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Operation Strategy of Electric Motors for Water Pumping On Malang City Regional Water Supply Company (Pdam Kota Malang) For Electrical Energy Efficiency Improvement

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Abstract: *PDAM Kota Malang (Malang City Regional Water Supply Company) has several pumping stations that operate the water pump motors 24/7 with no breakdown period, while others operate the motors in rolling breakdown timing. Badut Pumping Station, Sumbersari Pumping Station, Supit Urang Pumping Station, and Istana Dieng Pumping Station use no breakdown period, since those utilize single or dual unit of motors. Wendit Pumping Station and Mojolangu Pumping Station use rolling breakdown timing, which using seven out of nine, or four out of six, available pump motors. In rolling breakdown timing, each pump motor operates in 1,000-hour start-and-stop sequence.*

This study analyzed the electrical energy consumption as well as water production, with the pipeline infrastructure and water reserving system excluded. The energy is limited to the PLN (state electrical company) source, regardless of every pumping station owns their diesel generator due to reliability of PLN as electrical power source. This study is based on assumption that lighting usage is negligible. Efficiency of the electrical energy usage is where this study focused on. Variables involved are mainly about power quality, power factor, motor efficiency, and the ratio of energy consumption on water production (specific energy consumption).

Finally, the expected result of this research is to provide useful recommendation for PDAM Kota Malang about the energy consumption efficiency and water production management

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I. Introduction

Malang City is divided by five districts, namely Sukun, Kedungkandang, Klojen, Lowokwaru, and Blimbing. As registered total citizen reached 881,794 in 2015 and 887,443 in 2016, this city has growth rate of 1.58% annually[1].Currently, Malang City uses two methods to deliver clean water to its inhabitants, i.e. by self-service and on PDAM service. The pipelining distribution is used for delivering clean water as PDAM service [2].

For the maximum size of pumping units considered in the standard possible working conditions are the most of the application of water supply system [3]. The entire water supply process requires energy consumption and a thorough assessment is needed to improve energy efficiency to reduce cost [4].

As the elevation between every water source varies, two systems must be implemented by PDAM for water delivering process, namely gravity assist and pumping. The gravity assisted delivering system is located in Banyuning (at Batu City), while several sources in Malang City, e.g. Sumbersari and Wendit, use pumping system. Water from Wendit is pumped to the Buring and Mojolangu reservoirs, alongside to the customers directly. Buring reservoir uses gravity assist to deliver water to customers. Mojolangu reservoir pumps the water both to the customers and to Tlogomas reservoir. In other word, water supply in Tlogomas reservoir undergoes pumping process twice, as the elevation varies between Wendit, Mojolangu, and Tlogomas itself. The pumping system is also implemented in Badut, Supit Urang, and Istana Dieng water source to its customers, as the source from the wells located inside the city with relatively small capacity. Every water source that implements the pumping system is then called as “the pumping station”, which operates pumping mechanism by water pump powered by electric motor [1].

In all of the pumping stations, the pumps are operating continuously. Badut, Sumbersari, Supit Urang, and Istana Dieng pumping station operate all pumps continuously in the same time, since there are only single or two pumps. On the other side, Wendit and Mojolangu pumping station operate 3 of 4 pumps (or 4 of 5 pumps) continuously in rolling period of 1,000-hour mode [1].

This study analyzes power consumption and water production, which utilizes power only from the state electrical company by kWh meter and kVArh meter installed. The efficiency of power usage will be the main focusof this research, which consists of power quality and the ratio of energy used against water production (specific energy consumption).

The goal of this study is to provide recommendations to PDAM about energy consumption efficiency and water production management. Some of the problem definition includes: water production management, energy consumption, analysis of energy consumption on water production, and the recommendations required to PDAM.

II. Theoretical Basis

Induction Motors

Induction motors are the most common of AC motors. The current passes through the rotor is inducted current from relative difference between rotor rotations with respect to the rotating magnetic field produced by stator current. The stator is shown in Figure 1, with its coil generates synchronous rotating magnetic field [5].

Fig. 1 Thestator of an induction motor [5].

The rotating magnetic field generated by the stator cuts out the conductors in rotor, and as the Lentz Law, the rotor rotates after the field.

Fig. 2 The cage rotor of an induction motor [5].

The difference in the relative rotation between the stator and the rotor is then called slip. Increasing the load will amplify the motor coupling and amplify the induced current on the rotor; hence,the slip between the stator rotation and rotation of the rotor will increase. In contrary, when the motor load increases, the rotation of the rotor will tend to decrease. There are two types of induction motors, namely:

1. Induction motor with rotor winding; and
2. Induction motor with cage rotor [5].

Fig. 3 The coil rotor of an induction motor [5].

Figure 2 shows the cage rotor of an induction motor, while Figure 3 shows the coil rotor.

