Circuit: Jurnal Ilmiah Pendidikan Teknik Elektro
Volume 9 No. 1 September 2024 - February 2025
ISSN: 2549-3698; E-ISSN: 2549-3701
DOI: 10.22373/crc.v9i1.27241

Performance Analysis of Centrifugal End Suction Pump and Three Phase Induction Motor in The Distribution Pumping Station of PDAM Tirta Mountala, Aceh Besar Regency

Fathurrahman[a], Habibi Akbar[a], Ramdhan Halid Siregar[a], Rika Sri Utami[a], Mahdi Syukri[a], Muhammad Rizal Fachri[b], Malahayati[b]

[a] Universitas Syiah Kuala, Indonesia
[b] Universitas Islam Negeri Ar-Raniry Banda Aceh, Indonesia

E-mail: fathurrahman@usk.ac.id

Submission: 27-04-2024 Accepted: 10-07-2024 Published: 07-01-2025

Abstract

The purpose of this study is to evaluate the performance of PDAM's motor-pump system by analyzing its Specific Energy Consumption (SEC), electrical parameters of three-phase induction motors, and overall system efficiency. The optimization of the motor-pump system and the estimation of potential annual savings in electrical energy and operating expenses are other key areas of concentration. Hydrolysis and electrical parameter measurement are the research methods employed. The electrical parameters' performance is analyzed and compared with the system's hydrolysis performance after the measurement results are compiled. The study found that the PDAM motor-pump system operates at below 50% efficiency, highlighting the need for system rejuvenation. Electrical parameters showed a current imbalance of 5.65%–7.35%, voltage imbalance below 5%, and voltage variation under 10%. An SEC value below 0.44 kWh/m³ indicates potential for improved energy efficiency. A pump unit with less electrical power can be used in place of the pump system, according to the research of the pump work curve. The implementation of this rejuvenation could result in annual energy savings of up to 172,800 kWh per motor, which is comparable to an 18.4% reduction in operating costs.

***Keywords**: Energy Efficiency, Centrifugal Pump* end-suction, *Three-phase induction motor*

Abstrak

Penelitian ini bertujuan untuk mengevaluasi efisiensi kinerja sistem motor-pompa yang digunakan oleh PDAM. Fokus utama penelitian ini mencakup analisis efisiensi kinerja sistem, analisis parameter kelistrikan pada motor induksi tiga fasa, serta nilai Specific Energy Consumption (SEC). Fokus utama lainnya adalah optimalisasi sistem motor-pompa, serta perhitungan estimasi penghematan energi listrik dan biaya operasional yang dapat dihemat dalam satu tahun. Metode penelitian yang digunakan dengan pengukuran parameter kelistrikan dan Hidrolisis. Hasil pengukuran ditabulasi dan dilakukan analisa performance parameter kelistrikan dan membandingkannya dengan performance hidrolisis yang bekerja pada sistem. Hasil menunjukkan efisiensi kinerja sistem motor-pompa PDAM berada di bawah 50%, yang menandakan perlunya revitalisasi sistem secara menyeluruh. Pada inspeksi parameter kelistrikan ditemukan bahwa deviasi tegangan berada di bawah 10%, ketidakseimbangan tegangan di bawah 5%, dan ketidakseimbangan arus antara 5,65% hingga 7,35%. Nilai SEC berada di bawah 0,44 kWh/m³, menunjukkan adanya potensi efisiensi energi. Berdasarkan studi kurva kerja pompa, sistem pompa dapat diganti dengan unit pompa yang daya listriknya lebih rendah.

Implementasi revitalisasi ini berpotensi menghemat energi hingga 172.800 kWh per motor per tahun atau setara dengan penghematan biaya operasional sebesar 18,4%.

Kata Kunci: Efisiensi Energi, Pompa Centrifugal E*nd-suction*, Motor Induksi Tiga Fasa,

Introduction

The Regional Drinking Water Company or kwon as PDAM (Perusahan Daerah Air Minum) use the three-phase induction motors as the drivers for end-suction centrifugal pumps in clean water distribution systems. Induction motors convert electrical energy into mechanical energy; however, their performance is significantly influenced by the quality of the voltage supplied and the frequency. Voltage fluctuations, imbalances in voltage, and current can reduce motor efficiency, leading to increased heat generation, reduced torque, and higher energy consumption [1]. According to IEEE standards, the permissible voltage fluctuation tolerance is ±10% of the nominal voltage, with a maximum voltage imbalance of 3% and a maximum current imbalance of 10%. These parameters are used as a standard in evaluating the motors performance [2].

Induction motor is highly inductive loads, which generate reactive power during operation. As inductive loads, these motors operate by utilizing magnetic fields produced by wire coils or windings to create the motion [3]. Based on the concept of reactive power, low power factor results in high reactive power, which in turn increases power losses in the motor. The power factor is defined as the ratio of active power to apparent power in an AC circuit, typically expressed as cos φ. The power factor ranges between 0 and 1, where a value close to 1 indicates good performance. In terms of power consumption, the standard acceptable power factor is 0.85 [4]. In addition to induction motors, centrifugal pumps are essential components that transport the drinking water by converting mechanical energy into specific energy (head) of the fluid. The relationship between pressure (head) and water flow rate affects the efficiency of PDAM's distribution system. Inefficiencies may arise from poor pump design or operation, such as the use of improperly selected impellers, resulting in increased energy consumption [5].

The efficiency of the pump system, which reflects its ability to convert electrical energy into mechanical energy, can be assessed using established parameters and formulas. In industrial systems, including PDAM, analyzing specific energy consumption (SEC) is critical. SEC measures the energy efficiency of motor-pump systems by calculating the electrical energy consumed per unit volume of water pumped. Efficient systems have SEC values below 0.4 kWh/m³ [6], [7]. High SEC values indicate inefficiencies, potentially caused by electrical imbalances, poor pump sizing, or performance degradation of motors and pumps due to aging or inadequate maintenance. If the pump system classification falls below established standards, revitalization plans for the motor-pump system are required to enhance overall efficiency. The research aims to analyze the performance of PDAM's motor-pump system, evaluate electrical parameters of the motors, assess the system's specific energy consumption, and identify revitalization strategies to improve system performance. Additionally, the study includes an analysis of cost-saving estimates resulting from system revitalization. The findings are expected to provide actionable recommendations for improving the operational performance and efficiency of PDAM's motor-pump systems.

Literature Review

a. Induction Motor

An induction motor is an alternating current (AC) electrical machine that operates based on electromagnetic principles to convert electrical energy into mechanical energy [8]. It consists of two primary components: the stator (stationary part) and the rotor (rotating part). Its working principle is grounded in Lorentz's Law and Faraday's Law, where the interaction between a magnetic field and electric current generates electromotive force (EMF) that rotates the rotor [9]. When an AC current flows through the stator windings of an induction motor, it produces a rotating magnetic field. This rotating magnetic field induces an electric current in the rotor windings, which in turn generates electromagnetic force, causing the rotor to rotate [9]. Based on its construction, a three-phase induction motor has two types of rotors: the squirrel-cage rotor, which is simple and efficient, and the wound rotor, which provides better speed control but requires more complex maintenance [10]. These motors are particularly well-suited for industrial applications such as water pumps and compressors due to their stability and efficiency in operation [11].

b. Voltage Fluctuation

Voltage fluctuation refers to variations or changes in voltage levels within a three-phase electrical system. These fluctuations can manifest as overvoltage or undervoltage, characterized by deviations above or below the nominal voltage value. Typically, voltage fluctuations arise from load variations, disturbances in the power grid, or internal issues within the distribution system. To ensure proper motor performance, the allowable voltage fluctuations must adhere to applicable standards. According to IEEE Standard 141-1993, the permissible voltage fluctuation for induction motors is ±10% of the nominal voltage [2]. The magnitude of voltage fluctuation can be calculated using the following equation:

$$\Delta V = \frac{Vovervoltage,LL - Vnominal,LL}{Vnominal,LL} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

or

$$\Delta V = \frac{Vnominal,LL - Vundervoltage,LL}{Vnominal,LL} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

c. Voltage and Current Unbalance

Voltage unbalance and current unbalance in a three-phase system occur due to differences in the magnitude and phase angle of the three phases. When voltage is unbalanced, a three-phase induction motor is forced to draw uneven currents in each phase. This happens because the motor attempts to maintain torque despite the non-ideal voltage distribution, resulting in current unbalance that is greater than the level of voltage unbalance itself [12]. A voltage unbalance of just 1% can increase current unbalance by 6-10%, depending on the motor's characteristics [13]. When voltage is unbalanced, a three-phase induction motor is forced to draw uneven currents in each phase.

