UDC 622.276.53

IMPROVING SUCKER ROD PUMP EFFICIENCY USING FREQUENCY CONTROLLED INDUCTION MOTOR

Samuel Isaac Tecle[1],
samuel47tecle@gmail.com

Anatolii M. Ziuzev[1],
a.m.zyuzev@urfu.ru

Alex V. Kostylev[1],
a.v.kostylev@urfu.ru

[1] Ural Federal University,
19, Mira street, Yekaterinburg, 620002, Russia.

Relevance. *In sucker rod pump installations, the cost of the prime mover's power use has substantial effect on the overall operational cost. Reduction in power consumption can lead to reduction in operating cost. Hence, as the sucker rod pump is dominant in the oil industry, any means which reduces the energy consumption can produce considerable economic benefit and help to meet the energy efficiency targets and standards. Due to the losses in the prime mover, surface transmission, and sucker rod string the power required to lift oil to the surface is always less than the power input to the prime mover. Induction motors, which are widely used as prime movers in sucker rod pump installations, operate at significantly lower efficiency and at a load lower than their rated capacity. Therefore, the demand for efficiency improvement is readily seen. This demand can be achieved by controlling motor losses through AC-DC-AC converter.*
The main aim *of the research is to develop control strategy that helps to operate the sucker rod pump drive at optimal efficiency.*
Objects: *electrical drive, sucker rod pump, oil producing well.*
Method: *integrated simulation model consisting of the models of AC-DC-AC converter, induction motor including iron loss, sucker rod pump; vector control; generation of optimal magnetizing current trajectory for one cycle of pump operation.*
Result. *The energy consumption of sucker rod pump unit for operation at rated flux and the one based on optimal magnetizing current trajectory were compared using an integrated simulation model. The simulation results indicate that about 1,6 % of the required energy can be saved when the sucker rod pump is operated based on the calculated optimal magnetizing current trajectory.*

Key words:
Sucker rod pump, optimized control, induction machine, core loss, field-oriented control, variable speed drive.

Introduction

Throughout the world, electric motors consume around 70 % of the total energy consumption and nearly 90 % of it is used up by three phase induction motors in the power range from 0,75 to 750 KW [1]. Induction motor (IM) is without doubt the workhorse of electric power industry [2]. It is the principal element in most applications like pump, lift, exhaust fans, hoist drives etc. Its simple, strong and effective construction, good efficiency, and low cost are the main factors that encouraged its use in wide applications. However, induction motors are inefficiently utilized in most industries because the use of the same electric motor (size, power, model) is common for reasons of standardization practices and maintenance costs [3]. In addition, the IM control is more difficult because it represents nonlinear system with a coupled multi-input multi-output system.

Motivated by the diversified application needs, electric motor manufacturers have produced different IM designs to improve the performance of induction motors. Depending on the torque-speed characteristics, National Electrical Manufacturers Association (NEMA) classifies induction motors into design A, B, C, D and E. The most significant machine parameter in this classification is the actual rotor resistance [2]. Since there are significant differences among the different designs in their torque-speed characteristics, familiarity with these standards is required for making correct decision during selection for a particular application. The most used designs are design B (normal torque) and design C (high torque) [4]. Design B motors have steep speed-torque, speed-current and speed-efficiency characteristics close to the nominal operational speed. They can suite for various application operated at nearly nominal speed. However, a small change in the speed causes large changes in the efficiency and stator current [5]. This means, when this type of motor does not maintain their nominal operational speed, for example when they drive a variable load such as sucker rod pump, a drastic decrease in efficiency can be observed. For these applications, induction motors with design D are preferred. Design D induction motors are characterized by high starting torque, low starting current and high operating slip [6].

Although the input energy to the electrical motor drive largely appears in useful work but there is usually energy lost in the motor winding, magnetic circuit together with conduction and commutation losses of the inverter. Thus, the total loss consists of converter losses and motor losses. At nominal operating condition, the efficiencies of converters can reach 98 % and the efficiencies of medium and high rating motors are over 95 % whereas, at partial loads the efficiency declines considerably [7]. For small drives, the converter losses can be neglected in efficiency optimal control [8, 9]. Power loss in the motor include stator and rotor copper losses, iron losses, windage and friction losses, additional losses [10, 11]. Copper losses

DOI 10.18799/24131830/2022/11/3955

and iron losses are controllable. However, development of a comprehensive model of losses for an electric drive system is fundamental to control system design. The copper losses appear in the form of heat loss in the stator and rotor resistors and hence their effect is included even in the most basic equivalent circuit. Mechanical losses occur in the form of frictional loss and the aerodynamic loss. The effect of mechanical losses can be integrated into the mechanical equation using viscous friction coefficient and dry friction torque. On the other hand, since iron losses have magnetic nature, their effect can be approximated using an equivalent torque in the mechanical equation [12] or an equivalent resistor [7–9, 12–14] in the equivalent circuit.

In the field-oriented coordinate system, the torque developed by IM is proportional to the product of rotor flux and torque producing current. The needed torque producing current is determined by speed controller, but the rotor flux remains degree of freedom for optimization. Studies conducted to examine the effect of rotor flux on power loss indicate that as rotor flux decreases, the copper losses increase but iron losses decrease. Therefore, operation at optimal efficiency can be achieved by acting on the reference flux. Several reports [15–26] have already been conducted aiming to reduce the power losses in induction motor drive. Based on the ways employed to reach the objective, efficiency optimization methods can be grouped into simple control, model-based control, search control, hybrid method (combination of model-based control and search control). When scalar control is used, optimal energy efficiency operation can be obtained by acting on the input voltage and frequency. In [27, 28], energy efficiency strategies for scalar control have been presented.

