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OPTIMIZATION OF OIL PRODUCTION BY USING SUCKER ROD PUMPS BY MAINTAINING OPTIMAL SYSTEM BALANCE

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Abstract: This paper explores the optimization of oil production by using sucker rod pumps while maintaining optimal system balance. Loss of efficiency due to unbalanced pump units and increased energy requirements are the key challenges in the exploitation of oil wells. In order to overcome these problems, an intelligent monitoring system has been explored and it integrates sensors, SCADA platform and predictive algorithms for real-time performance monitoring. The research has been conducted on five oil wells, where the key parameters, electric current, motor power and gearbox torque have been analyzed – before and after balancing the system. The results show a reduction in peak current and motor power, as well as the elimination of negative torque, thus increasing the efficiency and reliability of the equipment. Based on the calculation of electricity consumption, savings of 8% to 14% have been recorded, with an average value of 11%. In addition to energy efficiency, optimal balancing contributes to extending the service life of the gearbox and reducing the number of production downtime. The obtained results confirm that the combination of CBM approach and intelligent remote monitoring is a reliable basis for improving the exploitation of oil by using sucker rod pumps. This approach contributes to reducing operating costs, preserving equipment and achieving sustainable development goals in the oil industry.

Keywords: Optimization, Oil Production, Predictive, Sucker Rod, System Balanced

1 INTRODUCTION

After the drop in a formation pressure in the oil-producing wells by using reservoir energy, the mechanical method of exploitation (gas lift, sucker rod pump, electric submersible pump, hydraulic pump) is chosen in order to ensure the extension of the production life and increase the final utilization. The choice of method depends on the

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characteristics of the reservoir, well and fluid being produced. The oldest method of applying sucker rod pumps. The number of wells in the world that produce oil by using this method can only be assumed and is 21%, while their share in oil production is 7%. Given their large share in oil production, the main goal of the engineers is to safely manage the production of wells with the least amount of operating costs, downtime and failures of the equipment (Kis, 2021).

(Bode, 2019) states that such systems have shortcomings in terms of loss of efficiency due to poor system balance, paraffinization impact and reactive response due to the distance of oil fields. Precisely because of this loss of efficiency, it is proposed to introduce an intelligent system for monitoring the operation of sucker rod pumps, which consists of three levels: conventional pump unit with sensors, RMS level with industrial computers for collecting and sending data through the MODBUS protocol and from the level of the centralized control station (Aliev et al., 2018).

This paper describes the method of maintenance according to the state or predictive maintenance of the system in order to reduce the costs of oil exploitation, to reduce the consumption of electricity, which is directly related to the reduction of the negative impact on the environment, as well as the extension of the service life of the equipment.

2 METHODOLOGY

We live in a time when a new generation of industrial automation, intelligent production and advanced technologies is emerging, leading to Industry 4.0 and digital business.

Predictive maintenance of assets in production plants is a key component of the concept of e-production. Predictive maintenance systems, known as e-maintenance, allow production and operating systems almost zero frequency of downtime, through the use and integration of real-time monitoring (Wu et al., 2016). These systems are capable of comparing product performance through globally networked monitoring systems, enabling a shift of focus from fault detection and diagnostics towards predicting and forecasting degradation.

Remote monitoring and evaluation of the system performances in real time requires the integration of various technologies, including sensor devices, wireless communication, virtual integration and interface platforms (Gregor et al., 2016).

2.1 Maintenance method according to the condition

This paper is based on the application of modern technologies and methods of monitoring the parameters and their use within the maintenance of the oil production system by sucker rod pumps. The modern concept that deals with the detailed analysis of all aspects of maintenance is called the CBM concept, i.e. Condition-Based

Maintenance. In order to implement this concept in a thorough and quality manner, it is necessary to have the appropriate equipment within the maintenance system, which is the basic form of diagnostics, known as "Condition Monitoring".

This research paper will show all the measurements that have been used as the basis for the analysis, on the basis of which the appropriate conclusions and recommended steps for the improvement of production were made. These improvements are directly reflected in the more reliable operation of the oil production system, and accordingly in the increase in the efficiency of the systems.

When collecting data for the research, devices (sensors) have been used to constantly monitor the behavior of the parameters in real time, including the frequency controller for obtaining data on the operation of the electromotor for the analysis of the dependence of electricity consumption on the amount of fluid (oil) produced. In addition to the aforementioned sensors, data from the measuring gauge have been used to analyze the impact of the pump unit on the motor frequency, i.e. the impact of the system imbalance on the generation of the reactive motor power.

Based on all the collected data, the elimination of the causes of the problems that have affected the potential downtime as well as the reduction of the efficiency of the system has been initiated and the achieved results have been determined.

Traditional maintenance methods have evolved into modern approaches, such as condition-based maintenance (CBM). CBM makes maintenance decisions based on the current state of the machine, which is monitored through a measurement system (Jardine et al., 2006). This approach reduces the frequency of maintenance, with the performance of interventions only when really needed, which saves costs and improves consistency (Marseguerra et al., 2002). With the advent of the fourth industrial revolution and the advancement of computer and visualization technologies, a new era has emerged in the field of maintenance, known as prescriptive maintenance (Matyas et al., 2017). This concept goes beyond just predicting failures and focuses on proactive and smart maintenance planning, enabling machines to make their own decisions and guide users towards solutions (Lee et al., 2020).

The CBM concept consists of three key steps (Jardine et al., 2006; Lee et al., 2020) and they are:

1. Collecting relevant data to create a successful system,
2. Data processing (management of the received information), processing the signals important for understanding the problems with the system,
3. Making a decision on the manner of maintenance based on the collected data, proposing an effective maintenance policy

Figure 1. shows the three basic steps in the CBM concept, as defined by (Lee et al., 2020).

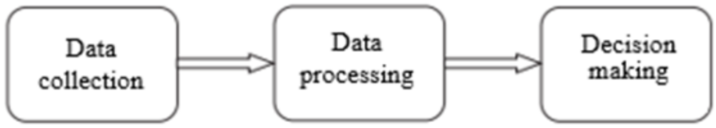

Figure 1 Three steps of the CMB concept

2.2 Basics of the oil production system by using sucker rod pumps

The oil production system with sucker rod pumps consists of a surface unit, a series of sucker rods and a sucker rod pump. The surface unit, called the pump unit, is the drive of the system. **Figure 2.** shows the scheme of the conventional design of the pump unit (Langbauer et al., 2021).

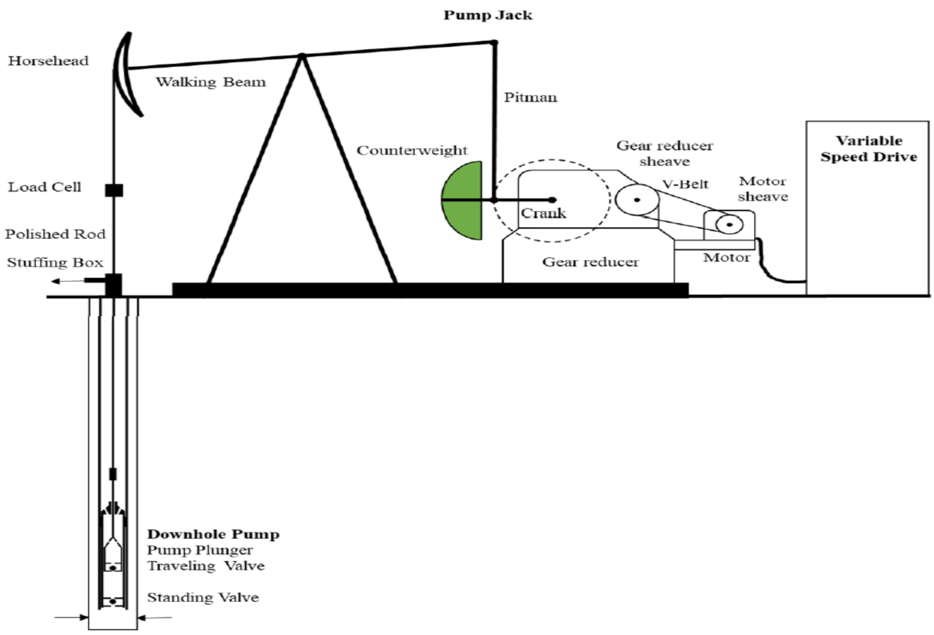

Figure 2. Oil production system by using sucker rod pumps

The first part of the pump unit reduces the rotation speed, while the second part transforms the rotation into translation. The pulley of the electromotor is driven by V-belt, which drives the pulley of the gearbox and is the first stage of speed reduction. The gearbox pulley is installed on the inlet shaft of the two-stage gearbox, which further reduces the rotation speed. A final speed is achieved on the output shaft of the gearbox.