According to IEEE standards, the acceptable tolerance for voltage unbalance is no more than 3%, while current unbalance should not exceed 10% [2]. To determine the values of voltage and current unbalance in an induction motor, equations based on NEMA (National Electrical Manufacturers Association) standards can be used, specifically the LVUP (Line Voltage Unbalance Percentage) for voltage and LCUP (Line Current Unbalance Percentage) for current [1].

1. Calculation of voltage unbalance
   - Calculate the Average Voltage (V_{avg})

     $$V_{avg} = \frac{V12+V23+V31}{3} \quad \text{.........................} \quad (3)$$

   - Calculate Voltage Deviation

     $$\Delta V_{LL} = |V_{LL} - V_{avg}| \quad \text{.........................} \quad (4)$$

     Max(ΔV_{LL}) is …

   - Calculate Voltage Unbalance Percentage

     $$LVUP = \frac{Max((Vrs-Vavg),(Vst-Vavg),(Vtr-Vavg))}{Vavg}\ x\ 100\% \quad \text{.........} \quad (5)$$

2. Calculation of current unbalance
   - Calculate the Average Current **(V_{avg})**

     $$V_{avg} = \frac{I1+I2+I3}{3} \quad \text{.........................} \quad (6)$$

   - Calculate Current Deviation

     $$\Delta I_{LL} = |I_{LL} - V_{avg}| \quad \text{............................} \quad (7)$$

     Max(ΔI_{LL}) is …

   - Calculate Current Unbalance Percentage

     $$LCUP = \frac{Max((IR-Iavg),(IS-Iavg),(IT-Iavg))}{Iavg}\ x\ 100\% \quad \text{.................} \quad (8)$$

d. Pressure (Head) in a Pump System

In general, the pump head is divided into two components: pressure head and elevation head. The pressure head represents the energy possessed by the fluid due to the pressure difference between the suction reservoir and the discharge reservoir. Meanwhile, the elevation head refers to the pressure resulting from the height difference between the fluid surface in the suction reservoir and the fluid surface in the discharge reservoir, with the pump axis serving as the reference point. Based on the position of the reservoirs relative to the pump axis, there are two types of installations: suction lift and suction head. [14].

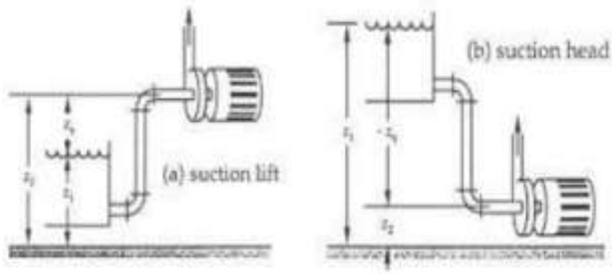

Figure 1. Suction Pipe Installation [14]

Suction head refers to a pump installation condition where the fluid surface in the suction reservoir is above the pump axis [14]. In this condition, the pump requires less energy to draw the liquid from the suction reservoir. The head pressure in such an installation can be calculated using the following equation:

$$H_t = H_d - H_s \quad \text{…………………………} \quad (9)$$

On the other hand, suction lift refers to a pump installation condition where the fluid surface in the suction reservoir is below the pump axis [14]. In this condition, the pump requires more energy to draw the liquid from the suction reservoir. The head pressure in such an installation can be calculated using the following equation:

$$H_t = H_d + H_s \quad \text{…………………………} \quad (10)$$

Where:

Hd : Head Discharge
Hs : Head Suction

e. Hydraulic Power in a Pump

Hydraulic power is the power used to move fluid from one point to another, overcoming resistance within the piping system, which is referred to as head pressure [15]. The formula to calculate hydraulic power is as follows:

$$P_h = \frac{Q \ x \ Ht \ x \ \rho \ x \ g}{1000} \quad \text{…………………………} \quad (11)$$

Where:

P_h : Hydraulic power (kW)
Q : Water flow rate (m^3/s)
H_t : Head (m)
g : Gravitational acceleration (9,8 m/s^2)
ρ : Water density (1000 kg/m^3)

f. Classification of Motor-Pump System Efficiency

Performance efficiency reflects a system's ability to deliver the desired output while utilizing energy optimally. Higher efficiency indicates a more effective system. Specifically, the efficiency of the motor-pump system in PDAM is calculated by comparing the electrical power consumed by the motor to the hydraulic power produced by the pump, using a standard performance analysis formula:

$$\eta_t = \frac{Ph}{Pi} \ x \ 100\% \quad \text{…………………………} \quad (12)$$

Where:

η_t : Total efficiency of the pump system (%)
P_h : Hydraulic power (kW)
P_i : Input power or active power (kW)

PDAM has established standard values for assessing the feasibility of the motor-pump system used. Here are the feasibility standards for the system.

Table 1. PDAM Pump System Feasibility Standards [15]

Efficiency (η)	Description
η > 60%	The system can still be maintained
50% < η < 60%	The system requires minor improvements
η < 50%	The system requires complete overhaul

g. Specific Energy Consumption (SEC)

Specific Energy Consumption (SEC) is a parameter used to measure energy efficiency in industries with high energy consumption. Generally, SEC can be defined as the value of specific energy consumption, indicating the amount of energy (kWh) required to produce a given volume of production (m^3) [16].

$$SEC = \frac{Energy\ (kWh)}{volume\ (m^3)} \quad \ldots\ldots\ldots\ldots \quad (13)$$

Each industry has its own parameter values used as a reference in calculating specific energy consumption (SEC). These differences are based on the energy consumption and total production required by each industry. For example, the sugar industry has an SEC standard value of below 166.66 kWh/Ton of sugar [17]. The SEC standard value for water supply industries such as PDAM is 0.4 kWh/m^3 [6], [7]. The smaller the SEC value in a system, the more efficient the system is.