The simple state control is the simplest method based on some facts that are observed during the operation of optimal efficiency. For example, it was observed in [9] that the variation of power factor is small when efficiency is optimal such that it can be considered constant. As alternate to power factor, in [17, 18] it has been demonstrated that optimal efficiency is maintained when the motor is operated at constant slip determined only from motor parameters. The disadvantage of this approach is that the accuracy of this method is limited to a narrow set of conditions for use and there could be shift of optimal operating point due to parameter variations. Model-based control is the fastest approach. However, analytical solution to minimum power loss model might be very difficult. In addition, parameter variation influences the accuracy of the obtained result. The search control does not require knowledge of motor or converter parameters, it simply decreases the stator current or rotor flux in steps until minimum input power for a given output is measured. This method slowly converges to the optimal point and has poor dynamic performance due to torque pulsations. The hybrid method combines the good characteristics of the model-based controller and search control. Hence, it gives fast convergence to operating point with minimum power losses and shows good dynamic performance and no sensitivity to parameter changes [22].

When IM drives a cyclic load, optimization problem formulation must fully involve the nature of the closed cycle operation. For such a problem, the possibility of obtaining optimal solution has been shown in [23, 24] using dynamic programing. In [24] a steady state loss minimization has also been extended to dynamic operation and results loss saving comparable to the optimal dynamic programming method.

This paper presents the strategy for improving sucker rod pump efficiency by optimally controlling IM. First, mathematical model of induction motor including core loss is presented. Based on this model, the expression for the total loss and for the optimal magnetizing current in steady state are derived. With the help of the expression for optimal magnetizing current and specified constraints, the permissible range for optimization is defined. Then with the required consideration, a numerical algorithm is outlined to find a good approximation of optimal magnetizing current trajectory. Finally, simulation results and conclusion of the work are presented.

Model of Induction Motor

Electromagnetic process in 3 phase AC machines can be clearly described with the help of equivalent circuits. IM model developed in a two phase reference frame is the most convenient representation with which equivalent circuit can be constructed [29]. The inverse Γ equivalent circuit (Fig. 1) is the most widely used equivalent circuit when designing controllers. The inverse Γ equivalent circuit contains four parameters with the total leakage inductance in the stator mesh and all the parameters that describe the model of IM can be determined by the standard tests. From Fig. 1, the stator mesh and rotor mesh can be written as:

$$\boldsymbol{u}_s = R_s\boldsymbol{i}_s + \sigma L_s\frac{d\boldsymbol{i}_s}{dt} + \omega_k\sigma L_s B\boldsymbol{i}_s + $$
$$+\left(1-\sigma\right)L_s\frac{d\boldsymbol{i}_m}{dt} + \omega_k\left(1-\sigma\right)L_s B\boldsymbol{i}_s,$$
$$0 = \left(\frac{L_m}{L_r}\right)^2 R_r\left(\frac{L_r}{L_m}\boldsymbol{i}_r\right) + \left(1-\sigma\right)L_s\frac{d\boldsymbol{i}_m}{dt} + $$
$$+\left(\omega_k-\omega\right)\left(1-\sigma\right)L_s B\boldsymbol{i}_m,$$

where R_s is the stator resistance; R_r is the rotor resistance; L_s is the stator inductance; L_r is the rotor inductance; L_m is the mutual inductance; ω is the rotor speed; ω_k is the synchronous speed.

$$\boldsymbol{u_s} = \left[u_{sd}\, u_{sq}\right]^T;\ \boldsymbol{i_s} = \left[i_{sd}\, i_{sq}\right]^T;\ \ \boldsymbol{i}_m = \left[i_{md}\, i_{mq}\right]^T;$$
$$\sigma = 1 - \frac{L_m^2}{L_s L_r};\ B = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}.$$

Electrical machines are made of high permeable ferromagnetic material, which helps to increase the machines efficiency. However, the time and space variation of the magnetic flux induces iron losses [30] that considerably affect the accuracy of the model used. For a time-dependent applied magnetic field, the total iron loss comprises hysteresis, classical eddy current loss and excess losses [31].

Assuming sinusoidal flux pattern is given by:

$$\psi(t) = dB_p \sin(2\pi f t),$$

where d is the thickness of the sheet, B_p is the peak value of flux density and f is the frequency, the total iron loss is calculated as in [31]:

$$P_{fe} = P_h + P_e + P_{ex} =$$
$$= aB_p^{\alpha} f + bB_p^2 f^2 + cB_p f\left(\sqrt{1+eB_p f} - 1\right), \quad (1)$$

where α, a, b, c, and e are the material related parameters fitted based on the loss measurements under sinusoidal flux condition.

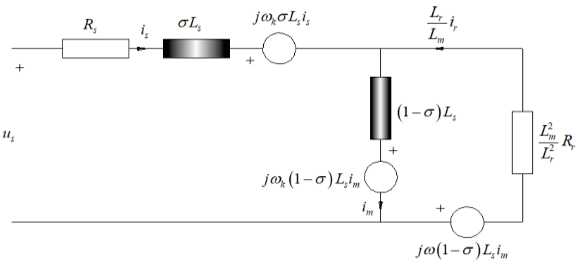

Fig. 1. *Inverse Г equivalent circuit*
Рис. 1. *Г-образная схема замещения*

The effect of iron loss can be represented by an equivalent resistance. However, since the iron loss expressed by (1) is a function of magnetic field and frequency, a fixed equivalent resistor cannot represent the effect of iron loss in the dynamic model. The equivalent resistor could be placed in series or in parallel to the magnetizing inductance. In both approaches, the no load test and locked rotor test can be used to determine the value of the equivalent resistance. Fig. 2 shows the steady state model of IM including core loss with the leakage inductance in the stator mesh. Using Kirchhoff's voltage and current laws, the following equations can be written:

$$\boldsymbol{u_s} = R_s \boldsymbol{i_s} + \sigma L_s \frac{d\boldsymbol{i_s}}{dt} + \omega_s \sigma L_s B \boldsymbol{i_s} +$$
$$+(1-\sigma)L_s \frac{d\boldsymbol{i_m}}{dt} + \omega(1-\sigma)L_s B\boldsymbol{i_m}, \quad (2)$$

$$\boldsymbol{i_s} = \boldsymbol{i_m} + (1-\sigma)L_s\left(\frac{1}{R_f} + \frac{T_r}{(1-\sigma)L_s}\right)\frac{d\boldsymbol{i_m}}{dt} +$$
$$+(1-\sigma)L_s\left(\frac{\omega_s}{R_f} + \frac{(\omega_s - \omega)T_r}{(1-\sigma)L_s}\right)B\boldsymbol{i_m}, \quad (3)$$

$$R_f \boldsymbol{i}_f = (1-\sigma)L_s \frac{d\boldsymbol{i}_m}{dt} + (1-\sigma)L_s \omega_s B \boldsymbol{i}_m,$$

where $\boldsymbol{i}_f = \left[i_{fd}\, i_{fq}\right]^T$.

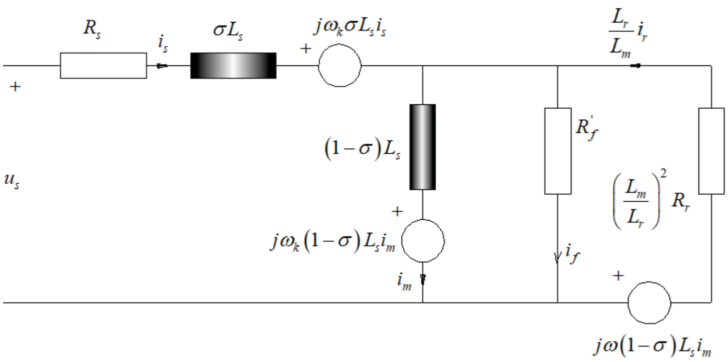

Fig. 2. *Equivalent circuit of IM including core loss*
Рис. 2. *Эквивалентная схема АД с учётом потерь в стали*

Equations (2) and (3) can be expressed along the mechanical equation in state space form as:

$$\frac{d\boldsymbol{i_s}}{dt} = -\frac{1}{T_\sigma}\boldsymbol{i_s} - \omega_s B\boldsymbol{i_s} + A\boldsymbol{i_m} - AT_r\omega B\boldsymbol{i_m} + \frac{\boldsymbol{u_s}}{\sigma L_s},$$

$$\frac{d\boldsymbol{i_m}}{dt} = -\frac{1}{T_{rfe}}\boldsymbol{i_m} + \frac{1}{T_{rfe}}\boldsymbol{i_s} - \left(\omega_s - \frac{T_r}{T_{rfe}}\omega\right)B\boldsymbol{i_m}, \quad ,$$

$$\frac{d\omega}{dt} = \frac{z_p}{J}\left(M_e - M_L\right),$$

$$M_e = 1.5 z_p (1-\sigma) L_s \left(i_{md} i_{rq}' - i_{mq} i_{rd}'\right),$$

where M_L, z_p, and J are the load torque, pair of poles and equivalent moment of inertia respectively and the rest of the terms are defined as follows $\boldsymbol{i_r} = \left[i_{rd}\, i_{rq}\right]^T$;

$$T_r = \frac{L_r}{R_r};\; T_{rfe} = T_r + \frac{(1-\sigma)L_s}{R_{fe}};\; \frac{1}{T_\sigma} = \frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_{rfe}};$$
$$A = \frac{1-\sigma}{\sigma T_{rfe}};\; R_r' = \left(\frac{L_m}{L_r}\right)^2 R_r;\; i_r' = \frac{L_r}{L_m} i_r.$$

Loss model and optimal I_{sd} generation

Mechanical losses are independent of the stator current, but they depend on the speed. Therefore, the total electrical losses can be obtained by:

$$P_{loss} = R_s\left(i_{sd}^2 + i_{sq}^2\right) + R_r'\left(i_{rd}'^2 + i_{rq}'^2\right) + R_{fe}\left(i_{fd}^2 + i_{fq}^2\right).$$

Optimal magnetizing current generation in steady state

Using vector control, IM can have DC machine like performance. The stator voltage space vector can be oriented with respect to space vector of either rotor flux, air gap flux or stator flux. Applying rotor-flux-oriented constraints, we get:

$$\psi_{rq} = (1-\sigma) L_s i_{mq} = 0,$$

$$i_{sd} = i_{md} + T_{rfe} \frac{di_{md}}{dt},$$

$$\omega_{slip} = \frac{1}{T_{rfe}} \left(\frac{i_{sq}}{i_{md}} - \left(T_{rfe} - T_r \right) \omega \right),$$

$$M_e = K_t i_{sq} i_{md},$$

where $K_t = 1.5 z_p (1-\sigma) L_s$.