This transmission system usually reduces the motor speed from 1,000 rpm by a factor of about 150 to 200. Finally, the system speed (number of strokes) in the range between 3 and 15 rpm is reached. The crankshafts carry a counterweight, which balances the weight of the rods, and are connected to one end of the balance beam. At the other end of the balance beam, a horse head is placed. The horse head hangers carry a polished rod, which passes through the sealing head and the blowout preventer. The polished rod is connected to a series of sucker rods, which transmits the movement of the pump unit to the pump rod (Langbauer et al., 2021).

2.3 Remote monitoring of the system operating parameters

In practice, there are several alternative methods that can be used to detect the degree of balance, such as time ratios, peak current, total power consumption and peak torque between downward and upward movement of a polished rod. These methods have a high practical value, but the labor costs are high without help of the automatic system for assessing the degree of balance.

The remote monitoring platform consists of two parts, including the database and the web server, as well as the remote monitoring unit. The database and web server receive real-time status data sent from different oilfields via GPRS (General Packet Radio Service), store it in the database and deliver web pages to remote terminals. The remote monitoring unit allows customers to monitor the operating states of the pump units by using a browser on a computer and respond to abnormal situations in a timely manner, as described in the relevant paper (Lv et al., 2016).

On Figure 3. a scheme of the remote monitoring system of well operation is presented.

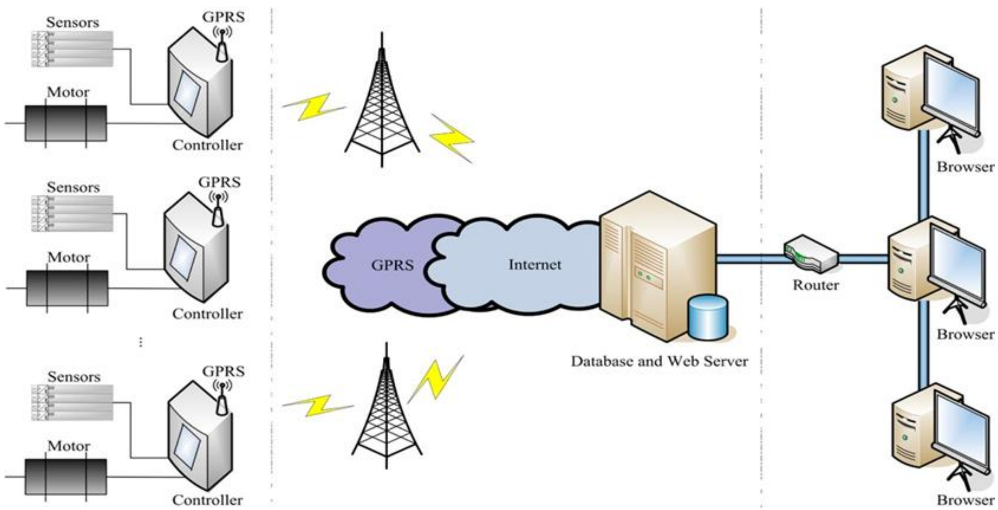

Figure 3. Remote monitoring system (Lv et al., 2016)

2.4 System balance

The best method that the operator can use to balance the net peak torque on the pump unit gearbox is to simultaneously apply power and mechanical methods to determine the existing net torque of the gearbox. When analyzing the net torque graph, the power torque overlaps with the net torque of the gearbox obtained by the mechanical gauge, which allows easy visual reassessment of the graph and identification of discrepancies. The dynamogram and power data can be further analyzed to determine the current net torque of the gearbox. This torque is calculated for upward and downward movement conditions, and then the recommended distance for the movement of the counterweights to balance the unit is displayed. Balancing the pump unit is facilitated by using this combination of motor power measurement and dynamogram. If the net torque of the gearbox on the pump unit is kept in balance, then the peak torque on the motor and gearbox is lower, the peak power supplied by the motor is lower, and the peak current drawn by the motor is reduced, thus reducing energy costs and increasing the service life of the equipment (Rowlan et al., 2005).

2.4.1 Net torque

In general, three types of torque can be distinguished on the pump unit gearboxes (Gibbs, 1992):

1. The torque of the rod is the result of the load of the polished rod and can be calculated based on the kinematic parameters of the unit.
2. The torque of the counterweight is necessary to move the counterweights. It has a sinusoidal shape relative to the angle of the crankshaft in mechanisms that use rotary counterweights.
3. Inertial torque is the energy stored in parts of the pump unit, which is used to accelerate or decelerate, whereby it is released during operation. This torque can be significant if the variation in crankshaft speed is significant.

The net torque on the speed gearbox is the sum of the above-stated components. This is the torque that must be provided by the power input from the main drive. Detailed methods of calculating the net torque components of the crankshaft are presented below (Takacs & Kis, 2021).

On Figure 4. The torques being the components of the net torque as a function of time for one pumping cycle are presented (Kis, 2021).

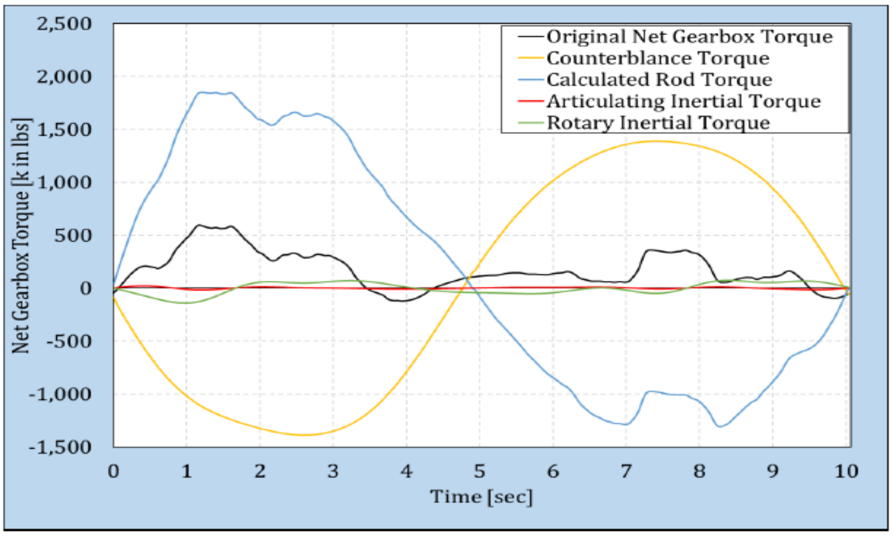

Figure 4. The components of the net torque as a function of time for one pumping cycle

2.4.2 System balance

For each complete stroke, the net torque of the load on the gearbox is cyclic, usually with two maximum and two minimum peaks. The upward peaks occur during the upward and downward movement of the polished rod, and the minimum peaks occur in the upper and lower position of the polished rod. For balanced operation, the magnitude of the peaks should be approximately equal. The pump unit manufacturers use different types of balancing and mechanical characteristics to reduce the peak torque of the gearbox and mitigate the cyclic impacts of the load.