Method

This study employs a quantitative approach to analyze the efficiency of the PDAM motor-pump system, encompassing the evaluation of electrical parameters such as voltage fluctuations, voltage and current unbalance, and power factor. Energy efficiency analysis is conducted based on Specific Energy Consumption (SEC) parameters and the planning of system revitalization through the replacement of pumps with more efficient models. The study also estimates annual energy savings and operational cost reductions. Secondary data were obtained from PDAM Tirta Mountala, Aceh Besar, over six days within seven hours daily (10:00 AM–5:00 PM). Electrical parameters were measured using a 3-phase power analyzer model DW-6195. The supporting data for this research were collected from PDAM Tirta Mountala and include:

1. Pump specifications and performance curves
2. Three-phase induction motor specifications
3. Electrical measurement data for the three-phase induction motor
4. Water flow measurement data

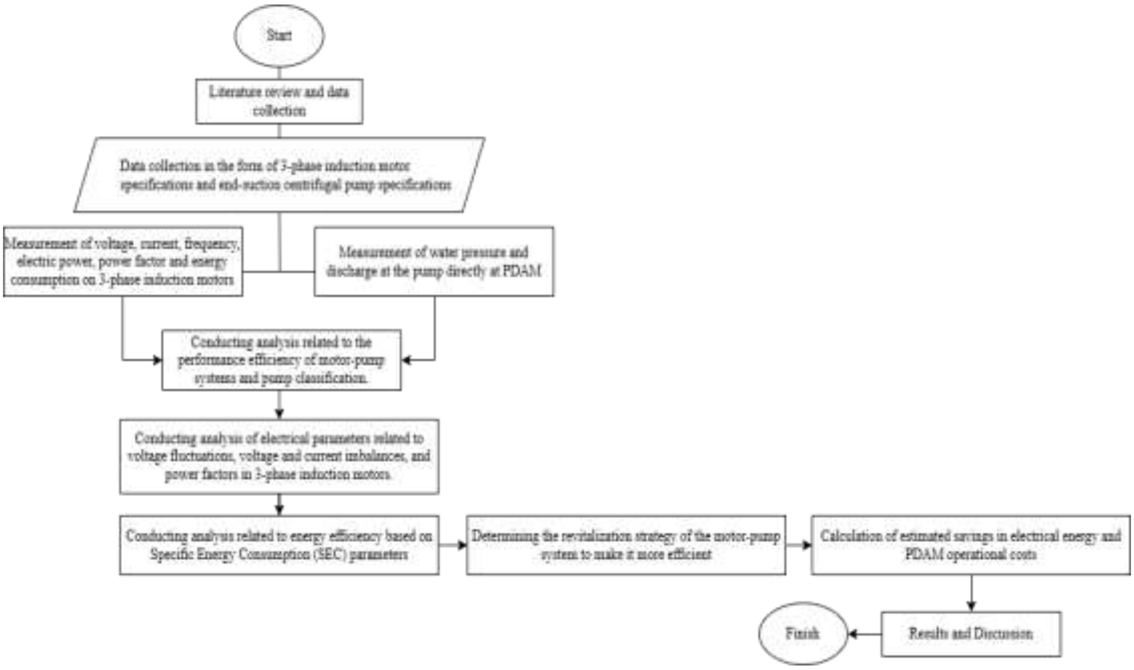

Figure 2. Research Flowchart

a. Data of Average Electrical Measurement Calculations for Induction Motors 1 and 2**

The following are the average values from the research data collected over 3 days within a 7-hour period for induction motors 1 and 2. These averages include several electrical parameters: line-to-line voltage, line-to-neutral voltage, current, electrical power, power factor, and frequency.

Table 2. Average Electrical Measurement Data for Induction Motor-1

Time (WIB)	Voltage V_{LL} (V)			Voltage V_{LN} (V)			Current (A)			Power			PF	Freq (Hz)
	V_{12}	V_{23}	V_{31}	V1	V2	V3	A_1	A_2	A_3	$P_{(SUM)}$ (kW)	$S_{(SUM)}$ (kVA)	$Q_{(SUM)}$ (kVAR)		
10:00	409,2	416,1	412,3	235,3	238,9	240,2	107,8	121,0	118,9	70,5	82,6	43,1	0,85	50
11:00	408,2	415,1	411,2	234,7	238,5	239,5	107,7	121,1	119,2	70,4	82,5	42,9	0,85	50,0
12:00	406,0	412,9	409,3	233,5	237,2	238,6	107,5	121,0	119,1	70,1	82,0	42,6	0,85	50,0
13:00	402,8	410,2	406,6	231,7	235,5	236,9	107,6	121,4	119,4	70,0	81,6	41,9	0,85	50,0
14:00	405,4	412,4	409,1	233,2	236,7	238,2	111,8	121,9	124,6	72,2	84,4	43,8	0,85	49,9
15:00	410,5	417,7	413,7	236,3	239,7	241,1	113,4	127,1	125,7	74,9	87,4	45,0	0,85	50,0
16:00	412,1	419,7	415,8	237,1	240,6	242,2	107,7	121,4	119,6	71,0	83,5	44,0	0,84	50,1
17.00	410,9	417,1	413,7	236,1	239,7	240,8	108,4	121,5	119,3	71,0	83,2	43,5	0,85	50,1
Overall average value														
Time (WIB)	**Voltage V_{LL} (V)**			**Voltage V_{LN} (V)**			**Current (A)**			**Power**			**PF**	**Freq (Hz)**
	V_{12}	V_{23}	V_{31}	V_1	V_2	V_3	A_1	A_2	A_3	$P_{(SUM)}$ (kW)	$S_{(SUM)}$ (kVA)	$Q_{(SUM)}$ (kVAR)		
10.00-17.00	408,1	415,2	411,5	234,7	238,4	239,7	109,0	122,1	120,7	71,3	83,4	43,4	0,8	50,0

Table 3. Average Electrical Measurement Data for Induction Motor-2

Time (WIB)	Voltage V_{LL} (V)			Voltage V_{LN} (V)			Current (A)			Power			PF	Freq (Hz)
	V_{12}	V_{23}	V_{31}	V1	V2	V3	A_1	A_2	A_3	$P_{(SUM)}$ (kW)	$S_{(SUM)}$ (kVA)	$Q_{(SUM)}$ (kVAR)		
10:00	408,6	416,2	412,2	235,0	238,9	240,3	109,1	116,5	121,3	70,6	82,4	42,5	0,85	50,1
11:00	406,5	413,8	410,2	233,9	237,5	239,1	109,0	116,3	121,5	70,3	81,9	42,1	0,85	50,0
12:00	408,9	417,1	412,7	235,3	239,3	240,7	108,1	116,2	121,2	70,2	82,2	42,8	0,85	50,0
13:00	406,6	414,2	410,5	233,9	237,7	239,1	108,5	116,7	121,7	70,2	82,0	42,3	0,85	50,0
14:00	406,5	414,3	409,7	233,7	237,7	239,1	108,9	116,8	121,7	70,4	82,1	42,2	0,85	50,1
15:00	407,1	414,3	410,4	234,1	237,7	239,4	109,6	117,3	122,4	70,8	82,6	42,6	0,85	50,0

16:00	403,4	411,2	407,5	232,4	235,9	237,5	109,6	117,8	122,9	70,8	82,2	41,8	0,86	50,0
17.00	405,7	413,4	409,6	233,5	237,1	238,8	108,0	116,1	121,3	69,9	81,5	41,9	0,85	50,0

Overall average value

Time (WIB)	Voltage V_{LL} (V)			Voltage V_{LN} (V)			Current (A)			Power			PF	Freq (Hz)
	V_{12}	V_{23}	V_{31}	V_1	V_2	V_3	A_1	A_2	A_3	$P_{(SUM)}$ (kW)	$S_{(SUM)}$ (kVA)	$Q_{(SUM)}$ (kVAR)		
10.00-17.00	406,7	414,3	410,4	234,0	237,7	239,3	108,9	116,7	121,7	70,4	82,1	42,3	0,85	50,0

b. Measurement data on centrifugal end suction pump systems 1 and 2

The following are the average values from the research data collected over 3 days within a 7-hour period for distribution pump-1. These averages include parameters such as reservoir height, pump pressure, and water flow rate.

