Journal of Sustainable Development of Energy, Water and Environment Systems

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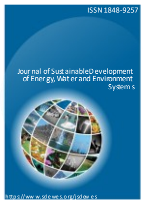

Year 2027, Volume 15, Issue 1, 1140767

Original Research Article

Energy-Water Efficiency of Variable Frequency Drive Control in Irrigation Pumping Stations

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Cite as: Kan, E., Mukhammadiev, M., Majidov, T., Uralov, B., Li, M., Mukhitdinov, O., Energy–Water Efficiency of Variable Frequency Drive Control in Irrigation Pumping Stations, J.sustain. dev. energy water environ. syst., 15(1), 1140767, 2027, DOI: https://doi.org/10.13044/j.sdewes.d14.0767

ABSTRACT

Improving energy and water efficiency in irrigation pumping systems is essential for sustainable resource management in irrigation-dependent regions. Although variable frequency drives are widely used, their overall impact on energy-water performance under real-world irrigation operating conditions remains insufficiently quantified. Laboratory and full-scale field experiments were conducted, including testing at the Teshiktosh-1 irrigation pumping station in Uzbekistan. Pump, electric drive, and overall unit efficiencies were evaluated using dimensionless indicators normalised to nominal rotational speed. Statistical analysis was used to derive empirical efficiency-frequency relationships. Pump and drive efficiencies decrease nonlinearly as rotational speed decreases. At moderate speed reductions (up to ~50% of nominal speed), electric drive losses dominate, whereas at lower speeds, pump losses become the primary contributor to total energy losses. The obtained relationships differ from classical affinity-law assumptions. Field validation confirmed their applicability. Variable frequency drives implementation enabled water savings of about 313.6 thousand m³ (≈16%) and seasonal energy savings of about 107,700 kWh (≈14%). The findings demonstrate that variable-speed control improves overall energy-water performance despite a partial reduction in efficiency at lower rotational speeds.

KEYWORDS

Irrigation pumping station, Energy efficiency, Variable frequency drives (VFDs), Energy-water nexus, Sustainable water–energy systems.

INTRODUCTION

Energy and water conservation are the most important sustainable development goals in modern agriculture, especially amid increasing water scarcity and rising energy prices [1]. Irrigation systems account for a significant portion of global freshwater and energy

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consumption [2], underscoring the need to improve their efficiency to ensure the long-term sustainability of resources and protect the environment. Therefore, optimising the operating modes of irrigation pumping systems is extremely important [3], as these modes directly affect both energy consumption and water losses [4].

This observation is valid for the sustainable development of the agro-industrial sector of the Republic of Uzbekistan [5], where more than 1,600 reclamation pumping stations operate within the Ministry of Water Resources system and annually consume up to 8.0 billion kWh of electricity for water lifting [6]. The selection of an appropriate control strategy is a primary factor influencing pump performance, with modern approaches increasingly focused on high-efficiency regulation methods, such as impeller trimming [7] and variable frequency drives (VFDs) [8, 9]. Among these, VFDs offer the advantage of flexible shaft-speed control, enabling better alignment with water consumption schedules [6], reducing unproductive water losses, and achieving energy savings [10].

Numerous studies have assessed the economic and technical performance of VFDs in pumping stations under various conditions. For example, Cong Tian *et al.* [11] investigated a constant-pressure control system with VFDs in a mining pumping station. Frequency control was used to maintain pressure, significantly reducing energy consumption automatically. The authors did not provide quantitative energy savings data. Miladi *et al.* [12] conducted experimental studies on photovoltaic-powered pumping systems with standard frequency converters, comparing manual and VFD-based control. By eliminating the DC-DC converter and integrating MPPT into the VFD control, the system achieves efficient energy utilisation, reduced cost, and improved reliability. Mukhamadeev and Yagafarova [13] analysed energy savings in oil and gas pipelines using frequency converters, while Shkileva and Sidorenko [14] reported a 35% reduction in energy consumption after implementing VFDs at pumping stations. Research by Plua *et al.* [15] focused on the analysis of variable-speed control of pumps operating in turbine mode (Pumps as Turbines, PATs) to improve the energy efficiency and sustainable use of hydraulic systems. Napierała's study [16] showed that variable-frequency-driven pumps can adapt operating modes to changing time-of-use tariffs, minimising operating costs. Ahonen *et al.* [17] developed a method for optimal speed control of pumps in systems with reservoirs. It was shown that speed optimisation can improve the system's overall energy efficiency without the need to upgrade the pumping equipment.

The article by Yin and Zhang [18] examined the use of frequency converters in automated central heating control systems. Although the primary focus was on heating systems, the results are directly applicable to pumping systems, as the authors analysed the impact of frequency control on operational stability, energy consumption, and system reliability. The authors confirmed that the use of frequency converters provides smoother flow control and reduces energy losses compared to traditional control methods. Vasilev's work [19] focused on improving the efficiency of frequency converters themselves, particularly by optimising pulse-width modulation (PWM) algorithms. Dmitriev and Gerasimov's work [20] also analysed the energy efficiency of frequency-controlled centrifugal pump units. The authors demonstrated that the use of frequency converters significantly reduces specific energy consumption at partial loads compared to throttle control. The article by Kazakbaev *et al.* [21] was devoted to a comprehensive analysis of the energy efficiency of variable-speed pump drives using two types of electric motors: asynchronous motors (IM) and synchronous reluctance motors (SynRM). The use of SynRM in the drive leads to higher losses in the frequency converter than with IM, due to a lower power factor and higher current consumed. The article [22] stated that significant energy savings, approximately 36%, were achieved after implementing new motors with variable-frequency drives. However, the introduction of VFDs increased harmonic current distortion (THDI) by approximately 10%, which negatively impacted power quality. Harmonic filtering or high-pulse drives were recommended.

The reviewed studies highlighted the benefits of VFDs, yet they often focused on single operating scenarios or non-irrigation applications, limiting their generalisability. Most of the works are based on classical models of pumping characteristics and are limited to analytical approaches. Irrigation pumping stations have specific operational characteristics, including relatively uniform water consumption schedules and softer requirements for maintaining precise pressure and flow compared to water supply systems [6]. Consequently, the energy-saving potential of VFDs in irrigation pumping stations is not straightforward and may vary depending on operating conditions. Changes in pump shaft rotation frequency affect not only energy consumption but also pump efficiency, creating a trade-off that requires careful analysis. Despite extensive research on VFD applications, the integrated effect of shaft speed control on both energy efficiency and water conservation in real-world irrigation pumping stations remains insufficiently quantified. In particular, the efficiency-frequency relationships under variable irrigation schedules and their implications for sustainable water-energy management have not been systematically studied.

Analysis of the operation of pumping units with deviations in rotation speed from the nominal value shows that traditional affinity laws do not provide sufficient accuracy for deep speed regulation. This observation was discussed in the studies of Li *et al.* [23], Marchi *et al.* [24], and Afify *et al.* [25]. They identified key aspects to consider when assessing the efficiency of frequency converter use in pumping units at irrigation stations.