The gearbox is said to be under-balanced if the upward peak is higher, and the gearbox is said to be over-balanced or too heavy if the downward peak is higher. Since in the rotating system the torque and power are directly related, the above-stated statements can be equally applied to the cyclic nature of the motor power developed during the complete stroke of the pump unit. Figure 5. illustrates these concepts and definitions for the torque (Nm) or power (kW) markings of the motor (McCoy et al., 1999). If the net torque of the gearbox is kept in balance, then the peak torque imposed on the motor, the peak power supplied by the motor and the peak current drawn by the motor are reduced, thus reducing energy costs (Rowlan et al., 2005).

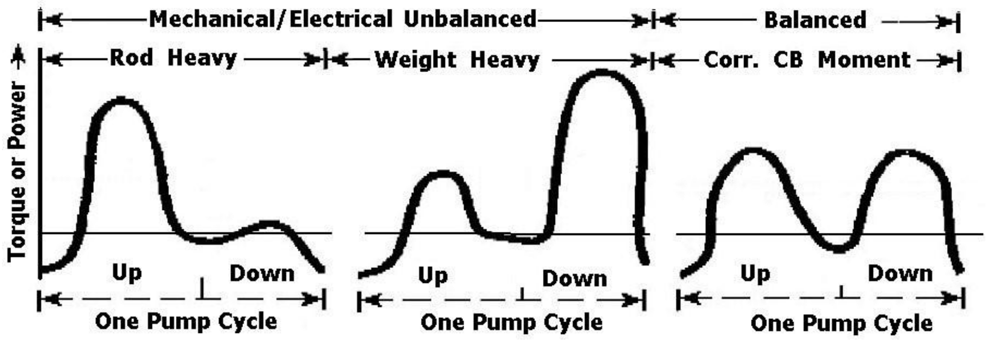

Figure 5. Torque (Nm) or power (kW) for unbalanced/balanced systems

Figure 6. shows that the torque, calculated from the electrical power on the motor, behaves in almost the same way as the net mechanical torque on the gearbox, calculated from the load measurement on the polished rod. Both the motor output torque and the gearbox torque have a peak (maximum) and a drop (minimum) on the part of the pump cycle, when moving upward and downward. The power and mechanical torque data show that this crankshaft balanced pump unit is too heavy (over-balanced) and the counterweights should be moved inwards from the end of the crankshaft to balance the torque peaks. Also, notice that when the gearbox shows a negative mechanical torque, this also happens with the motor. The negative torque of the motor is the result of a combination of the torque of various moving elements (including crankshafts, weights, beam and rod loads) that drive the motor over its synchronous speed where it operates in the "regenerative power" mode during that part of the stroke (Rowlan et al., 2005).

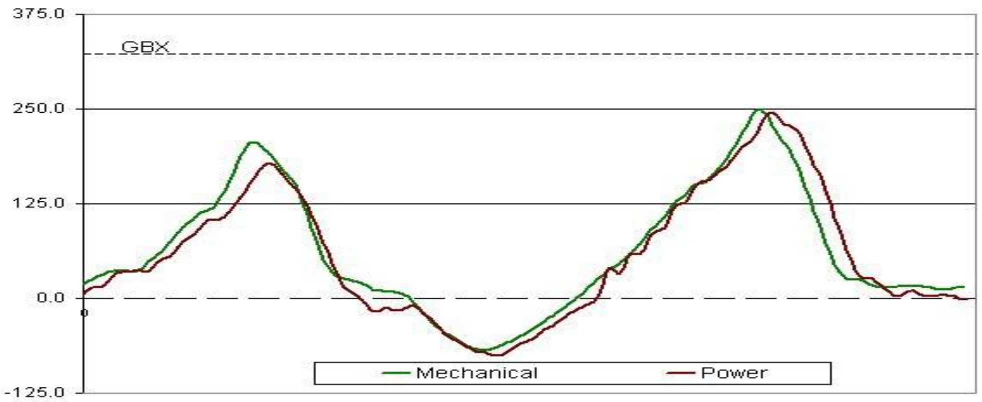

Figure 6. Comparison of the torque diagram from the dynamogram and motor power in one pumping cycle

2.4.3 Gearbox service life

The most important parameter that determines the service life of the gearbox is the ratio between the nominal torque of the unit and the torque load during its operation. Figure 7. illustrates the effect of the overload, showing that only 10% of the increased torsional load relative to the nominal value can reduce the service life of the gear by half, and 20% of the overload can result in only one fifth of the service life specified by the manufacturer (Kis, 2021).

A common problem due to overload is pitting corrosion – a type of the surface fatigue – when the stress on the surface of the gear teeth exceeds the limit of the periodic load material. These surface cavities can lead to gear teeth failures at overloaded gearboxes, in accordance with ANSI/AGMA 110.04, Gear Tooth Failure Mode Nomenclature (Elliott et al., 2018). Therefore, achieving the optimal torque load improves the service life of the most expensive part of the sucker rod pump installation. This can be achieved by applying the appropriate balance of the pump unit.

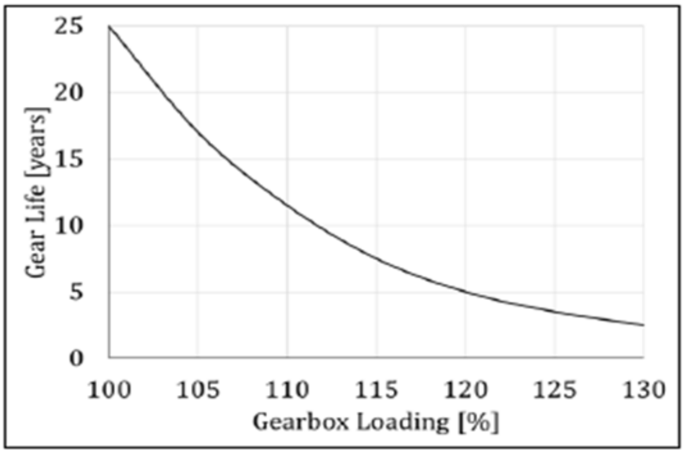

Figure 7. Dependence f the gearbox service life and operational overload (Clegg & Lake, 2007; Kis, 2021)

2.4.4 Optimal balancing benefit

Proper balancing of the pump unit gearboxes brings a number of direct and indirect benefits, which are summarized below (Podio et al., 2001; Rowlan et al., 2005; McCoy et al., 1999):

The torque size required for the gearbox can be significantly reduced compared to the unaccounted state, thanks to lower peak torque. The required electromotors can have a lower nominal power due to smaller changes of the load and a lower load coefficient.

The service life of the equipment, especially the gearbox, may be extended due to a reduced number of torque fluctuations. Operating costs are reduced due to lower energy costs, resulting from the reduced energy consumption for heating the motor, as well as lower maintenance and replacement costs due to the balanced operation of the gearbox.

3 RESULTS AND DISCUSSION

For the purpose of analyzing the impact of the optimal system balance, the conventional system for the mechanical method of oil exploitation has been used with sucker rod pumps with an integrated system of an intelligent control and real-time data transfer. Figure 8. shows one such system.