Table 4. Average Measurement Calculation Data for Distribution Pump-1

Overall average value					
Time (WIB)	**Reservoir Height (m)**	**Pressure (bar)**	**Pressure (mH2O)**	**Flow (l/s)**	**Flow (m^3/s)**
10.00 - 17.00	1,7	6,4	65,4	52,97	0,0530

Table 5. Average Measurement Calculation Data for Distribution Pump-2

Overall average value					
Time (WIB)	**Reservoir Height (m)**	**Pressure (bar)**	**Pressure (mH2O)**	**Flow (l/s)**	**Flow (m^3/s)**
10.00 - 17.00	1,9	6,6	67,3	50,55	0,0506

Results and Discussion

a. Analysis of The Performance of The Motor-Pump Distribution System

As a sample calculation, the researcher takes the overall average values from the calculation data of the distribution pump-1 measurements in Table 4.

- The calculation of the pressure value produced by the pump uses Equation 9 as follows.
  Given:
  Hd = 65,4 mH2O
  Hs = 1,7 m
  Thus:
  Ht = 65,4 mH2O – 1,7 m
  = 63,7 m

- The calculation of the hydraulic power produced by the pump uses the mathematical equation 11 as follows.
  Given:
  Q = 0,053 m^3/s
  Ht = 63,7 m
  g = 9,8 m/s2 (Earth's gravitational force)
  ρ = 1000 kg/m3 (Density of water)
  Thus:

$$Ph = \frac{0,053\ m^3/s\ x\ 63,7\ m\ x\ 1000\ kg/m^3 \text{ x } 9,8\ m/s^2}{1000}$$

  = 33, 08 kW

Here is the calculation of the system performance efficiency using equation 12. The input power (active power) value can be seen in the table of average electrical measurement data of induction motor-1 (Table 2).

Given:

Ph = 33,08 kW

Pi (P_{SUM}) = 71,3 kW

Thus:

$$Ht = \frac{33{,}08 \text{ kW}}{71{,}3 \text{ kW}}\ x\ 100\%$$

$$= 46{,}4\%$$

The results of the analysis can be classified according to the pump conditions in Table 1.

Table 6. Results of System Performance Classification

Time (WIB)	Pump	Input Power (kW)	Hydraulic Power (kW)	Efficiency	Description
10.00 - 17.00	Pump 1	71,3	33,08	46,4%	System needs total overhaul
	Pump 2	70,4	32,43	46,06%	

b. Analysis of Voltage Fluctuation Levels on Induction Motors

As a sample calculation related to the analysis of voltage fluctuations on both induction motors, the researcher uses the average line-to-line voltage data at 10:00 WIB on induction motor 1 (Table 2) with Equation 1.

$$\Delta V_{12} = \frac{409{,}2\ Volt - 400\ Volt}{400\ Volt} \times 100\%$$

$$= 2{,}3\%$$

$$\Delta V_{23} = \frac{416{,}1\ Volt - 400\ Volt}{400\ Volt} \times 100\%$$

$$= 4\%$$

$$\Delta V_{31} = \frac{412{,}3\ Volt - 400\ Volt}{400\ Volt} \times 100\%$$

$$= 3{,}1\%$$

In the same manner, the analysis is conducted at each time for induction motors 1 and 2 based on the data in Tables 2 and 3. The results of the analysis can be seen in the following table.

Table 7. Voltage Deviation Between Phases (VL-L) on Induction Motor-1

No	Time (WIB)	Voltage $_{L-L}$ (V)			Nominal Voltage(V)	Voltage Deviation			Description
		V_{12}	V_{23}	V_{31}		ΔV_{12}	ΔV_{23}	ΔV_{31}	
1	10.00	409,2	416,1	412,3	400	2,3%	4,0%	3,1%	Overvoltage
2	11.00	408,2	415,1	411,2		2,1%	3,8%	2,8%	
3	12.00	406	412,9	409,3		1,5%	3,2%	2,3%	
4	13.00	402,8	410,2	406,6		0,7%	2,6%	1,7%	
5	14.00	405,4	412,4	409,1		1,3%	3,1%	2,3%	

6	15.00	410,5	417,7	413,7		2,6%	4,4%	3,4%	
7	16.00	412,1	419,7	415,8		3,0%	4,9%	4,0%	
8	17.00	410,9	417,1	413,7		2,7%	4,3%	3,4%	

Table 8. Voltage Deviation Between Phases (VL-L) on Induction Motor-2

No	**Time (WIB)**	**Voltage $_{L-L}$ (V)**			**Nominal Voltage(V)**	**Voltage Deviation**			**Description**
		V_{12}	**V_{23}**	**V_{31}**		**ΔV_{12}**	**ΔV_{23}**	**ΔV_{31}**	
1	10.00	408,6	416,2	412,2	400	2,3%	4,0%	3,1%	Overvoltage
2	11.00	406,5	413,8	410,2		2,1%	3,8%	2,8%	
3	12.00	408,9	417,1	412,7		1,5%	3,2%	2,3%	
4	13.00	406,6	414,2	410,5		0,7%	2,6%	1,7%	
5	14.00	406,5	414,3	409,7		1,3%	3,1%	2,3%	
6	15.00	407,1	414,3	410,4		2,6%	4,4%	3,4%	
7	16.00	403,4	411,2	407,5		3,0%	4,9%	4,0%	
8	17.00	405,7	413,4	409,6		2,7%	4,3%	3,4%	

The results of the analysis of the voltage deviation values can be depicted in the following graph.

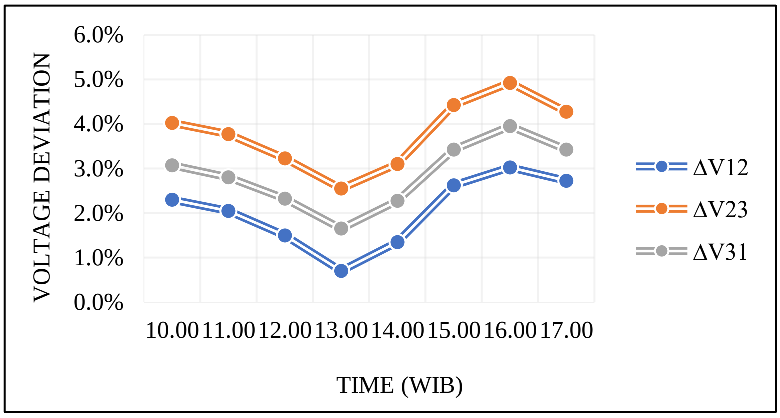

Figure 3. Voltage Deviation Graph On Induction Motor-1

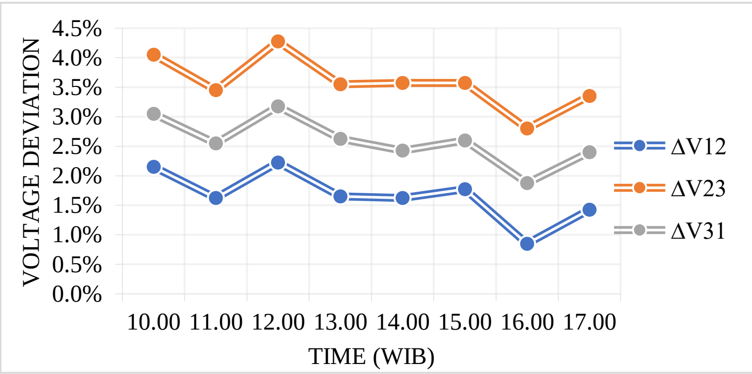

Figure 4. Voltage Deviation Graph On Induction Motor-2

Based on the data analysis of the voltage deviation values, it can be concluded that the phase-to-phase voltage deviation values on induction motors 1 and 2 comply with the IEEE standard, which is below 10%. Thus, the electrical system of this 3-phase induction motor operates within acceptable tolerance limits, ensuring the motor can function properly without significant risk of damage due to voltage fluctuations.

c. Analysis of Voltage Unbalance on Induction Motors

As a sample calculation related to the analysis of voltage unbalance on both induction motors, the researcher uses the average line-to-line voltage data at 12:00 WIB on induction motor 1 (Table 2) using equations 3, 4, and 5.