In steady state

$$i_{mq} = 0;\ i_{rd}^{'} = 0;\ i_{fd} = 0;\ i_{sd} = i_{md};$$

$$i_{fe} = i_{fq};\ i_r^{'} = i_{rq}^{'};\ i_{sq} = i_{fe} + i_r^{'}$$

and using KVL in rotor circuit $i_r^{'}$ can be written as:

$$i_r^{'} = \frac{R_f}{R_f + R_r^{'}} i_{sq} - \omega \frac{(1-\sigma) L_s}{R_f + R_r^{'}} i_{sd}.$$

Therefore, the total power loss can be written as:

$$P_{loss} = R_d i_{sd}^2 + R_q i_{sq}^2,$$

where

$$R_d = R_s + \frac{(1-\sigma)^2 L_s^2}{R_f + R_r^{'}} \omega^2;\ R_q = R_s + \frac{R_f R_r^{'}}{R_f + R_r^{'}}.$$

Obviously, both direct and quadrature components of the controlled current have effect on the total energy loss. So, for a given torque producing current (i_{sq}) the optimal flux producing current (i_{sd}) exists which minimizes the electric motor losses.

The power loss can also be given in terms of operating condition:

$$P_{loss} = R_d i_{sd}^2 + R_q \frac{M_e^2}{K_t^2 i_{sd}^2}.$$

For constant torque, differentiating the loss function, the optimal flux producing current (i_{sd}) can be calculated as follows:

$$i_{md}^{opt} = i_{sd}^{opt} = \left(\frac{\gamma}{R_d} \right)^{0.25}, \quad (4)$$

where $\gamma = R_q \frac{M_e^2}{K_t^2}$,

then optimal rotor flux can be determined by:

$$\psi_r^{opt} = L_m i_{sd}^{opt}. \quad (5)$$

The optimal rotor flux is a function of speed and torque. It can be computed using (5) for each possible torque-speed operating point. However, in practice there are voltage and current constraints which reduce the range of values to be searched.

Optimal magnetizing current generation under voltage and current constraints

In practice, the problem of efficiency optimized control of induction motor drive aims to minimize energy consumption under voltage and current constraints. To avoid magnetic saturation, the rotor flux is further limited to its rated value. Furthermore, to maintain controllability and limit peak currents, the rotor flux is not reduced below an arbitrarily minimum level. Therefore, no optimization can be recommended in the region shaded by red in Fig. 3. Consequently, the reference flux is set equal to rated value. As it is shown in Fig. 3 the rotor flux can be optimized for torque load less than 149 at base speed and less than 40 at 10 percent of base speed.

In steady state for field-oriented coordinate system, the stator voltage equations can be written as:

$$v_{sd} = R_s i_{sd} - \omega_s \sigma L_s i_{sq},$$

$$v_{sq} = R_s i_{sq} + \omega_s \sigma L_s i_{sd} + \omega_s (1-\sigma) L_s i_{md}.$$

If the voltage drop due to stator resistance is neglected, the voltage constraint can be stated as:

$$\left(\omega_s \sigma L_s i_{sq}\right)^2 + \left(\omega_s L_s i_{sd}\right)^2 \le v_{max}^2.$$

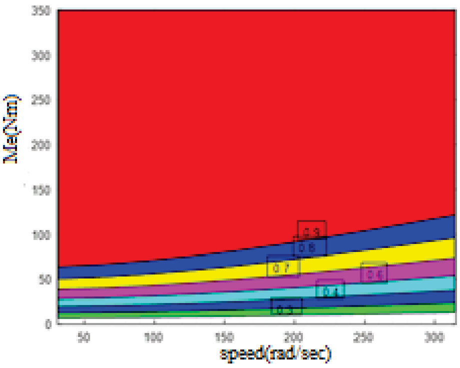

Fig. 3. *Optimal rotor flux values per load torque and speed requirement*

Рис. 3. *Оптимальные значения магнитного потока ротора в функции момента нагрузки и скорости*

Considering the constraints mentioned, the problem is formulated as:

$$\min\left\{ P_{loss}\left(i_{sd}, i_{sq}\right)\right\}, \quad (6)$$

subject to:

$$M_e = K_t i_{sd} i_{sq},\ i_{sd}^2 + i_{sq}^2 - I_{max}^2 \le 0,\ i_{sd} \le i_{sdn},$$

$$i_{sd} \ge i_{sd\,min},\ 0 \le v_d^2 + v_q^2 < v_{max}^2.$$

In the basic speed range, the voltage limitation is not effective. Fig. 4 shows the relation between optimal flux producing current and torque producing current in the basic speed range. For the region inside the inequality, the optimal flux producing current can be calculated by (4) and the following relation holds between torque producing current and flux producing current:

$$i_{qs} = \left(\frac{R_d}{R_q}\right)^{0.5} i_{sd}.$$

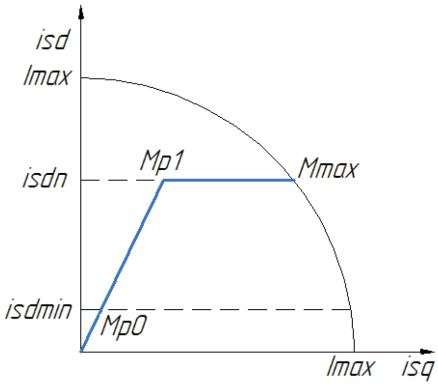

Fig. 4. *Relation between optimal flux and torque producing currents in base speed range*

Рис. 4. *Связь намагничивающей и моментной составляющих тока статора в диапазоне базовых скоростей*

The lower limit of flux producing current defines the torque M_{p0}:

$$M_{p0} = K_t \left(\frac{R_d}{R_q}\right)^{0.5} i^2_{sd\,\min}.$$

The upper limit of the flux producing current defines the torque M_{p1}:

$$M_{p1} = K_t \left(\frac{R_d}{R_q}\right)^{0.5} i^2_{sdn}.$$

The maximum torque (M_{max}) is defined by the maximum value of flux producing current and maximum stator current as:

$$M_{\max} = K_t i_{sdn} \left(I^2_{\max} - i^2_{sdn}\right)^{0.5}.$$

For a load torque greater than M_{p1} and less than the maximum torque (M_{max}), the following relation holds:

$$i_{sd} = i_{sdn}; \quad \left(\frac{R_d}{R_q}\right)^{0.5} i_{sdn} < i_{sq} \le \left(I^2_{\max} - i^2_{sdn}\right)^2.$$

Optimal magnetizing current generation for sucker rod pump applications

The nature of the load exerted on sucker rod pump drive is cyclic. Therefore, efficiency optimal control strategy for sucker rod pump drive deals with minimizing the total loss in a cycle under given constraints. Consequently, the objective function in (6) is replaced by:

$$\min\left\{\int_0^T P_{loss}\left(i_{sd}, i_{sq}\right)dt\right\}, \quad (7)$$

where T is the period of one cycle of pump operation.