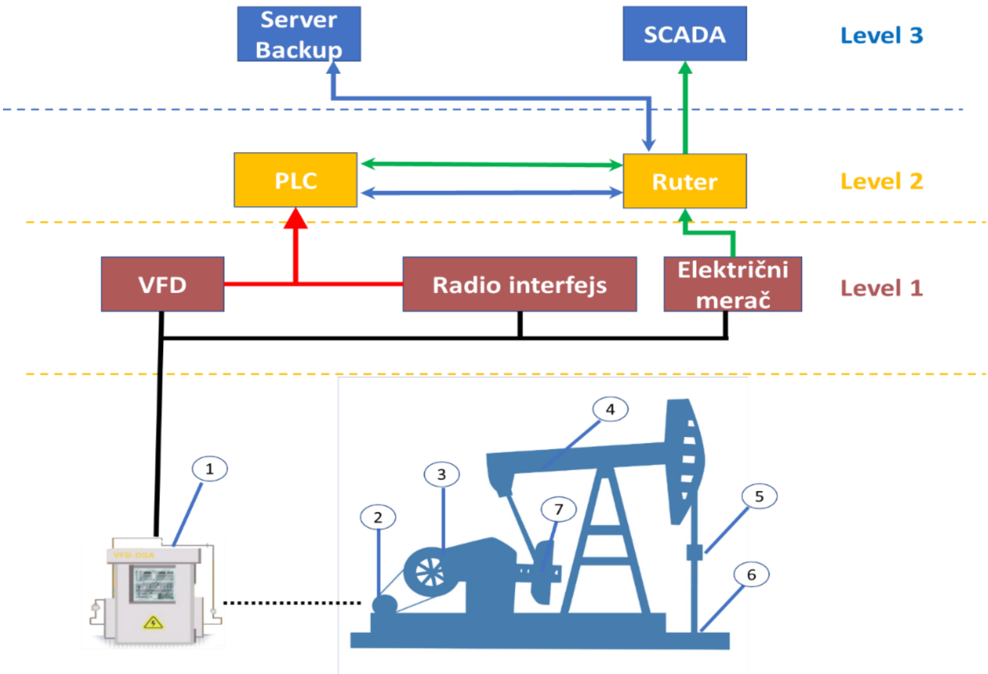

Figure 8. Data transfer from the well to the user (SCADA), (1-Intelligent Control Station (ISU), 2-electromotor, 3-gearbox, 4-balance beam, 5-dynamograph, 6-sonologist, 7-weights)

As highlighted in the theoretical research of this paper, the pump unit balance is monitored through a combination of motor power parameters (kW) and data from the dynamogram (load in N). If the net torque of the gearbox on the pump unit is kept in balance, then the peak torque on the motor and gearbox is lower, the peak power supplied by the motor is lower, and the peak current drawn by the motor is reduced, thus reducing energy costs and increasing the service life of the equipment. These are the conditions for optimizing the cost of oil production with sucker rod pumps.

The implementation of an intelligent control system provides straightforward information on the need to balance the system. The intelligent management system monitors the mentioned operating parameters and, through software solutions, reports the problem to the monitoring specialist when the torque reaches the set limit value. Considering that the torque is directly proportional to the current power and motor power, when reaching the maximum value of peak power and peak current, the ISU activates an alarm that the torque set value has been reached. At that point, the monitoring specialist has sufficient time to issue a request to balance the pump unit and bring the system into balance. In addition, by monitoring the growth trend of the peak current and peak motor power, the specialist can predict before the alarm when balancing will be required. Timely balancing saves energy, protects equipment from breakage and optimizes oil production.

The research has been conducted on five oil wells and similar results have been obtained on each of the wells. Predictive maintenance has saved energy, protected equipment from malfunction and reduced the number of production downtime to zero.

It should also be noted that the quality balance annuls the reactive motor power and protects the power supply system from damage and reduces the cost of charging for energy returned to the power supply network. The research will show the impact of a good balance on the reduction of the reactive energy of the electromotor.

The visualization of the parameters from the electric gauge has been done through the AVEVA platform and allows the specialists to notice the problem of imbalance and react to the problem in a timely manner by issuing a request for balancing the pump unit.

Figure 9. shows the parameters: frequency F(Hz), current I(A) and power P(kW) in real time, before balancing and after balancing the pump unit.

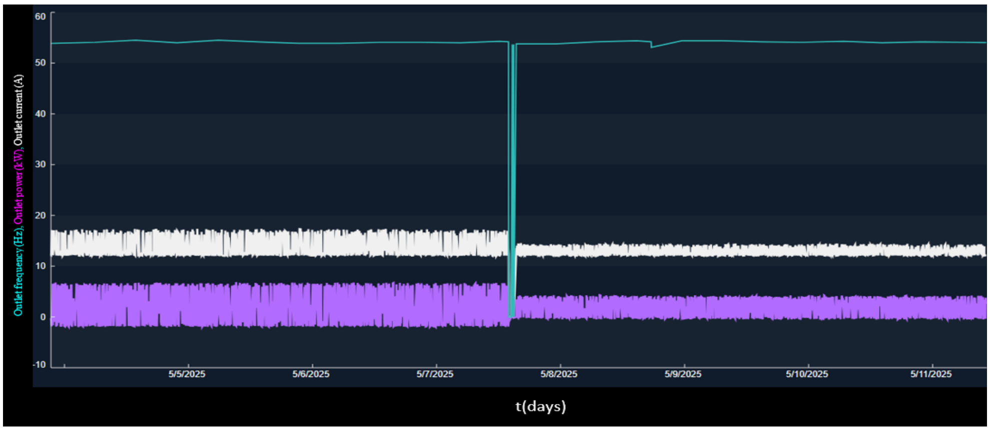

Figure 9. Display of operating parameters of the electric motor in real time - frequency F(Hz), current I(A) and power P(kW) in real time, before balancing and after balancing the pump unit

Considering that the torque is in direct proportional dependence on the current (motor power), as defined in the theoretical part of the research, the torque of the motor, i.e. the load on the gearbox is reduced and the negative torque value is neutralized.

Figure 10. Shows the motor torque before and after balancing the pump unit.

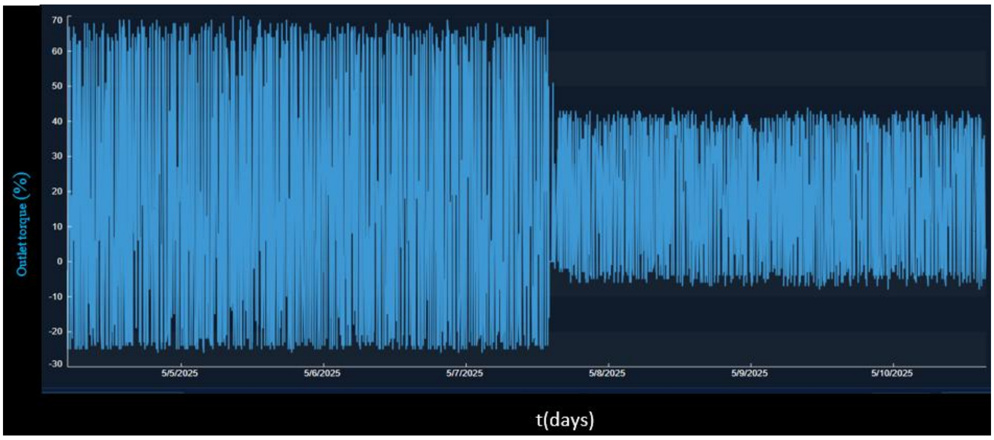

Figure 10. Diagram of the motor torque before and after balancing the pump unit

The research has been conducted on five wells (K-001, K-002, K-003, K-004 and K-005) where increase in peak currents, in peak motor power and in torque has been determined by remote monitoring. Special emphasis is placed on the reduction of electricity consumption after balancing, as well as on the reduction of the torque that impacts the extension of the service life of the surface equipment, especially the gearbox.

In Figures 11. and 12, the dynamograms before and after balancing are shown. It can be observed that the imbalance of the system does not affect the increase or decrease of the maximum and minimum load. Given that the oil production system uses a frequency regulator, the pumping speed is constant. To maintain a constant speed, electrical parameters such as current (I) and the power (P) consumed to drive the motor are adjusted.