- Calculating the average voltage value (V_{ave})

$$V_{ave} = \frac{406+412,9+409,3}{3}$$

$$= 409,4 \text{ Volt}$$

- Calculating the voltage deviation

$\Delta V_{12} = |406 - 409,4| = 3,4$ V

$\Delta V_{23} = |412,9 - 409,4| = 3,5$ V

$\Delta V_{31} = |409,3 - 409,4| = 0,1$ V

The maximum voltage deviation V_{LL} is 3,5 Volt

- Calculating the voltage unbalance

$$LVUP = \frac{\Delta \text{Vmax}}{Vave}\ x\ 100\%$$

$$= \frac{3,5 \text{ V}}{409,4 \text{ V}}\ x\ 100\%$$

$$= 0,85\ \%$$

In the same manner, the analysis is conducted at each time for induction motors 1 and 2 based on the data in Tables 2 and 3. The results of the analysis can be seen in the following table.

Table 9. Voltage Unbalance on Induction Motor-1

Time (WIB)	**Voltage, V_{LL} (V)**			**V_{ave} (V)**	**Voltage Deviation (V)**			**Maximum Deviation (V)**	**LVUP**
	V_{12}	V_{23}	V_{31}		V_{12}	V_{23}	V_{31}		
10:00	409,2	416,1	412,3	412,5	3,3	3,6	0,2	3,6	0,86%
11:00	408,2	415,1	411,2	411,5	3,3	3,6	0,3	3,6	0,87%
12:00	406	412,9	409,3	409,4	3,4	3,5	0,1	3,5	0,85%
13:00	402,8	410,2	406,6	406,5	3,7	3,7	0,1	3,7	0,92%
14:00	405,4	412,4	409,1	409,0	3,6	3,4	0,1	3,6	0,87%
15:00	410,5	417,7	413,7	414,0	3,5	3,7	0,3	3,7	0,90%
16:00	412,1	419,7	415,8	415,9	3,8	3,8	0,1	3,8	0,92%
17.00	410,9	417,1	413,7	413,9	3,0	3,2	0,2	3,2	0,77%

Table 10. Voltage Unbalance on Induction Motor-2

Time (WIB)	Voltage, V_{LL} (V)			V_{ave} (V)	Voltage Deviation (V)			Maximum Deviation (V)	LVUP
	V_{12}	V_{23}	V_{31}		V_{12}	V_{23}	V_{31}		
10:00	408,6	416,2	412,2	412,3	3,7	3,9	0,1	3,9	0,94%
11:00	406,5	413,8	410,2	410,2	3,7	3,6	0,0	3,7	0,89%
12:00	408,9	417,1	412,7	412,9	4,0	4,2	0,2	4,2	1,02%
13:00	406,6	414,2	410,5	410,4	3,8	3,8	0,1	3,8	0,93%
14:00	406,5	414,3	409,7	410,2	3,7	4,1	0,5	4,1	1,01%
15:00	407,1	414,3	410,4	410,6	3,5	3,7	0,2	3,7	0,90%
16:00	403,4	411,2	407,5	407,4	4,0	3,8	0,1	4,0	0,97%
17.00	405,7	413,4	409,6	409,6	3,9	3,8	0,0	3,9	0,94%

The results of the analysis of the voltage unbalance values can be illustrated in the following graph.

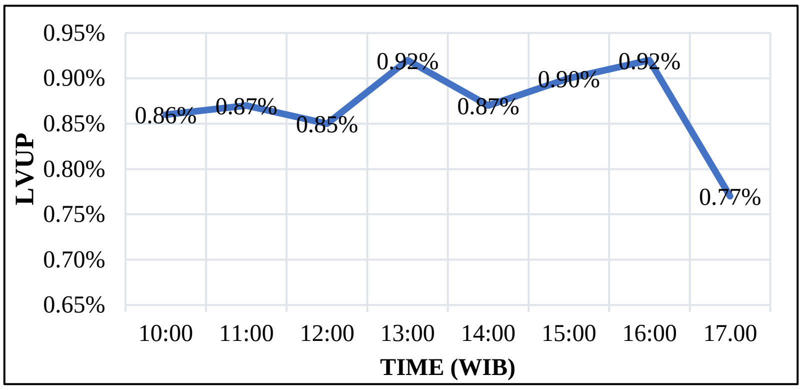

Figure 5. Voltage Unbalance Graph on Induction Motor-1

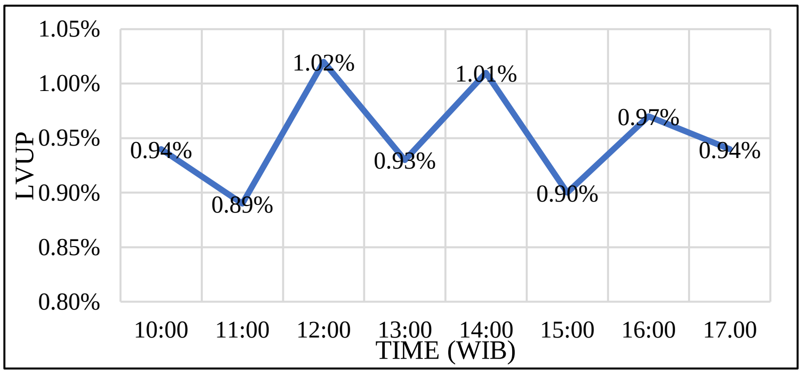

Figure 6. Voltage Unbalance Graph on Induction Motor-2

The variation in voltage unbalance values on the graph for both motors 1 and 2 at each time period is caused by fluctuations in the electrical network voltage, which is not always stable. Based on the analysis conducted, it is evident that the voltage unbalance values comply with IEEE standards as they are still below 3%. Thus, the electrical system of the motor operates within acceptable tolerance limits, ensuring that the motor can function properly without significant risk of damage due to voltage unbalance.

If the voltage unbalance between phases exceeds the specified standard limit, it will reduce the motor's performance efficiency. Voltage values also affect the current. If the voltage is low, it will increase the current in the motor's electrical system, thereby raising the temperature and impacting the motor's lifespan.

d. Analysis of Current Unbalance on Induction Motors

As a sample calculation related to the analysis of current unbalance on both induction motors, the researcher uses the average line-to-line voltage data at 12:00 WIB on induction motor 1 (Table 2) using equations 6, 7, and 8.

- Calculating the average current value (Iave)

$$Iave = \frac{107{,}5+121+119{,}1}{3}$$

$$= 115{,}9 \text{ Ampere}$$

- Calculating the current deviation

$\Delta I1 = |107{,}5 - 115{,}9| = 8{,}4$ A

$\Delta I2 = |121 - 115{,}9| = 5{,}1$ A

$\Delta I3 = |119{,}1 - 115{,}9| = 3{,}2$ A

The maximum current deviation is 8,4 Ampere

- Calculating the current unbalance

$$LCUP = \frac{\Delta Imax}{Iave}\ x\ 100\%$$

$$= \frac{8{,}4\ A}{115{,}9\ \ A}\ x\ 100\%$$

$$= 7{,}22\%$$

Similarly, the analysis is performed for each time period for induction motors 1 and 2 based on the data in Tables 2 and 3. The results of the analysis are shown in the following table.