Despite the widespread use of variable frequency drive (VFD) technology in pumping systems, there remains a lack of experimentally validated data describing the relationship between pump and drive efficiency and changes in rotational speed under real-world operating conditions of irrigation systems (considering changes in pump efficiency from changes in rotational speed). The absence of such dependencies between efficiency and frequency limits the ability to predict energy- and water-saving potential accurately at irrigation pumping stations operating under variable seasonal demand.

In this context, this research addresses the identified gap by providing experimentally validated efficiency-frequency characteristics obtained from both controlled laboratory tests and full-scale field measurements at operating irrigation pumping stations. Unlike previous studies, which are primarily based on theoretical models or limited experimental setups, this work integrates real operational data under varying hydraulic loads and seasonal irrigation regimes. The novelty of the study lies in the combined assessment of pump and drive efficiency as a function of rotational speed, and the quantification of their joint impact on energy consumption and water-use efficiency under practical operating conditions.

This study aims to analyse changes in the efficiency of pumps and pumping units under VFD control, based on laboratory and field experiments, and to evaluate the impact of these changes on the integrated energy-water performance of representative irrigation pumping stations. The results provide a framework for optimising VFD implementation to support the sustainable operation of irrigation infrastructure.

MATERIALS AND METHODS

This study employed both laboratory and field experiments to investigate the energy and water efficiency of irrigation pumping units equipped with variable frequency drives (VFDs). The experimental methodology was designed to quantify pump, drive, and unit efficiency under variable rotational speeds, validate laboratory-derived efficiency-frequency relationships under real operating conditions, and assess the integrated energy-water performance of irrigation pumping stations.

Laboratory Experimental Setup

The primary laboratory experiments were conducted using a dedicated test rig, consisting of a Lowara CEA 70/33 centrifugal pump, pipelines with valves and fittings, measuring and recording instruments, and a Danfoss VLT Micro Drive FC 051 frequency converter. Figure 1 presents the photo of the laboratory bench, and Figure 2 shows the laboratory stand diagram.

The experimental procedure involved varying the alternating current frequency via the frequency converter, thereby adjusting the rotational speed of the pump shaft. At each rotational speed, the following parameters were measured:

- Inlet and outlet pressures using piezoresistive pressure sensors;
- Flow rate using an electromagnetic flow meter;
- Electrical parameters (voltage and current) using a multimeter.

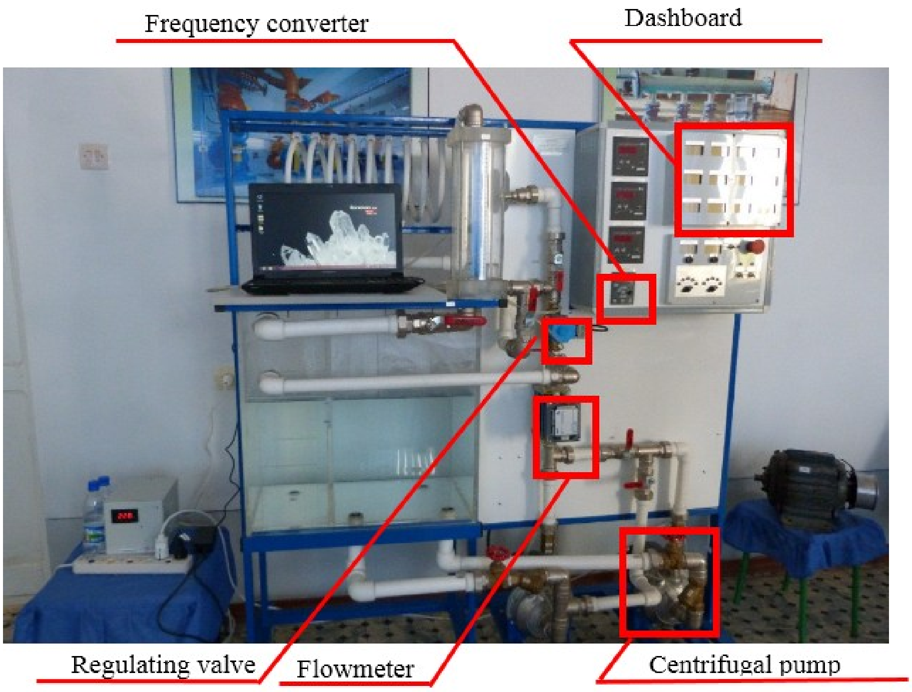


Figure 1. The laboratory stand

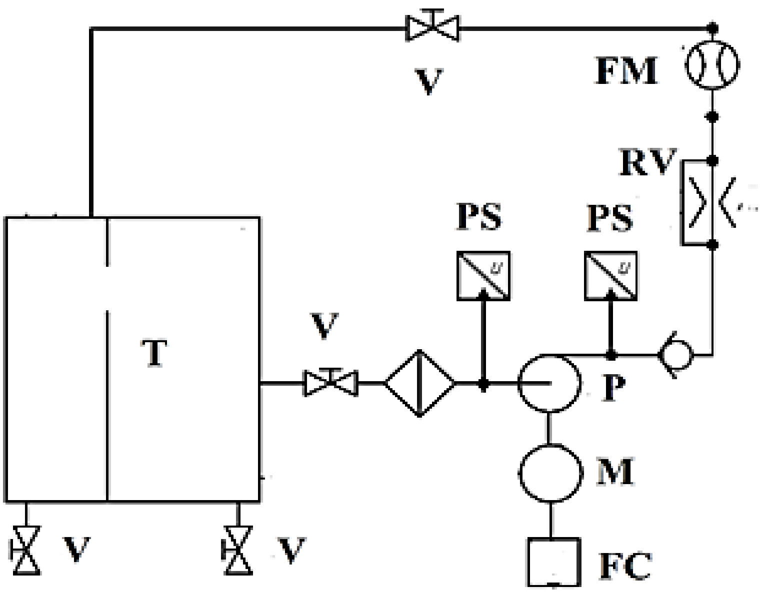
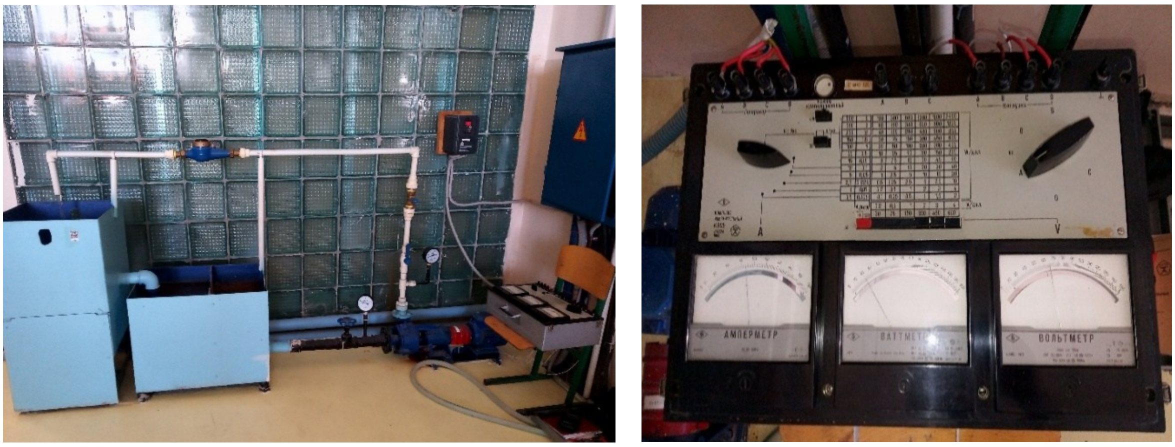