The task of the optimization is to find an optimal magnetizing current trajectory that satisfies the objective function (7). In offline for a given torque and speed trajectories, for all possible magnetizing current trajectories, the energy consumption is examined, and the optimal magnetizing current trajectory is stored and uploaded to the controller. Since for a given sucker rod pump installations a change on trajectory occurs after long time, one calculated optimal trajectory can be used for a longer time. However, if any change occurs another optimal trajectory must be recalculated.

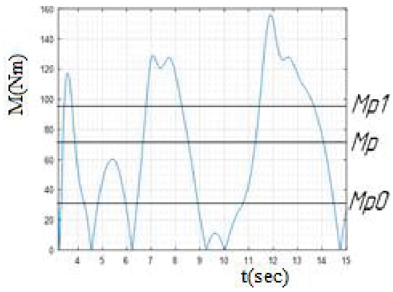

Fig. 5. *Absolute value of given load torque curve*

Рис. 5. *Абсолютное значение заданной диаграммы момента нагрузки*

To define rotor magnetizing current trajectory, the minimum and maximum flux producing current constraints and the minimum time interval for constant flux operation are considered. The minimum time interval for constant flux operation depends on the existing delay in the forming of rotor flux. Fig. 5 shows the absolute value of a given load torque trajectory. It is used for finding a good approximation of optimal magnetizing current trajectory. A simple numerical algorithm to find optimal rotor magnetizing current trajectory can be outlined as follows:

- calculate the steady state electromagnetic torque corresponding to lower limit of optimal flux producing current (M_{p0}) and upper limit of the optimal flux producing current (M_{p1});
- list constant torque (M_p) operations in the range from M_{p0} to M_{p1};
- select the steady state electromagnetic torques which divide the absolute value of the torque trajectory into time intervals greater than the minimum time interval for constant flux operation;
- for each selected steady state electromagnetic torque, define the flux producing current trajectory by setting its value to i_{sdn} for the part of torque trajectory above the selected steady state electromagnetic torque otherwise to the corresponding optimal flux producing current;
- for each flux producing current trajectory, calculate the energy loss for one complete cycle of pump operation;
- the flux producing current trajectory with minimum energy loss is selected as an optimal magnetizing current trajectory.

The required optimal operating conditions are obtained with the help of control system. Fig. 6 shows block diagram for closed loop vector control scheme proposed for sucker rod pump drive. In steady state, the PI regulator forces the measured speed and reference speed to be equal. The block PC LMA calculates optimal magnetizing current trajectory based on the proposed loss minimization strategy for a given speed and torque trajectories and stores it. The stored optimal magnetizing current trajectory is uploaded to the controller and used as a reference. But if the torque trajectory shows some change, a new optimal magnetizing current trajectory is calculated to consider the effect of the changes. T_φ is the time constant of a low pass filter. It presents a certain time delay in the forming of the rotor flux, which ensures decoupled flux and torque control in dynamic conditions.

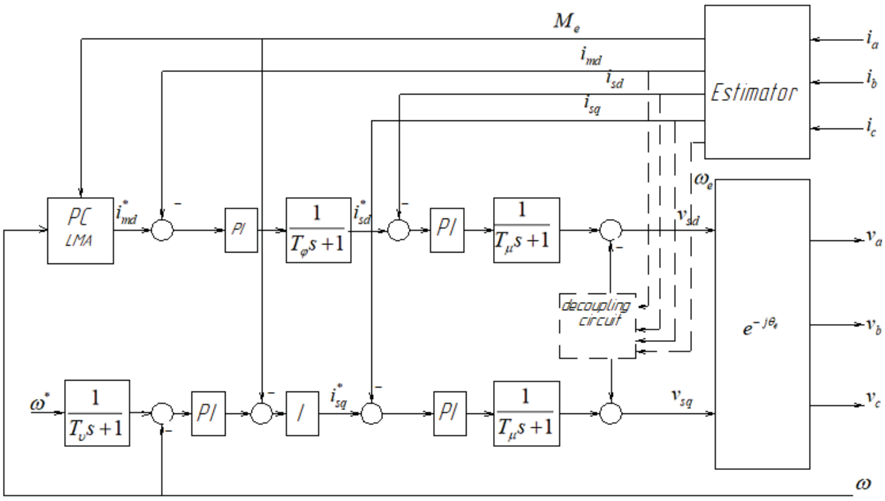

***Fig. 6.** Block diagram of proposed loss minimization strategy*

***Рис. 6.** Блок-схема предлагаемой стратегии минимизации потерь*

Simulation results

To investigate the power loss minimization strategy for induction motor driving sucker rod pump, a numerical simulation has been carried in Matlab software. In the simulation the following parameters are used: R_s=0,1815 ohm, R_r=0,0868 ohm; L_s=0,048 H; L_r=0,0481 H; L_m=0,0465 H; R_{fe}=400 ohm; f=50 Hz. Two cases: operation at rated flux and operation at optimal magnetizing current trajectory, were considered. Fig. 7 compares the input power for operation at rated rotor flux with the proposed optimal magnetizing current trajectory. Their difference is shown in Fig. 8 for clarity. From this result one can observe that the input power requirement at light loads is considerably reduced. As it is shown in the Table the energy consumed in one cycle of pump operation is lower when the efficiency optimized control strategy is applied than the operation at rated flux. 1,6 % of the required energy can be saved if the drive is run based on optimal magnetizing current trajectory than just running at constant rated magnetizing current. Since sucker rod pumps work for several hours per day, a small improvement in efficiency generates significant revenues.