Table 11. Current Unbalance on Induction Motor-1

Time (WIB)	Current (A)			I_{ave} (A)	Current Deviation (A)			Maximum Deviation (A)	LCUP
	I_1	I_2	I_3		I_1	I_2	I_3		
10:00	107,8	121	118,9	115,9	8,1	5,1	3,0	8,1	6,99%
11:00	107,7	121,1	119,2	116,0	8,3	5,1	3,2	8,3	7,16%
12:00	107,5	121	119,1	115,9	8,4	5,1	3,2	8,4	7,22%
13:00	107,6	121,4	119,4	116,1	8,5	5,3	3,3	8,5	7,35%
14:00	111,8	121,9	124,6	119,4	7,6	2,5	5,2	7,6	6,39%
15:00	113,4	127,1	125,7	122,1	8,7	5,0	3,6	8,7	7,10%
16:00	107,7	121,4	119,6	116,2	8,5	5,2	3,4	8,5	7,34%
17.00	108,4	121,5	119,3	116,4	8,0	5,1	2,9	8,0	6,87%

Table 12. Current Unbalance on Induction Motor-2

Time (WIB)	Current (A)			I_{ave} (A)	Current Deviation (A)			Maximum Deviation (A)	LCUP
	I_1	I_2	I_3		I_1	I_2	I_3		
10:00	109,1	116,5	121,3	115,6	6,5	0,9	5,7	6,5	5,65%
11:00	109	116,3	121,5	115,6	6,6	0,7	5,9	6,6	5,71%
12:00	108,1	116,2	121,2	115,2	7,1	1,0	6,0	7,1	6,14%
13:00	108,5	116,7	121,7	115,6	7,1	1,1	6,1	7,1	6,17%
14:00	108,9	116,8	121,7	115,8	6,9	1,0	5,9	6,9	5,96%
15:00	109,6	117,3	122,4	116,4	6,8	0,9	6,0	6,8	5,87%
16:00	109,6	117,8	122,9	116,8	7,2	1,0	6,1	7,2	6,14%
17.00	108	116,1	121,3	115,1	7,1	1,0	6,2	7,1	6,20%

The results of the analysis of the current unbalance values can be illustrated in the following graph.

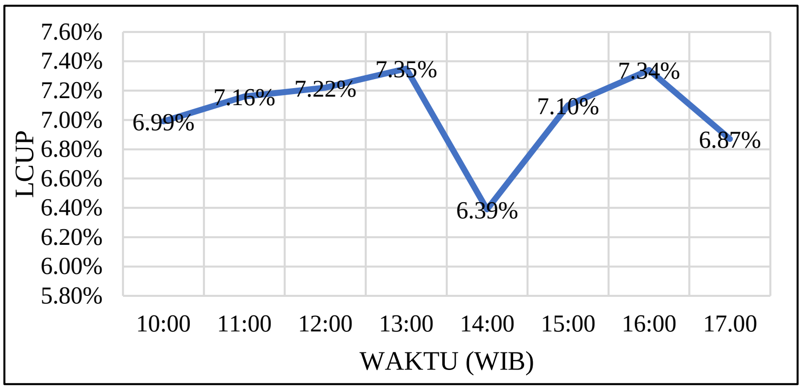

Figure 7. Current Unbalance Graph on Induction Motor-1

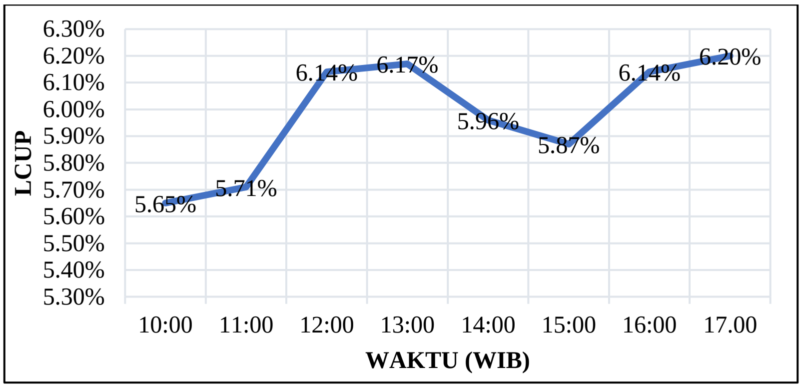

Figure 8. Current Unbalance Graph on Induction Motor-2

Based on the analysis results of the current unbalance values on induction motors 1 and 2, as shown in Figures 7 and 8, it is found that the current unbalance values vary between 5.65% and 7.35%, which is still below the acceptable limit according to the IEEE standard, which is 10%. This indicates that, although there is variation in the current, the induction motor continues to operate under safe conditions without causing significant disruptions to the motor's performance.

Voltage unbalance directly affects the current, where a 1% voltage unbalance can cause a current unbalance of 6-10%. This happens because the motor tries to maintain torque even though the voltage distribution is not ideal, which results in a current unbalance greater than the voltage unbalance itself. Based on the results shown in the current unbalance graphs in Figures 7 and 8, the average fluctuation of current unbalance follows the fluctuation of voltage unbalance (Figures 5 and 6). If the current unbalance exceeds the limit, the motor becomes less efficient, increases power consumption, raises the risk of overheating, and shortens the motor's lifespan.

e. Power Factor Analysis on Induction Motors

Based on the analysis of the electrical system on the motor using a 3-phase power analyzer, it is known that the induction motor used by PDAM for the distribution system has a power factor of 0.85, which complies with industry standards. A stable power factor of 0.85 on the 3-phase induction motor indicates that approximately 85% of the total power drawn from the electricity source is converted into useful active power, while the remaining power is reactive, which does not perform useful work but is needed to create the magnetic field in the motor. This shows that the motor operates efficiently with minimal reactive power wastage, in line with the expected technical specifications.

f. Analysis of Specific Energy Consumption (SEC) Values

SEC is the result of comparing the energy consumed (kWh) to the water production flow rate generated. To determine the water flow rate (m^3) produced by PDAM, Equation 10 will be used, incorporating the overall average water flow rate and the average electrical power used by each motor during the 7-hour period.

1. Motor-pump 1
   Given: The electrical power consumed can be seen in Table 2 (71,3 kW).
   The average water flow rate can be seen in Table 4 (0,0530 m^3/s = 190,8 m^3/h)

   $$SEC = \frac{71{,}3\ kW\ x\ 7\ jam}{190{,}8\ \ m^3 x\ 7\ jam}$$

   $$= \frac{499{,}1\ kWh}{1335{,}6\ m^3}$$

   $$= 0{,}37\ \text{kWh/m}^3$$

2. Motor-pump 2
   Given: The electrical power consumed can be seen in Table 3 (70,4 kW).
   The average water flow rate can be seen in Table 4 (0,0506 m^3/s = 182,16 m^3/h)

   $$SEC = \frac{70{,}4\ kW\ x\ 7\ jam}{182{,}16\ \ m^3 x\ 7\ jam}$$

   $$= \frac{492{,}8\ kWh}{1275{,}12\ m^3}$$

   $$= 0{,}38\ \text{kWh/m}^3$$

Based on the data analysis results, the obtained SEC value indicates that the specific energy consumption is below the established standard. This shows that the pump operates with good energy efficiency. Although the pump is already efficient in energy use per unit of water pumped, there are other factors that reduce the overall system efficiency (Table 6). Evaluation and improvement of other aspects of the system are still required to achieve more optimal efficiency.

g. Analysis of Required Motor-Pump Capacity

Based on the analysis results, the average water flow rate produced by the pump in distributing water is (52.97 l/s = 3.17 m³/min) on pump 1 and (50.55 l/s = 3.03 m³/min) on pump 2. The average total head (pressure) is (63.7 m) on pump 1 and (65.4 m) on pump 2. These results can be represented in the following pump curve graph.