Figure 2. The laboratory stand diagram: V pipeline valves, P – pump, M – motor, PS – pressure sensor, FC – frequency converter, RV – regulating valve, T – tank

The recorded measurements were used to calculate the efficiencies of the pump, electric drive, and overall pumping unit based on standard relationships between hydraulic power and electrical input (see Section "Theoretical Analysis of the Efficiency of the Pump and Pumping Unit" for detailed equations). This approach enabled the evaluation of energy consumption and hydraulic performance across a range of operating conditions.

Verification Laboratory Setup

To verify the laboratory results and assess reproducibility, a second experimental setup was assembled, featuring a serial console pump for both laboratory and field-scale experiments at a representative irrigation pumping station. This setup (**Figure 3a**) comprised receiving and pressure tanks, pipelines with shut-off and control valves, a pump (type K 1.5/18 with 1.5 kW electric motor), and a frequency converter (ZMK1V Series Vector Inverter, 0.75 kW, 3-phase 380 V from ZHIMING Group Co., Ltd). The setup was equipped with control and measurement devices, including a vacuum gauge on the suction line for monitoring suction pressure, a pressure gauge on the discharge line, a calibrated dimensional triangular spillway for flow measurements, a K 51 control and measurement complex for current and power evaluation (**Figure 3b**), and a multimeter for monitoring electrical parameters at the input to the frequency converter.



(a) (b)

Figure 3. General view of the laboratory stand (a) and the measuring complex K 51 (b)

Field Experiments

Field experiments were conducted at Teshiktosh-1 irrigation pumping station. Considered representative of its type, it is the first irrigation pumping station in the Republic of Uzbekistan to have frequency converters installed, enabling full-scale experiments under real operating conditions [26].

The Teshiktosh-1 pumping station in the Jalal Kuduk district of the Andijan region was commissioned in 1971 and has a capacity of 0.4/0.08 m^3/s. It draws water from the Teshiktosh canal and delivers it through two steel pressure pipelines to a pressure basin. The pumping station's technical specifications are presented in **Table 1**. The setup replicated the laboratory measurement protocol to evaluate pump performance under real operating conditions.

Measurements included:

- Pump rotational speed via frequency converter settings;
- Suction and discharge pressures using installed sensors;
- Flow rate using calibrated measurement devices;
- Electrical consumption of the pump-motor unit.

Table 1. The technical specifications of the Teshiktosh-1 pumping station

Parameter	Unit	Value
OVERALL		
Irrigation area	[ha]	467
Required pump flow rate	[m^3/s]	0.4/0.08
Maximum geometric pressure	[m]	88/60
Installed capacity	[kW]	250/75
Volume of pumped water per year	[10^6 m^3]	1,941
Electricity consumed per year	[10^6 kWh]	436,000
MAIN PUMPS		
Brand		200D-90
Number of units		4
Flow rate of one pump	[m^3/s]	0.08
MAIN PUMP ELECTRIC MOTORS		
Brand		A114-4, AO-291-4
Nominal power	[kW]	250/75
Voltage	[kV]	10/0.4
Rotation speed	[rpm]	1500/1470
Efficiency	[%]	92.5

The combination of laboratory and field data allowed for validation of laboratory-derived efficiency-frequency relationships and ensured their applicability to operational pumping stations. The measurement results were used to calculate pump efficiency, electric drive efficiency, and overall pumping unit performance, providing a robust dataset for assessing energy and water-saving potential.

Data Processing and Analysis

Pumps 200D-90 with electric motor drive of 75 kW capacity and frequency converter ZMK1V Series Vector Inverter 75 kW 380 V 3PH are presented in Figure 4. For each operating condition, relative dimensionless indicators were computed and normalised to the nominal rotation speed. These indicators included pump efficiency η_p, electric drive efficiency η_e, pumping unit efficiency η_{unit}, and specific energy consumption [kWh/m³].

(**a**) (**b**)

Figure 4. Pumps 200D-90 (a) and frequency converter (b) at Teshiktosh-1 irrigation pumping station

The procedure for conducting full-scale experiments was as follows: using a frequency converter, the alternating current frequency and, accordingly, the pump shaft rotation speed were varied. For each value of the pump shaft rotation speed, the electricity consumption parameters (voltage and current) and the electric motor power were measured. Measurements of electrical parameters were carried out at different phases at a specific rotational speed of the pump impeller shaft. The measured power values were used to analyse the effect of changes in drive-shaft speed on the efficiency of the electric drive (electric motor and frequency converter). Statistical analysis was conducted using least-squares regression techniques to quantify the relationship between pump efficiency and rotational frequency. Of the considered linear and polynomial regression models, the optimal model structure was selected based on goodness-of-fit criteria, including the coefficient of determination (R^2), adjusted R^2, and root mean square error (RMSE).

The statistical significance of model parameters was assessed using Student's t-test, while overall model adequacy was verified through analysis of residuals and Fisher's F-test. Data processing and regression analysis were performed using MS Excel. The obtained relationships were subsequently applied to evaluate the integrated energy and water performance of the irrigation pumping station. The normalisation approach, based on relative efficiency and frequency ratios, allows the obtained results to be generalised to pumping systems with similar operating conditions.

Theoretical Analysis of the Efficiency of the Pump and Pumping Unit

For the theoretical analysis of the problem, the relationships listed below were used [27]. Pump efficiency η_P is considered as the multiplication of hydraulic, volumetric and mechanical efficiencies:

$$\eta_P = \frac{P_U}{P} = \eta_h \eta_v \eta_m \tag{1}$$

where P_u denotes pump power output, and P – pump power input.

Volume efficiency η_v is defined as:

$$\eta_v = \frac{Q}{Q + Q_L} \tag{2}$$

where Q denotes the flowrate, and Q_L – leakage flowrate.

Hydraulic efficiency η_h is defined as:

$$\eta_\Gamma = \frac{H}{H + \Delta H} \tag{3}$$

where H denotes the pump total head, and ΔH – loss of head.

Mechanical efficiency η_m is defined as:

$$\eta_m = \frac{P - P_{J,ab}}{P} = \frac{P_a}{P} \tag{4}$$

where $P_{J,ab}$ denotes pump mechanical power losses.