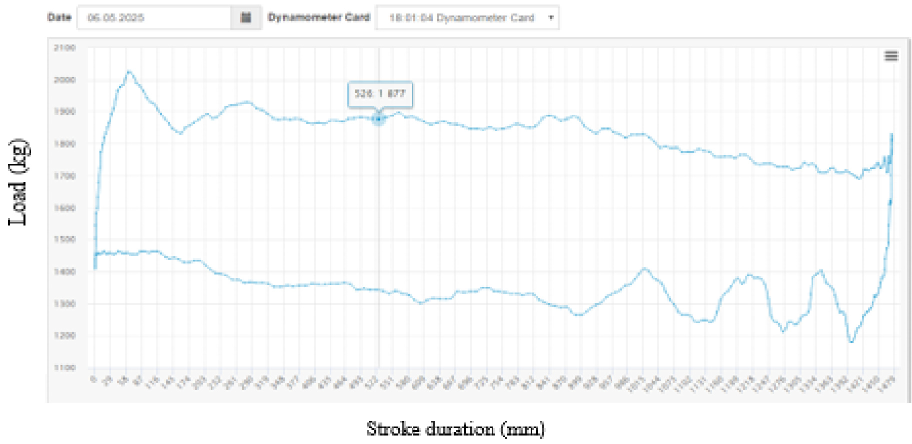

Figure 11. The dynamogram before balancing the system

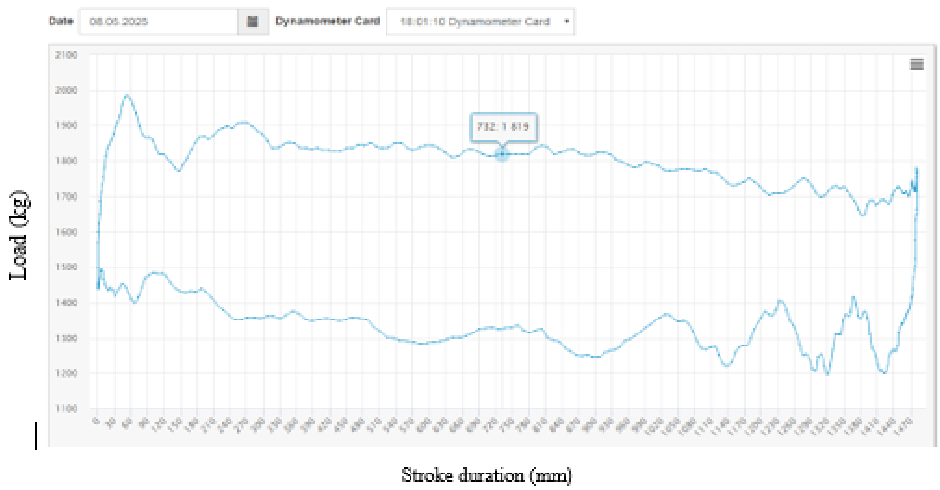

Figure 12. The dynamogram after balancing the system

In Table 1 the wells are presented along with the key operational parameters and installed pumps.

Table 1 The wells with the key operational parameters and installed pumps

Well	Pump	Installation depth (m)	Percentage of water (%)	Daily fluid production (m3)	Stroke duration (mm)	Number of strokes (o/min)
K-001	25-175-RHAM-12-3-2-0	1205.52	92	22	2151	4.6
K-002	25-175-RHAM-13-3-1-0	1192.46	87	12	1600	3.9
K-003	25-175-RHAM-13-4-1-0	900.32	91	17	1565	5.3
K-004	25-175-RHAM-12-3-2-0	1560.21	67	13	1470	4.3
K-005	25-175-RHAM-13-3-1-0	1599.23	58	12	1569	4

During the research, the analysis has been performed by using historical data from the SCADA platform. The analysis has been performed by monitoring the current before and after balancing, and the difference of the mean value of the current has been taken into account for the calculation of the consumed electricity before and after balancing.

3.1 Mathematical calculation of electrical energy consumption

In the oil extraction system using sucker rod pumps, an asynchronous motor is used as the driver. The asynchronous motor is connected to the electrical grid from the stator side, from which it draws electrical power P_1 (kW) (consumed power). The rotor is mechanically coupled to a reducer, which transmits useful mechanical power P (kW). The difference between the consumed electrical power P1 and the useful mechanical power P is equal to the total losses occurring in the motor, which consist of electrical, magnetic, and mechanical losses, specifically losses in copper, losses in iron, and losses due to friction and ventilation (Vukić et al., 2011).

The electrical power P is the rate of change of electrical energy W, which varies with time t. The unit of measurement is the watt (W).

$$P = \frac{W}{t} = U \cdot I \tag{1}$$

Where:

- W - electrical energy (J),
- t - time (s),
- U - voltage (V), and

- I - current (A).

Depending on the total load of the oil production system using piston pumps, a certain total power is consumed, referred to as the apparent power of the consumer S (VA), which is represented by:

$$S = U \cdot I \qquad (2)$$

Where:

- S - apparent power (VA) and I - current (A).

The apparent power consists of two different components:

1. Active power P (kW), which represents the useful component, and
2. Reactive power Q (VAr), which usually represents system losses.

The power triangle illustrates the relationship between useful power P, reactive power Q, and apparent power S as a function of the angle of the power components φ, as shown in Figure 13.

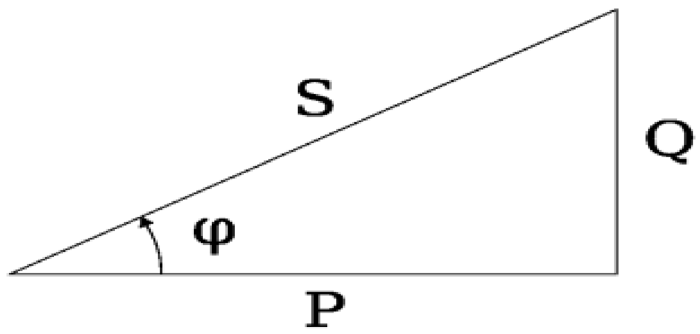

Figure 13. Power triangle (Vincetić, 2022)

The apparent power can be calculated using a triangle according to the equation (3):

$$S = \sqrt{P^2 + Q^2} \qquad (3)$$

Where:

- P - active power (W), and
- Q - reactive power (VAr).

The power factor cosφ is defined by the ratio of active (P) and apparent (S) power according to equation (4):

$$cos\varphi = \frac{P}{S} \tag{4}$$

Active power P is the useful power that transfers electricity from source to consumer. The unit of measurement of manpower is watt (W). It performs useful work and is converted into another useful form of energy. Also, the workforce depends on the work of consumers and power factors. The working power of P is equal to the product of the effective value of current and voltage at the input connections and the power factor of cosφ (for monphase engines) according formula (5):

$$P = U \cdot I \cdot cos\varphi \tag{5}$$

That is:

$$P = \sqrt{3} \cdot U \cdot I \cdot cos\varphi \tag{6}$$

for three-phase engines acoording formula (6).

Where:

- cosφ - power factor defined by the phase angle φ, which in passive networks can be $\pi/2 < \varphi < \pi/2$, so $0 \leq cos\varphi \leq 1$. If φ=0 i cos φ=1, there are no reactive elements in the system then.

The reactive power of Q is equal to the product of the effective values of the current, voltage and sinuses of the phase angle phi (for monophasic engines) according to equation (7):

$$Q = \sqrt{3} \cdot U \cdot I \cdot sin\varphi \tag{7}$$

That is:

$$Q = \sqrt{3} \cdot U \cdot I \cdot sin\varphi \tag{8}$$

for three-phase engines acoording formula (8).

The measuring unit is voltamper-reactive (VAR). The reactive power of Q is defined as the power of inductive consumers that is required for the formation of magnetic fields in the network. It is an imaginary energy that is not used in the system, it only burdens and returns energy to the grid.

The oil production system with sucker rod pumps is not linear and during one pumping cycle, loading changes in the system during cycles, so the electrical parameters are also variable over time (Vincetić, 2022).