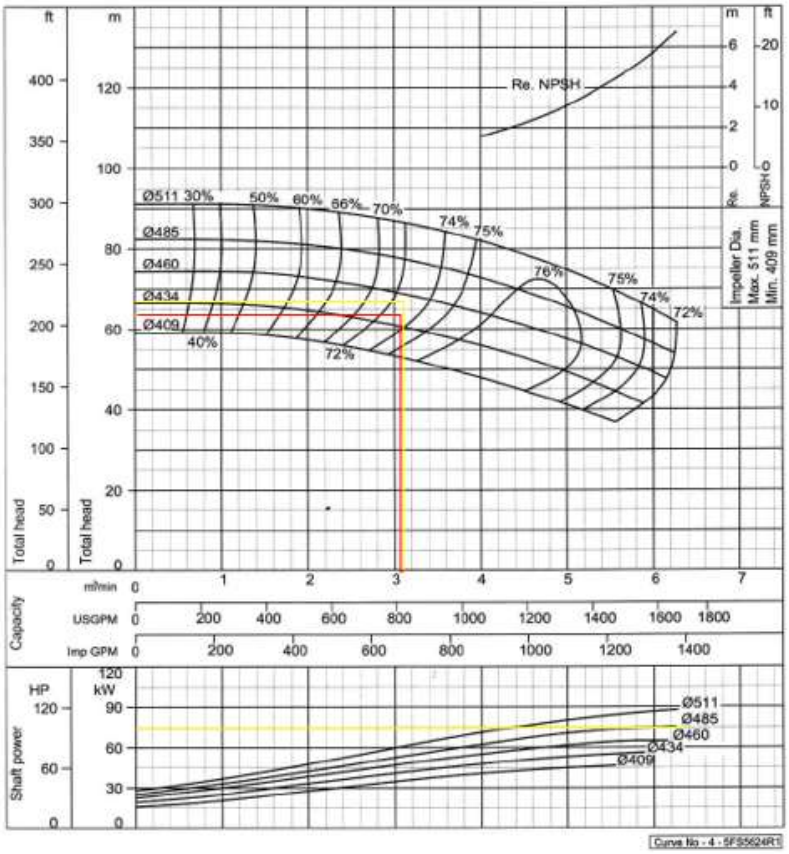

Figure 9. Pump Performance Curve Graph

Based on the motor specifications used by PDAM, namely a motor with a power rating of 75 kW, and the pump used to be equipped with an impeller Ø485, the performance curve analysis results indicate that the intersection point between the pressure and flow rate values lies below the performance curve line for the Ø485 impeller-type pump. This indicates that the pump operates in an inefficient condition, resulting in low performance efficiency. Therefore, the researchers recommend an alternative to replace the pump type to improve the system's performance efficiency.

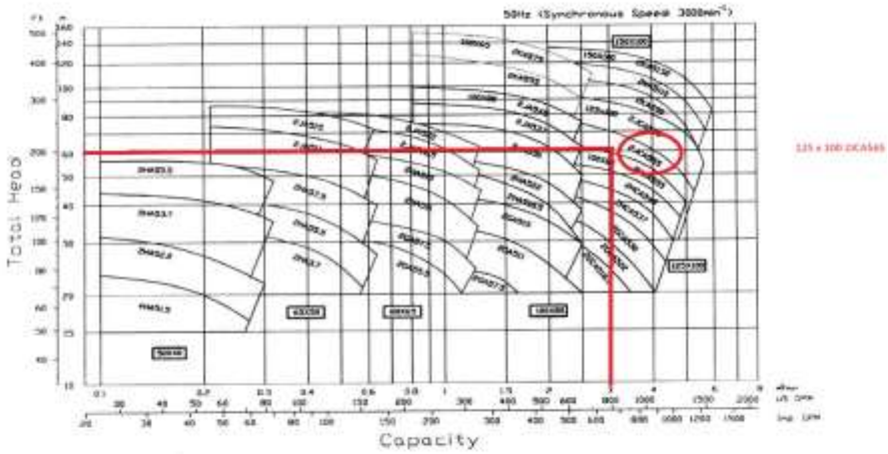

Figure 10. Selection of Existing Pump Recommendation

By maintaining a flow rate of 3 m³/min and an average pressure of 60 meters to achieve high efficiency, one alternative that can be applied is to replace the pump with the FS2JCA 125 x 100 type.

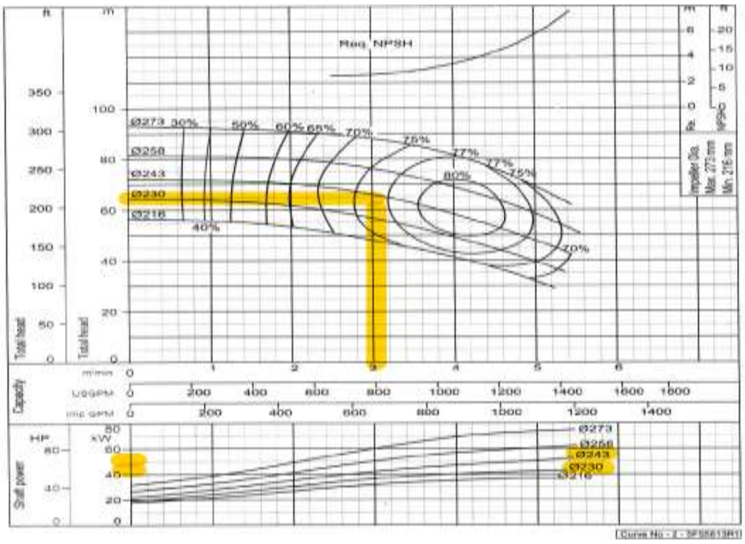

Figure 11. Recommended Performance Curve Graph for FS2JCA 125 x 100 Pump Type

125X100 FS2JCA	55	125	100	140	360	250	108	250SA	463.5	419	452	275	85	1040	680	185	195	440	440	4-M20	65	4	1387	625
	75							250MA	482.5	436	525	420	55	1220	650	175	195	540	540		100		1365	733

Unit:mm, unless otherwise stated

Figure 12. Motor Specification Requirements for the Selected Pump

Based on the graph above, at an average pressure (head) of 60 meters and to maintain a flow rate of 3 m³/min, a FS2JCA 125 x 100 pump is required, operating with an impeller diameter of Ø230. The motor specifications needed to drive the pump of this type include a motor with a power rating of 55 kW (Figure 13). With the proposed motor-pump revitalization plan, it is expected to save 20 kW of energy usage while achieving a high system efficiency of 70%.

h. Estimation of Energy and Cost Savings

The estimated savings after system revitalization will reduce the electrical power consumption of each motor by 20 kW. This will impact the electricity operational costs for PDAM. As a business customer in the medium voltage category with a P2 type for power above 200 kVA, PLN charges a tariff of Rp.1,415.01/kWh [18]. In this case, if the motor-pump system is revitalized, the cost savings over one year will be as follows.

Table 13. Estimation of Motor Power Savings and PDAM Operational Costs

No	Motor Power Savings	Total Daily Power	Total Monthly Power	Total Annual Power	Tariff/kWh	Total Cost Savings
1	20 kw	480 kWh	14.400 kWh	172.800 kWh	Rp.1.415,01	Rp.244.513.728
2	20 kw	480 kWh	14.400 kWh	172.800 kWh	Rp.1.415,01	Rp.244.513.728
Total Cost Savings						Rp.489.027.456

Based on the table above, the total electricity savings that can be achieved for each motor in one year is 172,800 kWh. The estimated annual savings in electricity operational costs that PDAM can achieve after the motor-pump system revitalization is Rp.489,027,456. This savings demonstrates the potential for significant cost reduction, which can improve operational efficiency and PDAM's budget allocation.