Fig. 9–11 show the response of actual magnetizing current, flux producing stator current, rotor speed respectively, when the efficiency optimization strategy is activated. The role of the delay introduced in the d-axis is apparent from the response of flux producing current.

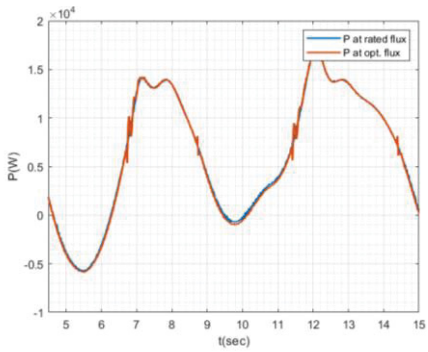

***Fig. 7.** Input power to the motor (blue – with rated flux, red – with optimal flux)*

***Рис. 7.** Входная мощность двигателя (синий – при номинальном потоке, красный – при оптимальном потоке)*

***Table.** Comparison of energy consumed for operation at rated flux and optimal magnetizing current trajectory*

***Таблица.** Сравнение энергии, потребляемой двигателем при работе с номинальным потоком и при оптимальной траектории тока намагничивания*

Case Вариант	Energy consumed in one cycle of pump operation (Joules) Энергия, потребляемая двигателем за один цикл работы насоса (Дж)	Fluid produced by downhole pump (m^3) for one cycle of operation Подача глубинного насоса ($м^3$) за один цикл работы	Volumetric efficiency (KWh/m^3) Удельная эффективность ($кВт.ч/м^3$)
Operation at rated flux Работа при номинальном потоке	65078	0,0575	0,314
Operation at optimal flux Работа при оптимальном потоке	64123	0,0575	0,309

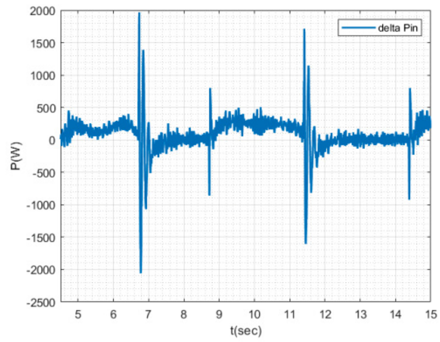

Fig. 8. *Difference between power input at rated flux and input power operation at optimal flux*

Рис. 8. *Разница между входной мощностью двигателя при номинальном потоке и при оптимальном потоке*

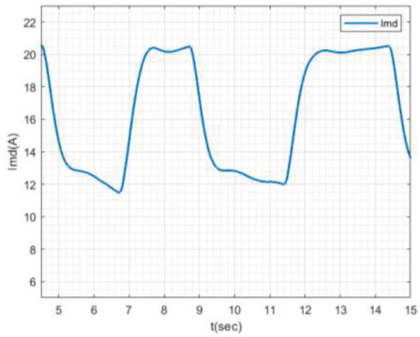

Fig. 9. *Magnetizing current*

Рис. 9. *Намагничивающий ток*

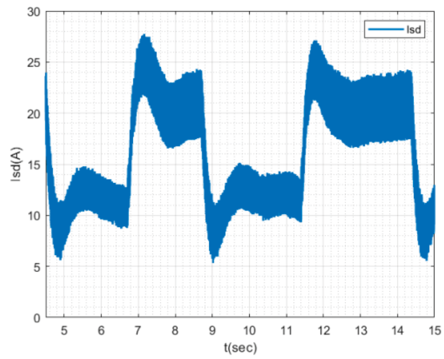

Fig. 10. *Flux producing stator current*

Рис. 10. *Намагничивающая составляющая тока статора*

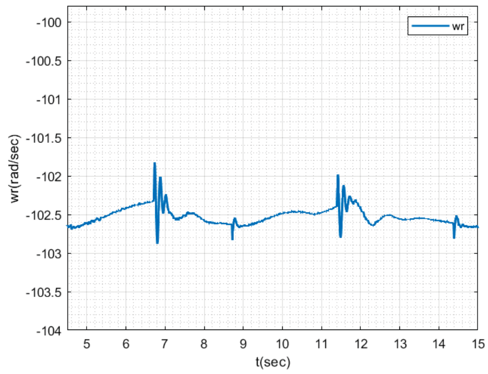

Fig. 11. *Rotor speed*

Рис. 11. *Скорость ротора*

Conclusion

Loss minimization strategy for sucker rod pump drive has been presented in this paper. The proposed strategy uses a steady state electromagnetic torque to define magnetizing current trajectory. Form a list of steady state electromagnetic torque in the range of M_{p0} and M_{p1}, the energy consumption for one cycle of pump operation have been examined for given torque and speed trajectory. The magnetizing current trajectory corresponding to minimum energy have been used by the developed controller as a reference. The simulation results show that the proposed strategy offers considerable loss reduction in one cycle of pump operation while maintaining acceptable dynamic performance. According to the performed simulation results we can conclude that a significant amount of energy can be saved every day if the optimal magnetizing current is used as a reference.

