: Q_C - the reactive power to be given by the capacitor bank to increase the power factor from $\cos\varphi_1$ to $\cos\varphi_2$, X_C – capacitor bank capacity reactance given by:

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C} = \frac{1}{314\ C}$$

where C is the condenser capacity expressed in F,

I_C – the current through the condenser [A].

$$I_C = I_1 \sin\varphi_1 - I_2 \sin\varphi_2$$

$$I_C = 26.8 \cdot 0{,}7 - 19{,}74 \cdot 0{,}312 = 18{,}76 - 6{,}16 = 12{,}6\ A$$

$$Q_C = \sqrt{3}\ U_1 I_1 \sin\varphi_1 - \sqrt{3}\ U_1 I_2 \sin\varphi_2 = 3X_C I_C^2$$

$$Q_C = \sqrt{3}\ U_1(I_1 \sin\varphi_1 - I_2 \sin\varphi_2) = 3 \cdot I_C^2 / 314C$$

$$\sqrt{3} \cdot 485 \cdot 12{,}6 = 3 \cdot \frac{12{,}6^2}{314\ C}.$$

Thus: $C = \dfrac{3 \times 12.6}{\sqrt{3} \times 485 \times 314}$; $C = 0.000143474\ F$

or: $C_Y = 143,474\ \mu F$

The value of the condenser's capacity determined above corresponds to its Y-connection (Y), as in fig.2a.

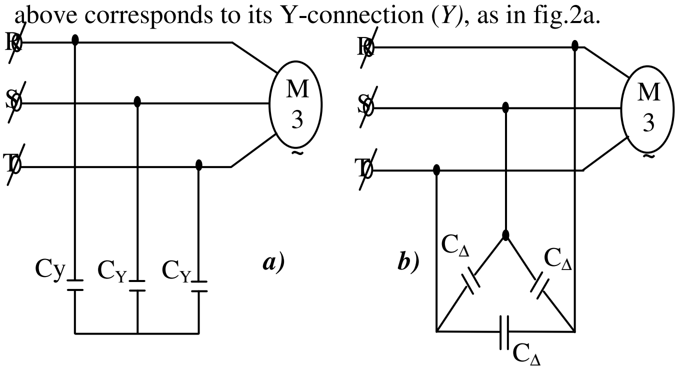


Fig.3 Capacitor bank Y-connection (a) and delta connection (b)

In case of the delta connection of the condensers *(Δ)*, the value of their capacity is:

$$C_\Delta = C_Y/3 = \frac{143.474}{3} = 47.82\mu\text{F}$$

4. CONCLUSIONS

Considering the way of choosing the pumping units driving motors as well as their specific operation conditions, the problem of reactive power compensation and of power factor improvement is a necessity.

Voltage drop and real power loss reduction in the supply networks as well as considerable reduction of reactive power expenditure are accomplished by reactive power local compensation (using static capacitor banks with stepping control placed inside CMPA cabin). The ultimate effect of these reductions consists in accomplishing substantial saving (hundreds of thousands euro – as shown by the presented numeric application) with a favorable impact on the price per ton of extracted oil.

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