Given that the system is completed with a frequency converter and a brake resistor, partial compensation of the reactive power can be carried out with thermal energy released on the brake resistor so that this energy does not return to the grid and causes damage to the grid. This compensation amounts to up to 10% of the power of the frequency converter, and in the tested case, it amounts to 1,5kW.

The limitation of such a system is the lack of a recuperator that would direct the reactive power as energy for supplying secondary consumers (lighting, video sensor, etc.). For this reason, by balancing the pumping unit, the aim is to completely eliminate reactive power and use only active power to the system. Then the apparent power taken from the system would be equal to the active power and savings in electricity consumption would be achieved.

Power and power consumption parameters will be shown in tables and graphically on a daily basis. These parameters will be presented by comparison for all five tested wells before and after balancing the system in Table 1.

Table 2. shows the measurement of electricity consumption as well as the savings achieved before and after balancing the pump units on five wells.

Table 2 Consumption and saving of electricity in kWh on a daily basis and in percentage terms

	Before balancing		After balancing		Savings	
Well	Power P(kW)	Electricity consumption (kWh/day)	Power P(kW)	Electricity consumption (kWh/day)	(kWh/day)	%
K-001	2.5	60.7	2.3	55.7	5.0	8%
K-002	2.8	67.2	2.4	57.6	9.6	14%
K-003	1.9	45.6	1.7	40.8	4.8	11%
K-004	3.1	74.4	2.7	64.8	9.6	13%
K-005	3.5	84.0	3.1	74.4	9.6	11%
					Average	11%

The analysis clearly shows that balancing the system leads to a decrease in electricity consumption. For example, a significant decrease in the average power is observed on K-002 well, resulting in daily savings of 9.6 kWh, i.e. 14% in relation to the consumption before balancing. A similar trend has been recorded on other wells, with average savings of 11%.

It could be concluded that, in addition to the savings, the reduction in the working power of the electromotor impacts the reduction in the torque of the gearbox (shown in Figure

10.). In addition to savings, the reduction of the torque of the gearbox extends its service life.

Figure 14. Shows the graphical comparative values of electricity consumption for each of the analyzed wells before and after balancing.

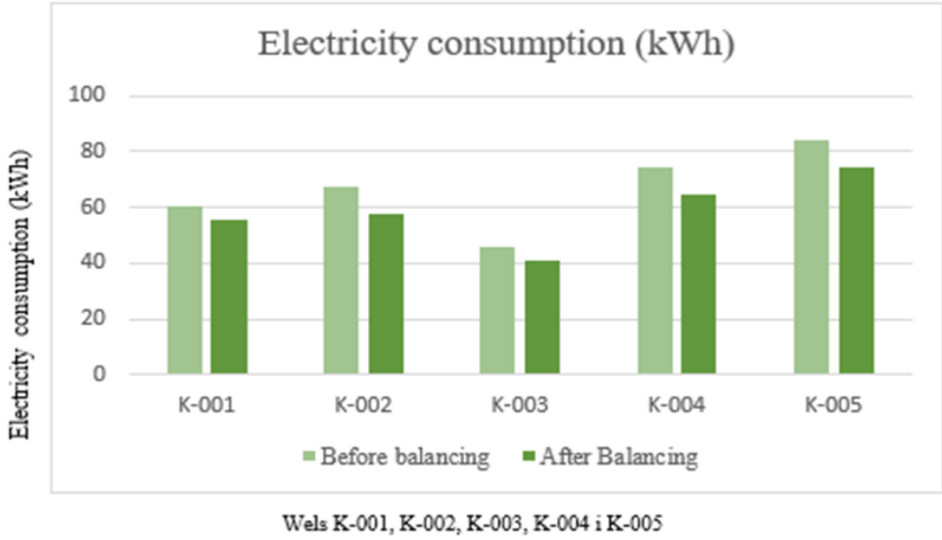

Figure 14 Graphical representation of comparative values of electricity consumption before and after balancing

According to the consumption analysis, it has been concluded that, depending on the nominal motor power, the electricity savings are in the range of 8%-14%, i.e. that the average value of savings in percentage terms is 11%.

Figure 15. shows the comparative values of the power before and after balancing

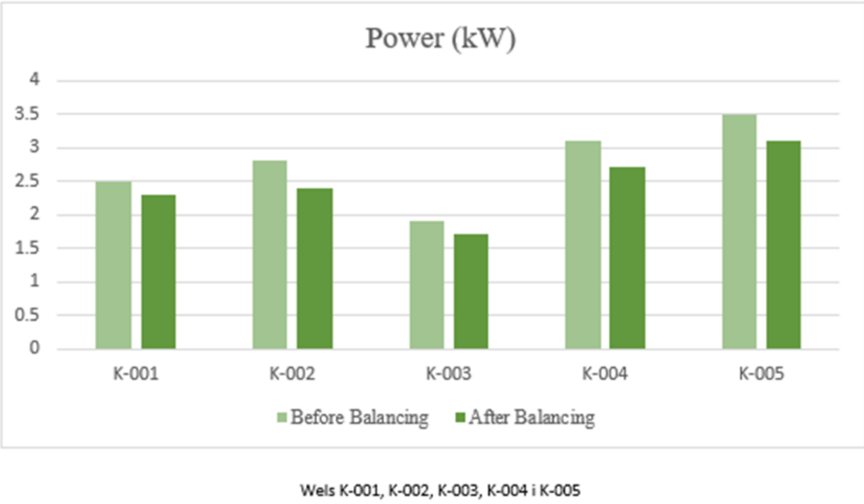

Figure 15. Graphical representation of comparative values of the power

3.2 Statistical Rigor

In Table 3 and 4 Calculation of average savings and standard deviation is presented.

Table 3 Calculation of average saving

Well	Saving P(kWh)	Saving in (%)
K-001	5,0	8%
K-002	9,6	14%
K-003	4,8	11%
K-004	9,6	13%
K-005	9,6	11%
Average	7,72	11%

Table 4 Standard deviation

Well	Saving P(kW)	Difference from average (kWh)	Square of difference
K-001	5,0	-2,72	7,40
K-002	9,6	1,88	3,53
K-003	4,8	-2,92	8,53
K-004	9,6	1,88	3,53
K-005	9,6	1,88	3,53
		Sum of squares:	26,02

The standard deviation (SD) is calculated according to the equation (9):

$$SD = \sqrt{\frac{\Sigma_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} = \sqrt{\frac{26,02}{4}} = 2,55\ kWh \qquad (9)$$

The Standard error (SE) represents the ratio of the standard deviation and the root of the number of samples and calculated according to the formula (10):

$$SE = \frac{SD}{\sqrt{n}} = \frac{2,55kWh}{\sqrt{5}} = 1.14\ kWh \qquad (10)$$

Confidence intervals for average savings, for the assumed level of call 95% and 4 degrees of freedom (n-1 = 4), value t = 2,776, therefore:

- Upper limit = 7,72kWh + 2,776kWh · 1.14 = 10,89kWh
- Lower limit = 7,72kWh - 2,776kWh · 1.14 = 4,55kWh

The average daily energy savings are 7.72 kWh, with a 95% confidence interval of 4.55 to 10.89 kWh. These values indicate statistically significant energy savings after balance, taking into account the inherent variability in measurements.

Further analysis will consider the impact of operating condition factors such as fluid properties and production variability, which may have a significant impact on system efficiency.

For the wells operating in constant mode with unchanged dynamic level, with a constant number of pump runs and unchanged water content in the produced fluid, the balance is not changed for a long time and the oil production system operates without the need for additional balancing.

In case of a water well increase, the fluid weight in the tubing above the pump system slowly increases, with the increase of the percentage of water in the production fluid falling out of balance. This case occurred in wells in K-001, K-003 and K-005, where after balancing, there is a saving of 8% to 11% in electricity consumption, i.e. an average of 6,47kWh/day per well. A graphic representation of electrical parameters is given in Figure 9. And Figure 10. - (well K-001 - water cut increase from 63% to 92%).