Finally, the pumping unit efficiency η_u is expressed as the product of the efficiencies of the unit's components:

$$\eta_u = \eta_p \eta_{mot} \eta_{FC} \eta_{transm} \tag{5}$$

where η_{mot} denotes motor efficiency, η_{FC} – frequency converter efficiency, and η_{transm} – transmission efficiency (in our case, η_{transm} = 1).

To evaluate and compare the changes in pump efficiency when the rotation speed changes, the laws of pump similarity (affinity laws) were used:

$$\frac{Q}{Q_{opt}} = \left(\frac{n}{n_{opt}}\right) \times \left(\frac{\eta_v}{\eta_{v,opt}}\right) \tag{6}$$

$$\frac{H}{H_{opt}} = \left(\frac{n}{n_{opt}}\right)^2 \times \left(\frac{\eta_h}{\eta_{h,opt}}\right) \tag{7}$$

$$\frac{P}{P_{opt}} = \left(\frac{n}{n_{opt}}\right)^3 \times \left(\frac{\eta_h}{\eta_{h,opt}}\right) \times \left(\frac{\eta_v}{\eta_{v,opt}}\right) \times \left(\frac{\eta_m}{\eta_{m,opt}}\right) \tag{8}$$

where Q, H, P, η_v, η_h, η_m denote flowrate, head, power, and volumetric, hydraulic and mechanical efficiency of the pump at a speed of rotation n, while Q_{opt}, H_{opt}, P_{opt}, $\eta_{v,opt}$, $\eta_{h,opt}$ denote flowrate, head, power, volumetric, hydraulic and mechanical efficiency of the pump at the optimum rated speed n_{opt}.

When analysing changes in the pumping unit's parameters, relative indicators were used. That is, all values were determined relative to the basic ones (parameter values at nominal speed and maximum efficiency). This approach will hold under the accepted hypothesis that using a frequency converter will decrease efficiency.

The efficiency of a pumping unit with a frequency converter (5) will change when the speed of the drive shaft changes:

$$\frac{\eta_u}{\eta_{u,opt}} = \frac{\eta_p \eta_{mot} \eta_{FC}}{\eta_{p,opt} \eta_{mot,opt} \eta_{FC,opt}} = \frac{\eta_v \eta_h \eta_m \eta_{mot} \eta_{FC}}{\eta_{v,opt} \eta_{h,opt} \eta_{m,opt} \eta_{mot,opt} \eta_{FC,opt}} = \frac{P_u}{P_{u,opt}} \frac{P_{mot,opt}}{P_{mot}} \tag{9}$$

where P_{mot} denotes driver power input and $P_{mot,u}$ – driver power output.

$$\left.\begin{aligned} P_{mot} &= \frac{P_{mot,u}}{\eta_{mot} \eta_{FC}} \\ P_{mot,u} &= \frac{P}{\eta_{transs}} \end{aligned}\right\} \qquad \left.\begin{aligned} P_{mot,u} &= P_{mot} \eta_{mot} \eta_{FC} \\ P &= P_{mot,u} \eta_{transs} \end{aligned}\right\} \tag{10}$$

Then, the efficiency of the drive (electric motor and frequency converter) will change when the pump shaft rotation speed changes:

$$\frac{\eta_{mot} \eta_{FC}}{\eta_{mot,opt} \eta_{FC,opt}} = \frac{P_u P_{mot,opt} \eta_{v,opt} \eta_{h,opt} \eta_{m,opt}}{P_{u,opt} P_{mot} \eta_v \eta_h \eta_m} \tag{11}$$

Considering expressions (10) and (11), expression (8) is transformed into:

$$\frac{P_{mot}\eta_{mot}\eta_{FC}\eta_{transs}}{P_{mot,opt}\eta_{mot,opt}\eta_{FC,opt}\eta_{transs,opt}} = \left(\frac{n}{n_{opt}}\right)^3 \times \left(\frac{\eta_h}{\eta_{h,opt}}\right) \times \left(\frac{\eta_v}{\eta_{v,opt}}\right) \times \left(\frac{\eta_m}{\eta_{m,opt}}\right) \tag{12}$$

Driver power input P_{mot} can be determined using the well-known formula:

$$P_{mot} = P_A + P_B + P_C = \sqrt{3}IU\cos\varphi \tag{13}$$

where I denotes current [A], U – voltage [V], and cos φ – motor power factor.

Thus, according to the obtained expression (12), to identify patterns of changes in the efficiency of the pump drive when using a frequency converter, it is necessary to consider the balance of energy losses in the pump when the shaft speed changes [27].

Let's first consider the change in the pump's volumetric efficiency ($\eta_v/\eta_{v,opt}$) as the rotation speed changes. The volume efficiency will change according to the formula:

$$\left(\frac{\eta_v}{\eta_{v,opt}}\right) = \frac{Q}{Q_{opt}}\left(\frac{n_{opt}}{n}\right) \tag{14}$$

Similarly, using expression (7), the dependence of hydraulic efficiency on shaft rotation speed is obtained:

$$\left(\frac{\eta_h}{\eta_{h,opt}}\right) = \frac{H}{H_{opt}}\left(\frac{n_{opt}}{n}\right)^2 \tag{15}$$

To obtain the dependence of the change in the mechanical efficiency of the pump when the shaft rotation speed changes, expressions (1), (11) and (12) are used. Expression (1) is converted first:

$$\eta_m = \frac{P_U}{P}\frac{1}{\eta_h\eta_v} \tag{16}$$

Then, the change in the mechanical efficiency of the pump will occur according to the following relationship:

$$\left(\frac{\eta_m}{\eta_{m,opt}}\right) = \frac{P_u P_{opt}}{PP_{u,opt}}\left(\frac{\eta_{h,opt}}{\eta_h}\right)\left(\frac{\eta_{v,opt}}{\eta_v}\right) = \frac{P_u P_{opt}}{PP_{u,opt}}\frac{H_{opt}}{H}\left(\frac{n}{n_{opt}}\right)^3\frac{Q_{opt}}{Q} \tag{17}$$

The change in the efficiency of the drive (motor and frequency converter) with engine shaft speed was analysed. To do this, the previously obtained expression (12) was transformed:

$$\left(\frac{\eta_{mot}\eta_{FC}}{\eta_{mot,opt}\eta_{FC,opt}}\right) = \left(\frac{n}{n_{opt}}\right)^3 \times \left(\frac{P_{mot,opt}}{P_{mot}}\right) \times \left(\frac{\eta_{transs,opt}}{\eta_{transs}}\right) \times \left(\frac{\eta_h}{\eta_{h,opt}}\right) \times \left(\frac{\eta_v}{\eta_{v,opt}}\right) \times \left(\frac{\eta_m}{\eta_{m,opt}}\right) \tag{18}$$

Taking into account that in our case $\eta_{transm} = 1$, it is possible to estimate the change in the efficiency of the drive (electric motor and frequency converter) when using a frequency converter:

$$\left(\frac{\eta_{mot}\eta_{FC}}{\eta_{mot,opt}\eta_{FC,opt}}\right)=\left(\frac{n}{n_{opt}}\right)^{3}\times\left(\frac{P_{mot,opt}}{P_{mot}}\right)\times\left(\frac{\eta_{h}}{\eta_{h,opt}}\right)\times\left(\frac{\eta_{v}}{\eta_{v,opt}}\right)\times\left(\frac{\eta_{m}}{\eta_{m,opt}}\right) \tag{19}$$