REFERENCES

1. Gupta V.K., Tiwari B., Dewangan B. Efficiency optimization of induction motor drive: a review. *International Journal of Innovative Sceince, Engineering & Technology*, 2015, vol. 2, pp. 650–665.
2. Bose B.K. *Modern power electronics and AC drives*. Upper Saddle River, New Jersey, Prentice Hall PTR, 2002. 711 p.
3. Farhani F., Zaafouri A., Chaari A. Real time induction motor efficiency optimization. *Journal of the Franklin Institute*, 2017, vol. 354, no. 8, pp. 3289–3304.
4. Hopper W.B., Rajan S. NEMA standards for induction motors and their application to the cement industry. *IEEE Transactions on Industry Applications*, 1974, vol. IA-10, no. 1, pp. 34–41.
5. Koncz Á. *Sucker rod pumping analysis based on measured electrical parameters*. Phd thesis. Miskolc, 2018. 109 p.
6. Zhang D., Ren Z., Koh C.-S. Multi-objective optimal design of a NEMA design D three-phase induction machine utilizing gaussian-MOPSO algorithm. *Journal of electrical engineering and technology*, 2014, vol. 9, no. 1, pp. 184–189.
7. Quang N.P., Dittrich J.-A. *Vector control of three-phase AC machines – system development in the practice*. 2nd ed. Berlin, Haidelberg, Springer, 2015. 364 p.
8. *New trends in technologies: devices, computer, communication and industrial systems*. Ed. by M.J. Er. London, United Kingdom, IntechOpen, 2010. Available at: https://www.intechopen.com/books/3720 doi: 10.5772/292 (accessed 15 August 2022).
9. Abrahamsen F., Blaabjerg F., Pedersen J. K., Thoegersen P.B. Efficiency-optimized control of medium-size induction motor drives. *IEEE Transactions on Industry Applications*, 2001, vol. 37, no. 6, pp. 1761–1767.
10. Đuran T., Šimović V., Komljen B.V. Comparison of different methods for efficiency determination acc.to IEC for specific induction motor. *44th International Convention on Information, Communication and Electronic Technology (MIPRO)*. Opatija, Croatia, 2021. pp. 172–176.
11. Hristova M.I., Ruseva V.S., Krasteva A.H. Constant losses in induction motors and possible solutions for their reduction. *8th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE)*. Ruse, Bulgaria, 2022. pp. 1–4.
12. Khoury G. *Energy efficiency improvement of a squirrel-cage induction motor through the control strategy*. Phd thesis. Toulouse, 2018. pp. 31–33.
13. Hung N.T., Nguyên Chí Thiên, Thanh Phương Nguyễn, Viet So Le, Do Anh Tuan. Optimization of electric energy in three-phase induction motor by balancing of torque and flux dependent losses. *AETA 2013: Recent advances in electrical engineering and related*

sciences. Verlag, Berlin, Haidelberg, Springer, 2014, vol. 282, pp. 497–507.

14. Baba A., Mendes E., Razek A. Losses minimisation of a field-oriented controlled induction machine by flux optimisation accounting for magnetic saturation. *1997 IEEE International Electric Machines and Drives Conference Record*. Milwaukee, WI, USA, 1997. pp. MD1–2.
15. Bruno A., Caruso M., Tommaso A.O.D., Miceli R., Nevoloso C., Viola F. Simple and flexible power loss minimizer with low-cost MCU implementation for high-efficiency three-phase induction motor drives. *IEEE Transactions on Industry Applications*, 2021, vol. 57, no. 2, pp. 1472–1481.
16. Sousa G.C.D., Bose B.K., Cleland J.G. Fuzzy logic based on-line efficiency optimization control of an indirect vector-controlled induction motor drive. *IEEE Transactions on Industrial Electronics*, 1995, vol. 42, no. 2, pp. 192–198.
17. Feng Xiaogang, Chen Boshi. Constant slip control of induction motor at light load. *IECEC 96. Proceedings of the 31st Intersociety Energy Conversion Engineering Conference*, 1996, vol. 3, pp. 1828–1833.
18. Abrahamsen F., Blaabjerg F., Pedersen J.K., Grabowski P.Z., Thogersen P. On the energy optimized control of standard and high-efficiency induction motors in CT and HVAC applications. *IEEE Transactions on Industry Applications*, 1998, vol. 34, no. 4, pp. 822–831.
19. Chakraborty C., Ta M.C., Uchida T., Hori Y. Fast search controllers for efficiency maximization of induction motor drives based on DC link power measurement. *Proceedings of the Power Conversion Conference*. Osaka, 2002. Vol. 2, pp. 402–408.
20. Eftekhari S.R., Davari S.A., Naderi P., Garcia C., Rodriguez J. Reducing the parameter dependency of model-based loss minimization method for induction motor drives. *IEEE International Conference on Industrial Technology (ICIT)*. Buenos Aires, Argentina, 2020. pp. 1106–1111.
21. Jung C., Torrico C.R.C., Giovani Carati E. Adaptive loss model control for robustness and efficiency improvement of induction motor drives. *IEEE Transactions on Industrial Electronics*, 2022, vol. 69, no. 11, pp. 10893–10903.
22. Blanusa B., Knezevic B. Simple hybrid model for efficiency optimization of induction motor drives with its experimental validation. *Advances in Power Electronics*, 2013, vol. 2013, pp. 1–8.
23. Blanusa B. New trends in efficiency optimization of induction motor drives. *New Trends in Technologies: Devices, Computer, Communication and Industrial Systems*. London, United Kingdom, IntechOpen, 2010. Available at: https://www.intechopen.com/chapters/12290 (accessed 15 August 2022). DOI: 10.5772/10427.
24. Mendes E., Baba A., Razek A. Losses minimization of a field oriented controlled induction machine. *Seventh International Conference on Electrical Machines and Drives* (Conf. Publ. No. 412). Durham, UK, 1995. pp. 310–314.
25. Bizhani H., Muyeen S.M., Tatari F.R., Gao F., Geng H. Comparative analysis of search algorithm based loss minimization techniques used in vector controlled induction motors. *2nd International Conference on Smart Power & Internet Energy Systems (SPIES)*. Bangkok, Thailand, 2020. pp. 386–390.
26. Tarvirdilu-Asl R., Nalakath S., Xia Z., Sun Y., Wiseman J., Emadi A. Improved online optimization-based optimal tracking control method for induction motor drives. *IEEE Transactions on Power Electronics*, 2020, vol. 35, no. 10, pp. 10654–10672.
27. Graciola C.L., Goedtel A., Angélico B.A. Energy efficiency optimization strategy for scalar control of three-phase induction motors. *J Control Autom Electr Syst*, 2022, vol. 33, pp.1032–1043.
28. Zhang Y., Baig S., Vahabzadeh T., Jatskevich J. Maximum efficiency volts-per-hertz control of induction motor drives considering core losses, saturation, and inverter losses. *International Conference on Electrical, Computer and Energy Technologies (ICECET)*. Pargue, Czech Republic, 2022. pp. 1–7.
29. Leonhard W. *Control of electrical drives*. 3rd ed. Berling, Heidelberg, Springer, 2001. 460 p.
30. Fratila M., Benabou A., Tounzi A., Dessoude M. Calculation of iron losses in solid rotor induction machine using FEM. *IEEE Transactions on Magnetics*, 2014, vol. 50, no. 2, pp. 825–828.
31. Kowal D., Sergeant P., Dupré L., Vandenbossche L. Comparison of iron loss models for electrical machines with different frequency domain and time domain methods for excess loss prediction. *IEEE Transactions on Magnetics*, 2015, vol. 51, no. 1, pp. 1–10.