Figure 13. Electricity Bill Payment Structure for PDAM

The operational cost for PDAM in one month is shown in Figure 13, amounting to Rp.221,349,754. Consequently, the estimated annual operational cost is Rp.2,656,197,048. By implementing the system revitalization, the annual savings for PDAM are calculated as follows:

$$\text{Savings (\%)} = \left(\frac{\text{Annual Savings}}{\mathit{Total\ Annual\ Operational\ Cost}}\right) x\ 100\%$$

$$= \left(\frac{\text{Rp.489.027.456,–}}{\text{Rp.2.655.388.584,–}}\right) x\ 100\%$$

$$\approx 18{,}4\%.$$

Thus, the system revitalization of the motor-pump can reduce annual operational costs by approximately 18.4%.

Conclusion

The efficiency of the motor-pump system is below 50%. This indicates that the system is not operating efficiently, requiring a complete revitalization, including replacing the pump with a more efficient capacity. Voltage deviation values are below the 10% standard, and voltage unbalance in induction motors 1 and 2 remains within the acceptable standard of below 3%. Current unbalance ranges between 5.65% and 7.35%, which complies with the standard of below 10%. The motor's power factor of 0.85 also meets industrial electrical standards. The specific energy consumption (SEC) value of the system is below 0.44%, aligning with industry standards and indicating good energy efficiency. This shows that the pump operates with minimal energy consumption for the volume of water produced.

Revitalizing the pump with the FS2JCA 125 x 100 type will enable it to operate with a Ø230 impeller at a high efficiency of 70%, using a motor with a power specification of 55 kW. This will save 20 kW of electrical energy usage. With the system revitalization, PDAM can save 172,800 kWh of electrical energy per motor annually. The estimated annual operational electricity cost savings achievable is Rp. 489,027,456. This revitalization can reduce PDAM's annual operational costs by 18.4%.

To improve the performance of the electrical system, it is recommended to use monitoring equipment that measures voltage, current, and power factor meter in real-time. This equipment will ensure electrical stability, detect fluctuations, provide accurate data on system performance, and enable preventive actions to maintain efficiency.

References

[1] M. A. Zahari, “Analisis Pengaruh Ketidakseimbangan Tegangan Terhadap Unjuk Kerja Motor Induksi 3 Fasa Menggunakan Matlab Simulink,” Universitas Islam Agung, Semarang, 2023.

[2] *IEEE Recommended Practice for Electric Power Distribution for Industrial Plants*, IEEE Std 141-1993., vol. 1. IEEE, 1994. doi: https://doi.org/10.1109/IEEESTD.1994.121642.

[3] L. Aditya dan A. R. Ilmianta, “Analisis Konsumsi Daya Pemasangan Kapasitor Bank Pada Sistem Jaringan Listrik Tegangan Rendah di Hotel The 101 Cengkareng,” *Jurnal Elektro*, vol. 10, no. 1, Jan 2022.

[4] Y. Esye dan S. Lesmana, “Analisa Perbaikan Faktor Daya Sistem Kelistrikan,” *Jurnal Sains dan Teknologi*, vol. 11, no. 1, Mar 2021.

[5] M. Rafi dan D. B. Santoso, “Analisis Efisiensi Pompa Distribusi Pada Instalasi Pengolahan Air (IPA) Leuwiliang Perumda Tirta Kahuripan Bogor,” vol. 12, no. 02, 2023.

[6] G. Asmara, “Peningkatan Efisiensi Energi Pada Sistem Distribusi Sumbersari Perumda Air Minum Tugu Tirta Kota Malang,” Thesis, Institut Teknologi Sepuluh Nopember, Surabaya, 2021.

[7] Q. Constantya, A. Slamet, dan G. N. R. Pandin, “Analisis Peluang Peningkatan Efisiensi Energi Pada Instalasi Pompa Wendit 3 Perumda Air Minum Tugu Tirta Kota Malang,” *Jurnal Ilmiah Indonesia*, vol. 6, no. 11, Nov 2021.

[8] Sarjono, R. Gianto, dan A. Hiendro, “Evaluasi Kinerja Motor Induksi 3 Fasa 100 HP / 75 kW Pada Panel Star–Delta di PDAM Tirta Raya Adi Sucipto Kubu Raya,” Universitas Tanjjungpura Pontianak, Pontianak.

[9] S. H. Prawira, “Analisis Efisiensi Daya Motor 3 Phase Sebagai Penggerak Boiler Penghisap Abu PT. Industri Invilon Sagita,” Universitas Pembangunan Panca Budi, Medan, 2022.

[10] M. M. Alam, “Analisis Efisiensi Motor Induksi Tiga Fasa Pada Kipas Sentrifugal di PT. Kimia Farma TBK. Plant Semarang,” Universitas Semarang, Semarang, 2022.

[11] L. Siregar, R. Silaen, dan J. L. Hutabarat, “Pengaruh Perubahan Beban Terhadap Putaran dan Daya Masuk Motor Induksi Tiga Fasa (Aplikasi Pada Laboratorium Konversi Energi Listrik FT-UHN),” *ELPOTECS Jurnal*, vol. 4, no. 1, 2021.

[12] E. Kusbiyantoro, “Analisa Tegangan Tidak Seimbang Terhadap Torsi dan Daya Motor Induksi Tiga Fasa dengan Simulasi Matlab ,” Universitas Islam Sultan Agung, Semarang, 2021.

[13] R. Patil dan Prof. H. B. Chaudari, “Behavior of Induction Motor at Voltage Unbalanced,” *International Journal of Engineering Research and Technology (IJERT)*, vol. 4, no. 05, Mei 2015.

[14] Z. H. Muhammad dan F. Anggara, “Analisa Head Pompa Water Intake Terhadap Self Cleaning Filter pada PT.XY,” *Jurnal Teknik Mesin*, vol. 8, no. 2, hlm. 56–63, 2019.

[15] F. S. Ramadani dan S. A. Devanti, “Analisis Efisiensi Pompa Distribusi dan Specific Energy Consumption Pada Proses Produksi Air Bersih di PDAM SurabayaYA,” Gresik, Agu 2021.

[16] M. Burhanuddin, “Audit Energi Pada Pompa Submersible di PDAM Guna Memperoleh Peluang Penghematan Energi,” Universitas Tidar, Magelang, 2022.

[17] M. T. , M. S. H. Suryono S.T., B. A. Raharjo, dan Ir. U. Wibawa M.Sc., “Studi Analisis Konsumsi dan Penghematan Energi di PT. P.G. Krebet Baru I,” *Jurnal Mahasiswa Teknik Elektro Universitas Brawijaya*, vol. 2, no. 1, 2014.

[18] web.pln.co.id, “Tarif Adjustment.”

[19] I, Fikri., M, Syukri., F, Fathurrahman, “Analisa Biaya Trafo Akibat Dari Rugi-Rugi Daya Total Dengan Metode Nilai Tahunan”, *Jurnal Komputer, Informasi Teknologi, dan Elektro*, vol. 9, no.1, 2024

[20] E, Saputra., R, Adriman., T, Tarmizi., F, Fathurrahman, “Outage Management Automation for Reducing Downtime Duration at the Samahani-Sibreh Feeder”, *2023 2nd International Conference on Computer System, Information Technology, and Electrical Engineering (COSITE)*, hlm.171-175, 2023