Finally, the change in the efficiency of the pumping unit (electric motor, frequency converter and pump) will be determined by the following relationship:

$$\left(\frac{\eta_{u}}{\eta_{u,opt}}\right)=\left(\frac{\eta_{mot}\eta_{FC}\eta_{u}}{\eta_{mot,opt}\eta_{FC,opt}\eta_{u,opt}}\right)=\left(\frac{n}{n_{opt}}\right)^{3}\times\left(\frac{P_{mot,opt}}{P_{mot}}\right)\times\left(\frac{\eta_{h}}{\eta_{h,opt}}\right)^{2}\times\left(\frac{\eta_{v}}{\eta_{v,opt}}\right)^{2}\times\left(\frac{\eta_{m}}{\eta_{m,opt}}\right)^{2} \tag{20}$$

The above relationships between the efficiencies and the rotational speed of the pump impeller shaft were used to process and analyse the results of laboratory and field experiments.

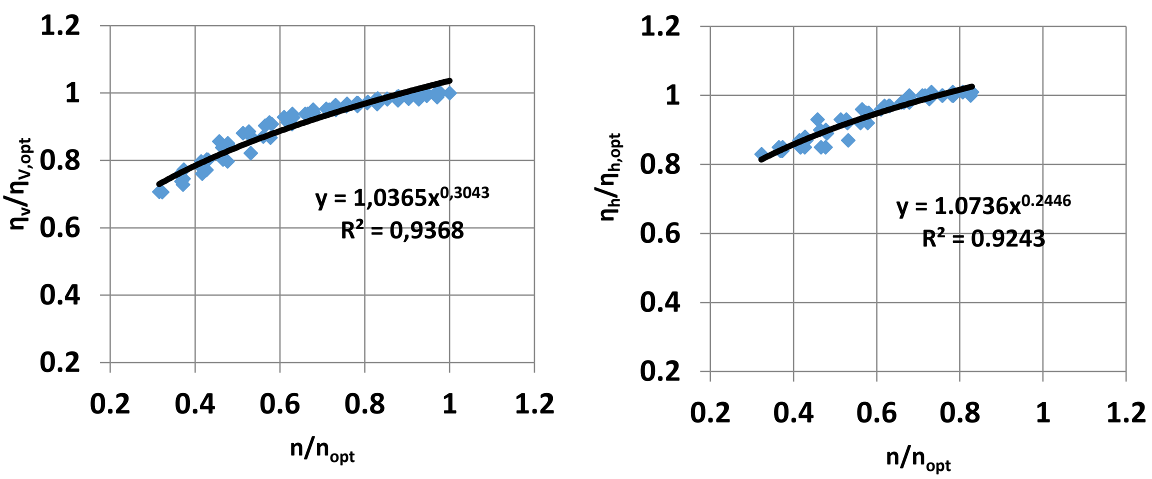
RESULTS

This section presents the results of the experimental and analytical study of the pumping unit performance under variable-speed operation. The analysis focuses on variations in individual efficiency components, drive efficiency, and overall system performance.

Variation of Pump Efficiency Components with Rotational Speed

As a result of the laboratory experiments, relationships describing how pumping unit parameters (head, flow rate, power consumption, and efficiency) vary with shaft rotational speed were obtained. All efficiency indicators were analysed in relative (dimensionless) form with respect to their values at nominal rotational speed corresponding to maximum efficiency. Using expressions (14), (15), and (17), changes in various types of efficiency in the pump resulting from changes in the rotational speed (relative to the nominal rotational speed of the pump shaft) were plotted as graphs. Figure 5 presents the relative variation in volumetric and hydraulic efficiencies as shaft speed decreases, and Figure 6 illustrates the relative changes in mechanical efficiency and overall pump efficiency.

Statistical processing of laboratory experimental data enabled the identification of empirical relationships describing how individual efficiency components vary with rotational speed.



a) b)

Figure 5. Graphs of changes in volumetric (a) and hydraulic (b) efficiency on the shaft speed, and results of statistical processing

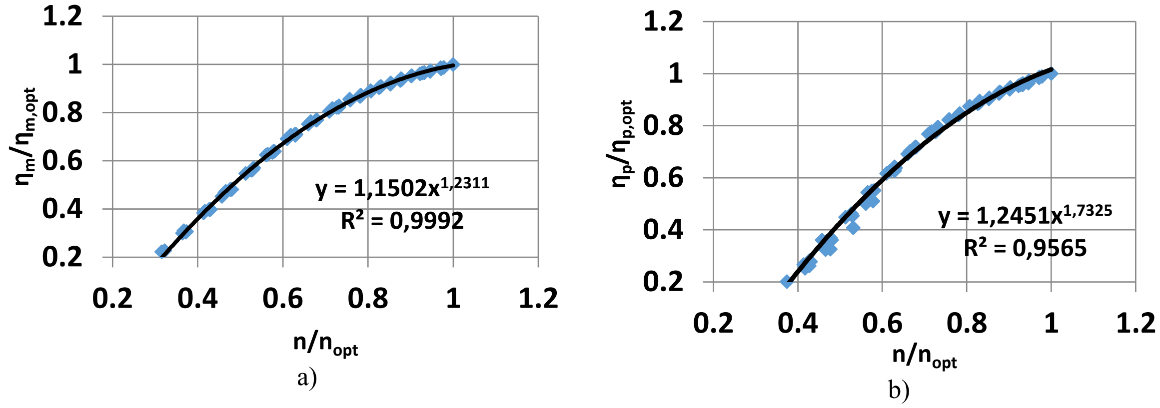


Figure 6. Graphs of changes in mechanical (a) and pump (b) efficiency on the shaft speed, and results of statistical processing

Drive Efficiency under Variable-Speed Operation

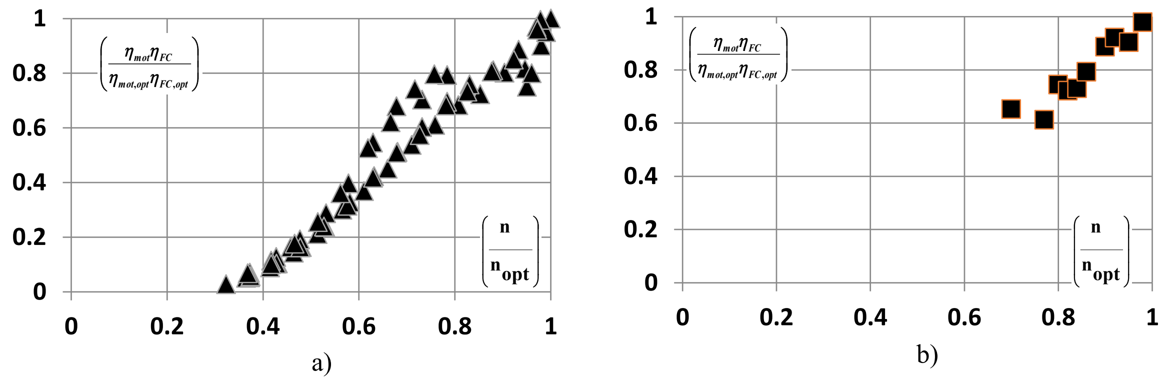


Figure 7. Graphs of the change in the drive efficiency with changing shaft speed: according to the results of laboratory experiments (a), and according to the results of field experiments (b)