Received 15 October 2022.
Reviewed 25 October 2022.

Information about the authors

Samuel Isaac Tecle, postgraduate student, Ural Federal University.

Anatolii M. Ziuzev, Dr. Sc., professor, Ural Federal University.

Alex V. Kostylev, Dr. Sc., Head of Department of Electrical Drives and Automation of Industrial Installations, Ural Federal University.

УДК 622.276.53

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ РАБОТЫ ЧАСТОТНО-РЕГУЛИРУЕМОГО ЭЛЕКТРОПРИВОДА ШТАНГОВОГО ГЛУБИННОГО НАСОСА

Самуэль Исаак Текле[1],
samuel47tecle@gmail.com

Зюзев Анатолий Михайлович[1],
a.m.zyuzev@urfu.ru

Костылев Алексей Васильевич[1],
a.v.kostylev@urfu.ru

[1] Уральский Федеральный университет,
Россия, 620002, г. Екатеринбург, ул. Мира, 19.

Актуальность. *В установках со штанговыми насосами стоимость электроэнергии, потребляемой приводным электродвигателем, составляет существенную долю затрат в общих эксплуатационных расходах на добычу нефти. Очевидно, что снижение энергопотребления электродвигателем приведёт к снижению эксплуатационных расходов. Поскольку штанговые насосы доминируют в нефтедобывающей отрасли, можно ожидать, что любые средства, обеспечивающие снижение потребления энергии, принесут значительную экономическую выгоду и позволят достичь целей и стандартов энергоэффективности. Анализ энергопотребления показывает, что из-за потерь в двигателе, наземной установке и колонне насосных штанг мощность, необходимая для подъема нефти на поверхность, ощутимо меньше мощности, потребляемой приводным двигателем. Асинхронные двигатели, широко используемые в штанговых насосных установках, работают с переменной нагрузкой, при этом среднецикловый КПД и коэффициент мощности значительно меньше номинального значения. Таким образом, спрос на повышение эффективности электропривода штанговых насосов очевиден. При использовании преобразователей частоты это требование может быть удовлетворено за счет уменьшения потерь в двигателе посредством коррекции закона частотного управления.*

Основной целью *исследования является разработка максимально эффективной по энергозатратам стратегии управления асинхронным частотно-управляемым электродвигателем штангового насоса на цикле работы механизма с переменной нагрузкой.*

Объекты: *частотно-регулируемый асинхронный электропривод, штанговый насос, нефтедобывающая скважина.*

Методы: *имитационное моделирование комплекса, состоящего из преобразователя частоты, асинхронного двигателя (с учетом потерь в стали), штангового насоса; аналитическое формирование оптимизированной траектории намагничивающей составляющей тока статора на цикле работы агрегата в системе векторного управления двигателем.*

Результат. *С использованием интегрированной имитационной модели сравнивались энергозатраты штанговой насосной установки при работе при номинальном потоке и при оптимизированной траектории намагничивающей составляющей тока статора. Результаты моделирования показывают, что около 1,6 % необходимой энергии может быть сэкономлено при работе штангового насоса на основе рассчитанной оптимальной траектории намагничивающего тока.*

Ключевые слова:
штанговый насос, оптимизированное управление, асинхронная машина, потери в стали, поле-ориентированное управление, привод с регулируемой скоростью.

Информация об авторах

Текле С.И., аспирант, Уральский Федеральный университет.

Зюзев А.М., доктор технических наук, профессор, Уральский Федеральный университет.

Костылев А.В., кандидат технических наук, заведующий кафедрой электропривода и автоматизации промышленных установок, Уральский Федеральный университет.

Поступила 15.10.2022.
Прошла рецензирование 25.10.2022.