In the event of an increase in production due to a change in operating parameters, the kinematic balance of the system will be disturbed due to a change in the transmission ratio and the pumping speed. Then the system has a big difference in torque and variation of current and power during one cycle. Another impact on imbalance is the deepening of the dynamic level of the well, due to the increase in production by increasing the pumping speed. This type of imbalance has been tested in wells K-002 I K-005. The operating parameters of these wells before and after balancing are given in Table 2, where you can see electricity savings of 13.5% on average, i.e. 9,6kWh/day per well.

Figure 16 graphically presents the electric parameters of the pumping unit before and after balancing. The picture shows that on 12 November 2025, the number of pump walks was changed and the pump unit worked with very high peak currents and forces. After balancing, which was carried out on 15 November 2015. the values of electrical parameters were reduced and electricity consumption was reduced.

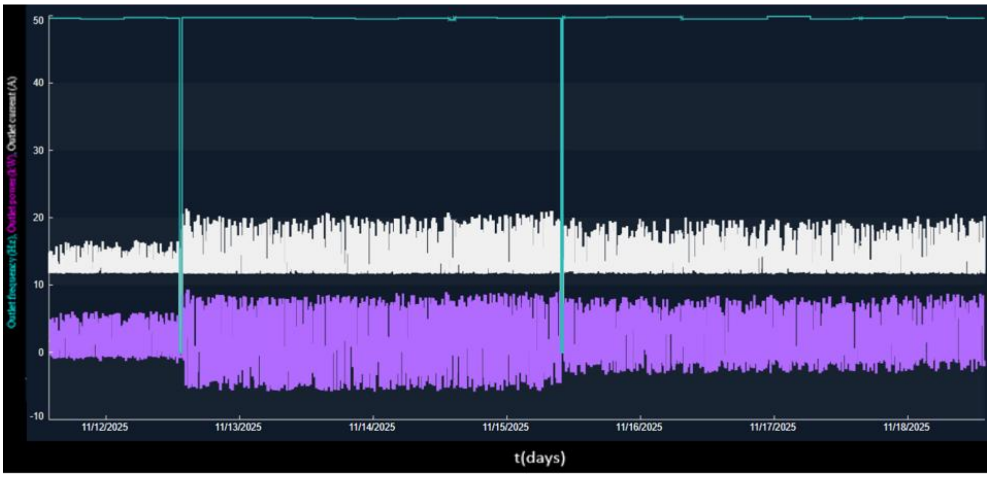

Figure 16. Electrical parameters of the pump operation after increasing the number of walks as before and after balancing the system.

3.3 CO_2 emissions

The calculation of CO_2 emissions is carried out by multiplying electricity consumption (kWh) by the emission factor (kg CO_2/kWh), which represents how many kg of CO_2 is emitted in the production of 1 kWh of electricity.

Equation (CO_2 into kg):

$$CO_2\ \text{kg} = \text{Consumption}\ /\text{kWh} \cdot\ \text{Emission factor kg/kWh} \tag{11}$$

In tons:

$$CO_2\ \text{in t} = CO_2\ \text{kg}/1000 \tag{12}$$

Or directly:

$$CO_2\ \text{t} = \text{Consumption}\ /\text{kWh} \cdot\ \text{Emission factor kg/kWh}/1000 \tag{13}$$

The emission factor depends on the network/source (e.g. in Serbia the share of coal is higher, so the factor is significantly higher than in countries with many renewable sources):

- 0.20 $kgCO_2/kWh$ - low value (places with a large share of low-carbon sources)
- 0.50 $kgCO_2/kWh$ - average value (the European average varies around this for mixed networks)
- 0.80 $kgCO_2/kWh$ - high value (places with a lot of coal), Serbia

The empiric factor of 0.80 $kgCO_2/kWh$ was used to calculate CO2 emissions (AERS, 2025; IPCC, 2025).

In table 5 Electricity consumption in (kWh) and CO_2 emissions were presented before and after balancing the tested wells, as well as the reduction of CO_2 emissions in (kg) and percentage on a daily basis.

Table 5 Comparative overview of electricity consumption and reduction of CO2 emissions before and after balancing

	Before balancing		After Balancing		Saving	
Well	Electricity consumption (kWh)	Daily emission of CO_2 (kg)	Electricity consumption (kWh)	Daily emission of CO_2 (kg)	CO2/day (kg)	%
K-001	60.7	48.6	55.7	44.6	4.0	8%
K-002	67.2	53.8	57.6	46.1	7.7	14%
K-003	45.6	36.5	40.8	32.6	3.8	11%
K-004	74.4	59.5	64.8	51.8	7.7	13%
K-005	84	67.2	74.4	59.5	7.7	11%
					Average	11%

Figure 16. shows the comparative CO_2 emissions before and after balancing on all 5 wells tested

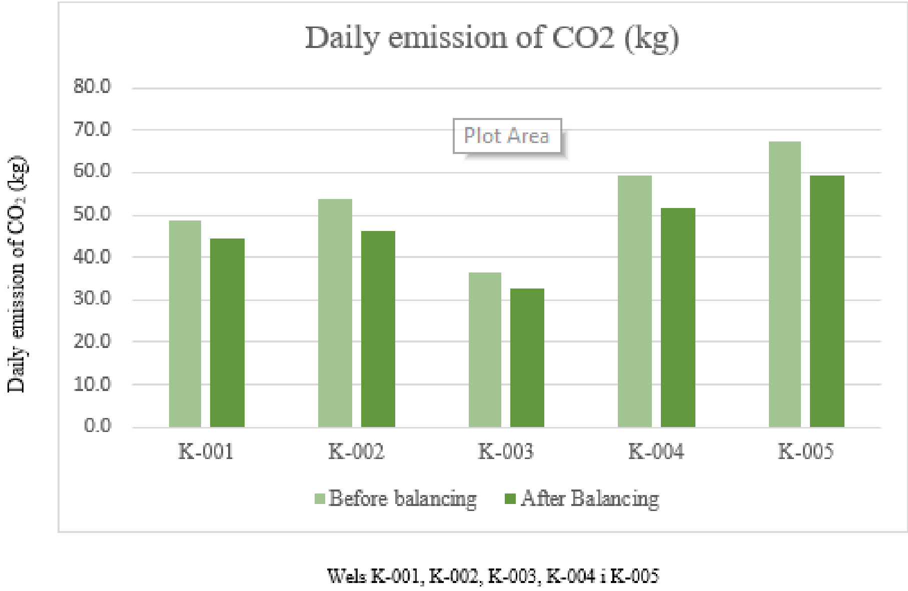

Figure 16. Comparative daily emissions of CO_2 before and after balancing on all 5 wells tested.

3.4 Measurement transparency

Electricity parameters were measured using the SIEMENS SENTRON PAC3220, LCD 96 x 96 mm, Power Monitoring Device, control panel instrument with measurement of electrical variables, protocol: Modbus TCP, with graphical display, Ue rated: 690/400V, 45-65Hz, Ie rated: X/1 A or X/5 A TT, auxiliary power: 100... 250 V + -10% TT/DC. This meter is installed on each of the tested wells in the intelligent control station. This meter is used for continuous measurement of electric current parameters and, in real time, they are sent via MODBUS protocol to the SCADA platform, where parameters are graphically visualised and published through the AVEVA platform. Figure 17 shows the meter used for measuring and monitoring the electrical operating parameters of the downhole equipment.

Figure 17. SIEMENS SENTRON PAC3220

Fulit limits reference condition for metering accuracy in accordance with IEC61557-12, IEC62053-22 and IEC62053-23.