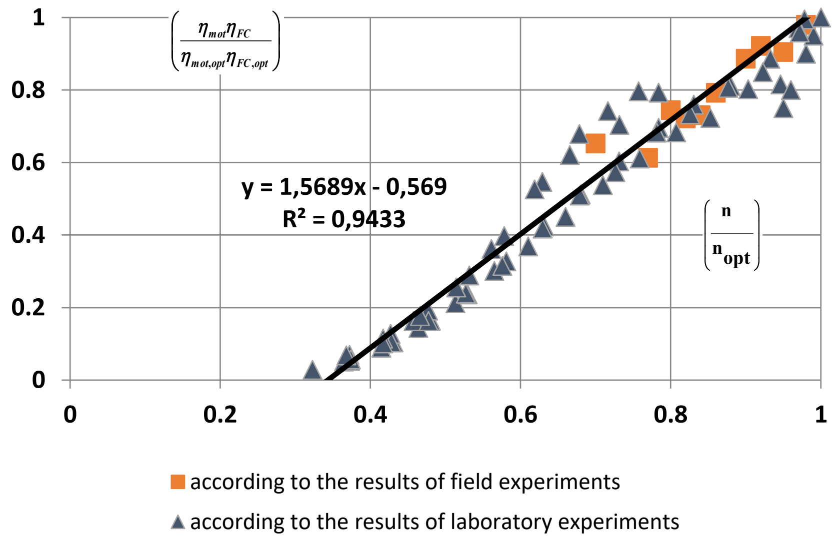


Figure 8. Graph of changes in drive efficiency depending on the change in rotational speed according to field and laboratory experiments

The efficiency variation of the electric drive system, including the electric motor and frequency converter, was evaluated using both laboratory and field experimental data. Figure 7 shows the relative change in drive efficiency as a function of shaft rotational speed obtained from laboratory experiments (Figure 7a) and full-scale field measurements at the irrigation pumping station (Figure 7b).

Statistical processing of data from laboratory and field experiments made it possible to identify the nature (curve in Figure 7) and analytical dependence of changes in the efficiency of an electric drive (motor and frequency converter) depending on changes in rotation speed.

Figure 8 presents the curve showing changes in drive efficiency as a function of rotational speed, based on field and laboratory experiments.

Overall Efficiency of the Pumping Unit

The combined effect of variations in pump and drive efficiencies determines the overall efficiency of the pumping unit under variable-speed operation. Figure 9 presents the relative change in the total efficiency of the pumping unit, including the pump, electric motor, and frequency converter. The balance of energy losses within the pumping unit is illustrated in (Figure 10) and (Figure 11).

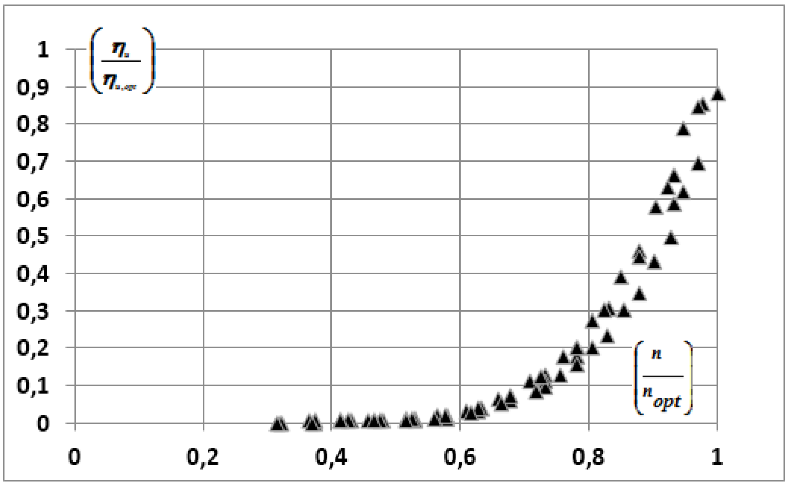


Figure 9. Graph of the change in the efficiency of the pumping unit when the shaft speed changes

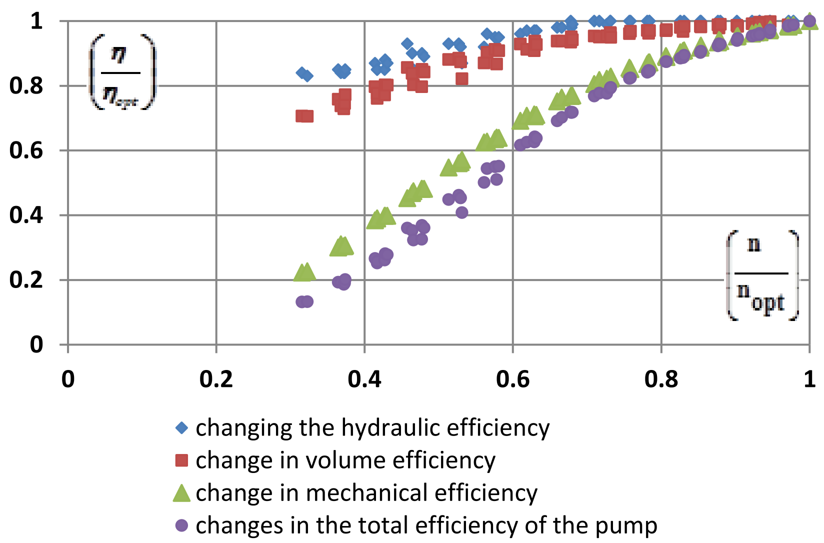


Figure 10. Efficiency changes affecting energy losses in the pump when the shaft speed changes

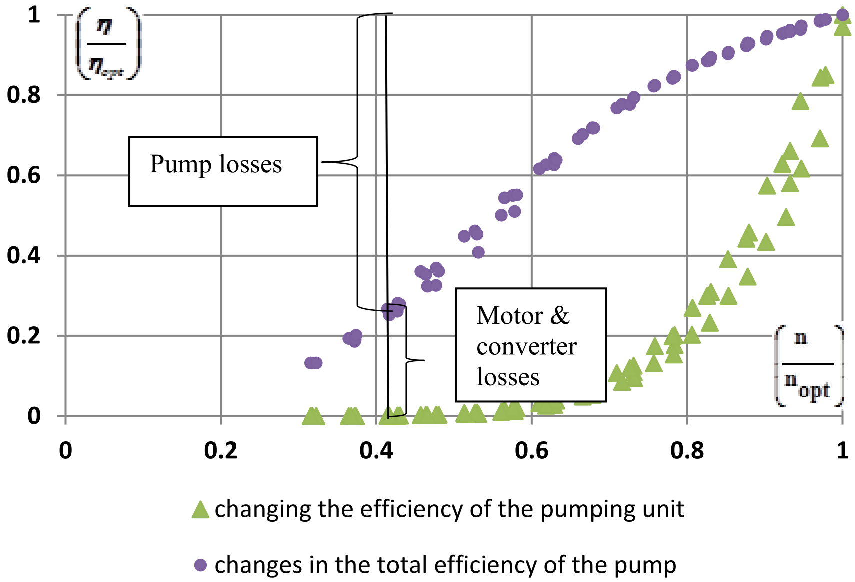


Figure 11. Balance of energy losses in the pumping unit when the shaft speed changes

DISCUSSION

The experimental results obtained in this study are discussed in terms of pump performance, energy-loss distribution, and the practical implications of variable-speed operation for irrigation pumping systems.

Variation of Pump Efficiency Components with Rotational Speed

The results of the experiments show that the internal energy balance of the pumping unit changes significantly when controlled at variable speed. The gradual decrease in volumetric efficiency at lower rotational speeds (Figure 5a) indicates that internal leakage losses do not scale linearly with flow and become the dominant factor at partial load. In contrast, the relative stability of hydraulic efficiency with a moderate decrease in speed ($n/n_0 > 0.75$) implies that the flow geometry inside the pump remains relatively stable until a critical threshold is reached. The high sensitivity of mechanical efficiency (Figure 6a) additionally confirms that fixed mechanical losses (friction in bearings and seals) account for a large share of total energy consumption as the useful output power decreases.

Drive Efficiency under Variable-Speed Operation

Both laboratory (Figure 7a) and field data (Figure 7b) show that drive efficiency decreases steadily as shaft speed decreases. However, the rate of efficiency decline differs between laboratory and field conditions, which differences in load characteristics, motor ratings, and operating modes can explain. Despite these differences, the overall trends are consistent, indicating that operating at partial load significantly reduces the efficiency of the electric motor-frequency converter system.

Overall Efficiency of the Pumping Unit

As shown in Figure 9, the overall efficiency decreases continuously as shaft speed decreases. This result highlights that, although variable-speed control can reduce energy consumption by matching flow rate to demand, it simultaneously leads to a redistribution and an increase in relative energy losses within the pumping unit. The redistribution of energy losses within the pumping unit strongly depends on shaft speed (Figure 10) and (Figure 11). At moderate speed reductions, losses in the electric drive become dominant, whereas at lower rotational speeds the relative contribution of pump losses increases. This behaviour indicates that pump and drive efficiencies should be evaluated simultaneously when assessing the performance of variable-speed pumping systems.

Comparison of Efficiency Calculation Formulas for Variable-Speed Pumps

The relationships that link the pump characteristics (flowrate Q, head H, power P) operating at different speeds (n_1, n_2) are described by the affinity laws. The approximation introduced in the power-speed relation implies that the efficiency will remain constant at speeds n_1 and n_2, i.e. that the efficiency curve will be shifted only to the left in the case of speed reduction [24]. Evaluating the economic efficiency of variable-speed pumps requires, first of all, assessing the pump's efficiency at reduced speeds. This task is usually accomplished by using the affinity laws [28].

The obtained results demonstrate that the efficiency of pumps and pumping units operating under variable-frequency control cannot be assumed constant, even for moderate deviations of shaft rotational speed from the nominal value. This finding challenges the commonly used assumption derived from classical affinity laws, according to which pump efficiency remains nearly unchanged for speed variations of up to 33–50% [25], [29], [30]. The present experimental results show that noticeable efficiency degradation occurs at significantly smaller speed reductions, which is consistent with recent experimental studies on variable-speed pump operation [24], [31]. However, unlike most existing works, which rely on simplified analytical models or limited laboratory conditions, the present study combines controlled laboratory experiments with full-scale field validation under real irrigation operating regimes. This approach allows for a more accurate representation of the actual performance characteristics of pumping units in irrigation systems.

Table 2 presents a comparison of the change in pump efficiency with a change in rotation speed, calculated using different formulas and experimental data for the Lowara CEA 70/33 pump. The magnitude of the change in rotational speed is 20% (from 2900 rpm to 2320 rpm), and the optimal efficiency is 42%.

Table 2. Comparison of the magnitude of the decrease in pump efficiency with a change in rotation speed between calculated and experimental data

Authors	Formula	Pump efficiency [%]	Change in pump efficiency [%]	Experimental efficiency [%]
Centrifugal pump Manufacturers [31]	$\eta_2 = \eta_1$	42	0	37
Anderson [32]	$\frac{0.9-\eta_2}{0.9-\eta_1} = \left(\frac{Q_1}{Q_2}\right)^{0.32}$	38.92	3	37
Borza & Sarbu [29]	$\eta_2 = 1-(1-\eta_1)\left(\frac{n_1}{n_2}\right)^{0.1}$	40.69	1	37
Bordeasu *et al.* [31]	$\frac{0.99-\eta_2}{0.99-\eta} = \left(\frac{1}{\frac{n_2}{n_1}}\right)^{0.8}$	30.86	11	37
Proposed formula	$\frac{\eta_2}{\eta_1} = 1.24\left(\frac{n_2}{n_1}\right)^{1.73}$	35.40	7	37

As shown in **Table 2**, the proposed formula yields the most accurate calculation of pump efficiency under a 20% speed change. Calculations using the Anderson formula also provide good results. The difference is that the Anderson formula will overestimate the actual pump efficiency. Therefore, when calculating the cost-effectiveness of implementing a frequency converter, the proposed formula is preferable.

Statistical processing of data from laboratory and field experiments (Figure 8) made it possible to identify the nature and analytical dependence of changes in the efficiency of an electric drive (motor and frequency converter) depending on changes in rotation speed:

$$\left(\frac{\eta_{mot}\eta_{FC}}{\eta_{mot,opt}\eta_{FC,opt}}\right) = 1.569\left(\frac{n}{n_{opt}}\right) - 0.569 \quad (21)$$

Statistical processing revealed a consistent empirical dependence of drive efficiency on rotational speed, demonstrating that even moderate reductions in shaft speed result in a noticeable decrease in drive efficiency. This effect must be taken into account when evaluating the energy performance of variable-speed pumping units.

The efficiency of the electric drive system, comprising the electric motor and frequency converter, was found to decrease with decreasing shaft speed. Both laboratory and field experiments revealed similar trends, despite differences in pump type, motor rating, and operating environment. This agreement indicates that partial-load operation of the electric drive is a critical factor affecting the overall energy performance of variable-speed pumping units. The derived empirical relationship (21) for the variation in drive efficiency provides a practical tool for estimating energy losses associated with the operation of frequency converters in irrigation pumping stations.