Relative total measurement inaccuracy:

1. For measured variable voltage +/- 0.2 %
2. For measured variable current +/- 0.2 %
3. For measured variable active power +/- 0.5 %
4. For measured variable reactive power +/- 1 %
5. For measured variable output factor +/- 0,5 %
6. For measured variable active energy Cl. 0.5 acc. to... IEC62053-22

For measured variable reactive energy Class 2 according to IEC61557-12 and/or IEC62053-23

3.5 Limitations and future works

Limitations in obtaining precise electrical parameters presupposes the problem of data storage on the server. In order to avoid overloading the server, sending data from the well via the MODBUS protocol is done once in 30 seconds. In this way, we cannot get a complete curve that represents the movement of engine power and current strength parameters in one pump operating cycle. This approach makes it impossible to remotely spot engine power and current peaks. On the graphics displayed as visualization in the AVEVA platform, only minimal and maximum values of these sizes can be observed. To some extent, this data can refer to problems in operation (system imbalance) if the engine power and current strength values increase over time from the nominal for a given electric motor to the maximum value.

In that case, the measurement of current strength at the engine phases at the location is initiated. By measuring the current strength in one pump cycle, peaks are recorded in the diagram, through the analysis of which we obtain information about the degree of system imbalance. In Figure 18. The corners of the four pumping unit weight positions (0^O, 90^O,180^O, and 270^O) are shown.

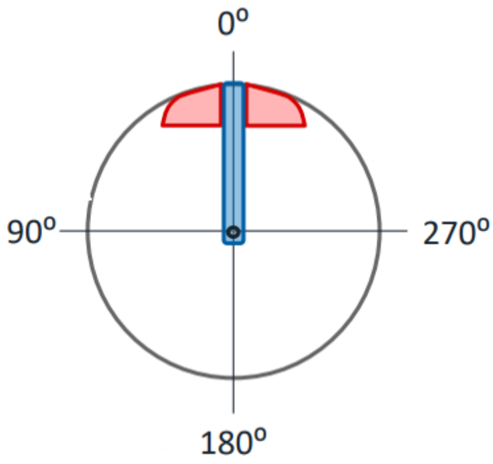

Figure 18. Weight position angles for one pump operation cycle

Based on the measured strength of currents when the weights are in the 90^O and 270^O position, we can calculate the system imbalance coefficient through the equation (14):

$$k = \frac{I\,90° - I\,270°}{I\,90° + I\,270°} \cdot 100 \tag{14}$$

If the value of the coefficient k> 5, we believe that the system is in balance and needs balancing.

This type of measurement is performed using the Fluke 355/353 True-rms 2000 A Clamp Meters device.

Measurement accuracy for currents higher than 10A is shown in Table 6.

Table 6 Measurement accuracy of Fluke 355/353 True-rms 2000 A Clamp Meters

Range	Resolution	Accuracy
40 A	10 mA	3.5 % rdg + 15 digits 0.50 A 2.50 A 0.50 A
400 A	100 mA	3.5 % rdg + 5 digits 5.0 A 2.5 A 2.5 A
2000 A	1 A	3.5 % rdg + 5 digits 5 A 8 A 8 A

This method of determining the imbalance of the System is reliable, but requires additional engagement of operators in the field.

For future operation, the use of the Node-RED platform for online recording of motor power diagrams and real-time current strength for one pumping cycle are under preparation. After implementing this approach and using artificial intelligence, the identification of the System's imbalance will be fully automated and will alarm this work disruption in real time.

For now, it remains an open question and space for exploring the method of used AI for these cases. The layout of the diagrams recorded using Node-RED, which is currently in testing, is shown in Figure 19. The X-axis represents the recording time and the Y-axis represents the engine power P (kW).

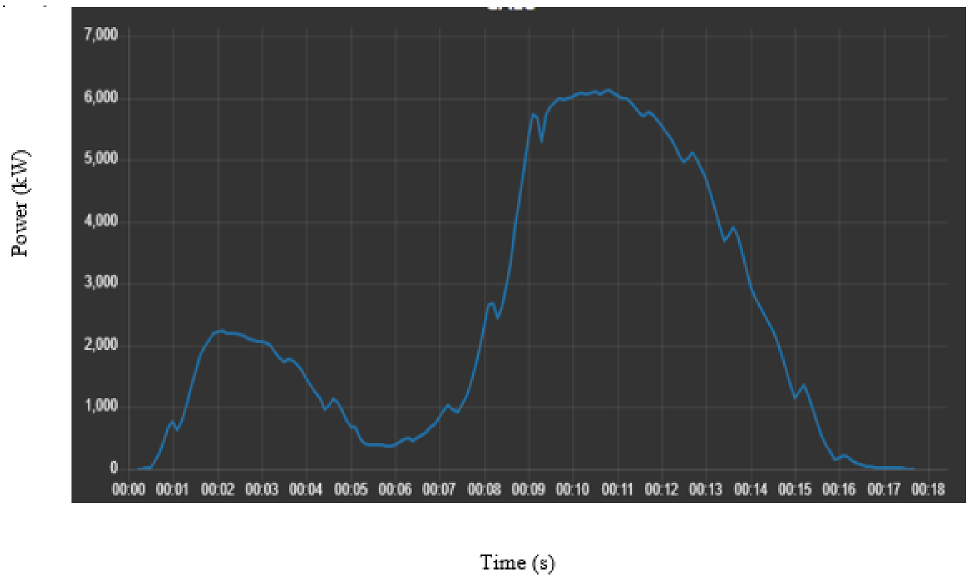

Figure 19. Diagram taken during one pump operation cycle

3.6 Economic profitability

The system for remote monitoring of the oil production system with piston pumps is complex and is used for monitoring a large number of parameters and collecting a large number of data that are used for analysis and making decisions for taking over the activities in order to optimize the product, with reduced costs and increased reliability of work.

The analysis of electricity savings is only one in a series of analyses that needs to be carried out and in order to determine the profitability of the installation of the remote monitoring system. These analyses remain an open topic for subsequent works, and the sum of all analyses will give a unique conclusion that will prove hypotheses about profitability in the shortest possible time and with countless benefits reflected not only in the financial perspective but also in the profit in the field of environmental protection and occupational health and safety in the oil industry.

Certainly, part of the impact on economic profitability has been proven through this work.

4 CONCLUSION

This research paper analyzes the key components of optimizing oil production through sucker rod pumps, with an emphasis on maintaining optimal system balance. Through the application of modern technologies, especially the intelligent monitoring and predictive maintenance system, significant results have been achieved in reducing operating costs, increasing efficiency and extending the service life of the equipment.

It has been identified that traditional maintenance methods, which rely on a schedule of regular interventions, are not effective enough in preventing downtime and failures. Given the complexity of modern systems, a condition-based maintenance (CBM) approach has proven to be a superior strategy. This approach allows maintenance decisions to be made based on the actual condition of the equipment, which leads to a reduction in the frequency of interventions and optimization of resources.

The analysis of the collected data from five oil wells has revealed that the application of predictive maintenance and the system balance results in a reduction in electricity consumption in the range of 8% and 14%, with average savings of 11%. These savings not only reduce the operating costs, but also contribute to reducing the negative impact on the environment, thus meeting modern environmental standards.

Remote monitoring of the system performances in real time enables a faster response to irregularities and potential problems, which further reduces the risk of production downtime. By introducing an intelligent management system, the monitoring specialists are able to identify and solve problems in a timely manner before significant consequences occur, which further optimizes the production process.

The research has also found that proper system balancing not only improves the operational efficiency of the pumps, but also reduces the stress on the mechanical components, thus extending their service life. This aspect is of particular importance for reducing the costs of maintenance and replacement of the equipment, especially in the context of the increasing demands for sustainable development of the industry.

In conclusion, optimization of oil production by sucker rod pumps through maintaining optimal system balance is a key component for increasing efficiency and reducing costs in the industry. This paper provides a basis for further research and application of modern technologies in the oil industry, with the aim of achieving a more sustainable and profitable business. The combination of modern monitoring and analysis methods, together with predictive maintenance, enables proactive production management and contributes to the global goals of energy efficiency and environmental protection.

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