Field Validation and Practical Application of Variable-Speed Pump Control

The agreement between laboratory and full-scale field experiments conducted at the Teshiktosh-1 irrigation pumping station [26] confirms the applicability of the derived efficiency-frequency relationships under real irrigation operating conditions. Unlike many previous studies that rely primarily on laboratory-scale experiments or simplified analytical approaches, the present work validates the relationships obtained using full-scale operating data.

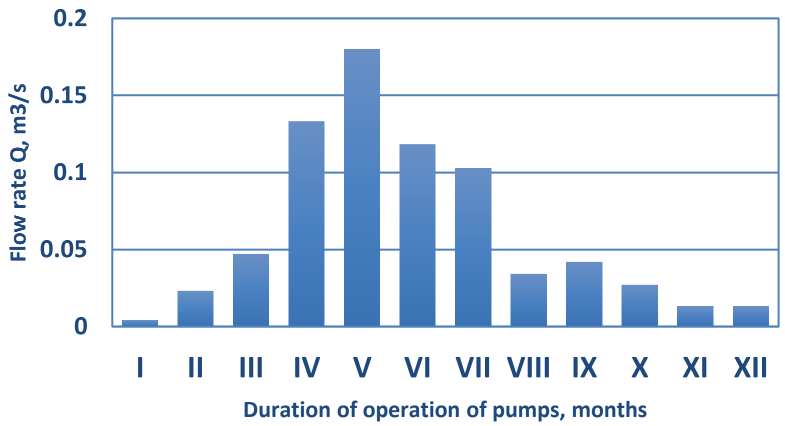


Figure 12. Schedule of pumping station water supply

During certain periods: May, June, July, and August (Figure 12), the actual water supply exceeds the water supply limit. During these periods, it is possible to reduce water supply consumption using a frequency converter. Water supply savings during the above periods can amount to 313.6 thousand m^3 (for three operating pumps) with a slight decrease in the efficiency of the pumping units (up to 20–30% from the graphs in Figure 10**).** Energy savings during the growing season amounted to approximately 107,700 kWh. That is, water savings amounted to

16%, and electricity savings were approximately 14 %. Application of the proposed formula (21) made it possible to increase the accuracy of energy savings calculations by 1–2%, taking into account the decrease in pumping unit efficiency when using a frequency converter.

From a practical perspective, these results are particularly relevant for irrigation pumping stations, which typically operate under relatively stable flow and pressure requirements compared to municipal water supply systems. In such systems, the primary benefit of variable-frequency control lies in improved water management, reduced unproductive water losses, and enhanced operational flexibility rather than in direct energy savings alone [6]. The limitations of classical similarity (affinity) laws are clearly demonstrated by the present study. When efficiency variations and energy-loss redistribution are neglected, the use of standard affinity relationships may yield incorrect estimates of pump performance and economic efficiency under variable-speed operation. Therefore, the use of experimentally validated efficiency-frequency relationships is recommended for feasibility studies and operational optimisation of pumping units equipped with frequency converters [4].

A unique feature of this study is its comprehensive assessment of pump and drive efficiency under variable frequency control in real-world irrigation pumping systems. Unlike previous studies, which typically examined either the pump or drive separately, this one considers both components together and their interactions under different operating conditions. Furthermore, the study presents efficiency-frequency relationships derived from laboratory and field test data. These relationships account for the redistribution of energy losses between the pump and drive – a factor not always accurately reflected in traditional theoretical models or classical scaling laws. This more accurate assessment helps better predict energy consumption and potential water savings in irrigation pumping systems. Another important aspect was integrating energy-efficiency and water-consumption indicators into a single analytical framework.

The integration of energy and water performance indicators is particularly important for regions with high irrigation dependence and limited water resources. The proposed methodology supports decision-making in irrigation modernisation programs, enabling more accurate prediction of both energy consumption and water resource use.

Despite the consistency of the results, certain limitations should be acknowledged. First, the empirical relationships were derived for specific pump types (centrifugal) and motor ratings common in irrigation; their applicability to high-viscosity fluids or different pump geometries (e.g., axial flow) requires further verification. Second, this study focused on short-term performance metrics and did not account for the potential impact of long-term equipment wear and cavitation on the efficiency-speed relationship. Future research should explore these factors to enhance the longitudinal accuracy of the proposed models.

CONCLUSIONS

The objective of this study was to evaluate the impact of a variable frequency drive (VFD) on the efficiency of a pump and pumping unit, and to assess its impact on combined energy and water yield under real-world operating conditions in irrigation systems. Based on the obtained results, the following conclusions can be drawn:

1. Experimental results from laboratory and field tests show that the efficiency of the pump, drive, and the entire unit decreases with decreasing shaft speed. The assumption of constant efficiency, based on classical scaling laws, is invalid even with moderate speed changes.

2. An analysis of energy losses shows that their distribution within the pumping unit depends on the operating mode. With moderate speed reductions, energy losses in the electric drive predominate, whereas at lower speeds, losses in the pump dominate. This observation confirms the need to consider both pump and drive performance when evaluating variable-speed operation.

3. The obtained empirical dependences of efficiency on frequency, validated under real-world operating conditions, provide a higher accuracy in predicting energy consumption compared to

traditional approaches. These relationships allow for a more reliable assessment of VFD performance in irrigation pumping systems.

4. Despite the reduction in pump unit efficiency at partial loads, the use of variable frequency drives (VFDs) significantly improves overall system performance.

5. Field test results (from Teshiktosh-1 pumping station) show water savings of approximately 16% and energy savings of approximately 14%, confirming the effectiveness of variable speed control in irrigation systems.

Overall, the study demonstrates that VFD implementation should be assessed within the framework of an integrated energy-water system. The proposed methodology provides a more accurate performance assessment and can be used to optimise and modernise irrigation pumping stations operating under variable demand.

NOMENCLATURE

Symbols

H	pump total head	[m]
I	current (amperage)	[A]
n	speed of rotation	[rpm]
n_{opt}	optimum rated speed	[rpm]
P	pump power input	[W]
$P_{J,ab}$	pump mechanical power losses	[W]
P_{mot}	driver power input	[W]
$P_{mot,u}$	driver power output	[W]
P_u	pump power output	[W]
Q	flowrate	[L/m, m^3/s]
Q_L	leakage flowrate	[L/m, m^3/s]

Greek letters

γ	specific gravity	[kg/m^3]
η_{FC}	frequency converter efficiency	
η_h	hydraulic efficiency	
η_m	mechanical efficiency	
η_{mot}	motor efficiency	
η_p	pump efficiency	
η_{transm}	transmission efficiency	
η_v	volume efficiency	
ρ	density	[kg/m^3]
ΔH	loss of head	[m]

Subscripts and superscripts

max	maximum
min	minimum
opt	optimum

Abbreviations

FC	frequency converter
FM	flowmeter
M	motor
P	pump

PS	pumping station
PU	pump unit
RV	regulating valve
V	pipeline valve
VFD	variable frequency drive

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Paper submitted: 07.02.2026
Paper revised: 25.06.2026
Paper accepted: 10.07.2026