Water Pumps

Water pumpsare the equipment used to convert mechanical energy to the compressive energy of the pumped water. The conversion can be achieved in several ways, including:

1. Byusing tools such as blades or impellers with a particular shape;
2. By using alternating motion of piston or similar tools;
3. By energy exchange using an intermediate fluid, both gas and liquid (jet pump); and
4. Byhigh-pressure air or gas, which is injected into a channel, containing the pumped water.

There are wide ranges of pumps, which are based on:

1. Output pressure (low, medium, and high);
2. Capacity generated (low, medium, and high);
3. Fluidthat handled (water, oil, milk, etc.); and
4. Position (horizontal, upright, etc.).

A stronger pump classification system is based on how energy is added to the pumped fluid. In this classification system, the outline of the pump can be divided into:

1. Positive displacement pump (positive displacement pump).
2. Dynamic pumps (dynamic pump or non-positive displacement pump) [5].

Power Flow Analysis

The load flow analysis aims to determine the magnitude and voltage phase angle of each bus and the active power and reactive power flowing in each channel [6].

In completing the power flow analysis, the bus is divided into three classifications, namely [6]:

1. Slack bus or swing bus.
2. Control bus or generator bus.
3. Load bus.

In the system bus, there are four parameters or magnitudes, namely:

1. Active power, symbolized as P.
2. Reactive power, symbolized as Q.
3. Voltage scalar value, symbolized as |V|.
4. Voltage phase angle, symbolized as θ.

Out of the four parameters, on each bus there are only two types of magnitudes determined [6].

Electrical Power

Electrical power is defined as the rate of conductivity of electrical energy in the electrical circuit. The units of electrical power are VA (volt-ampere), W (watts), or VAr (volt-ampere reactive). The absorbed power (energy transmitted in any given time range) by a load at any time is the product of the voltage across the load in units of V with the current flowing in the load in unit A. In a three-phase AC, there are three types of power known, namely:

1. Virtual power;
2. Active power; and
3. Reactive power [6].

These three types of power form a complex power, with their absolute values described as virtual power. Active power is a real component, while reactive power is an imaginary component.

The occurrence of three types of power on the AC back and forth due to the existence of alternating current caused by the voltage that is also back and forth, there is a current delay to the voltage (current lagging) or current that precedes the voltage (current leading). The multiplication between effective voltage the effective current supplied by an AC source is called the virtual power, symbolized by S with the VA unit. P symbolizes active power in unit W. Reactive power as imaginary power is symbolized by Q with VAr units. The angle of lagging (or leading) of the current to the voltage is represented by φ. The efficiency of the received power is called the power factor, which is denoted by cos φ [6].

$$P_1 = V_f \cdot I_f \cdot \cos\phi \tag{1}$$

$$P_3 = \sqrt{3} \cdot V_L \cdot I_L \cdot \cos\phi \tag{2}$$

$$Q_1 = V_f \cdot I_f \cdot \sin\phi \tag{3}$$

$$Q_3 = \sqrt{3} \cdot V_L \cdot I_L \cdot \sin\phi \tag{4}$$

$$\boldsymbol{S} = P + jQ \tag{5}$$

$$\bar{S} = \sqrt{P^2 + Q^2} \tag{6}$$

To obtain the value of active power in single-phase is shown in Equation (1), while Equation (2) shows how to obtain the value of active power in three-phase. The way to obtain the value of reactive power in single-phase is shown in Equation (3), while Equation (4) shows how to obtain reactive power values in three-phase. Equation (5) shows the relationship between the complex power and its constituent components, i.e. the active power as the real component and the reactive power as the imaginary component. In Equation (6), it is shown that the virtual power is the absolute value of the complex power [6].

Capacitors

Capacitors are widely used in power systems for power factor correction. Inductive loads will absorb the reactive power, resulting in a voltage drop at the receiving end. With the installation of capacitors, the load will be supplied by reactive power supply, preventing voltage drop. Compensation by capacitors can reduce the absorption of reactive power system by the load. Thus, the voltage drop that occurs on the system can be then reduced. Setting the voltage using capacitors, in addition to fixing the voltage profile, can also increase the power factor value [6].

Variable Frequency Drive

Variable frequency drive (VFD), or often called variable speed drive, is a motor speed regulator by changing the frequency supplied into the motor. This frequency value setting is intended to obtain the desired motor rotation and torque speed or as needed. In simple terms, the basic principle of VFD is to alter the frequency by converting AC voltage into DC voltage then convert to as AC voltage again with different frequency that can be set using microcontroller and MOSFET [7].

III. Method of Research

This study used two main sources as initial input, specifically reference study and data retrieval. In accordance with Figure 4, the reference study was conducted first to determine the direction of this study. In the study phase of thesereferences, theories will be collected relating to:

1. Transfer of water from underground to the surface using pumping techniques.
2. Transfer of water from one place on the ground to another with a difference in elevation, using pressure pumping techniques or gravity assist.
3. Structures in the water pumps, the types, and drives used.
4. Consumption of electrical energy and its derivatives (consumption of electric power) which is used to drive the water pump.

Data acquisition stage is the next part done on PDAM.

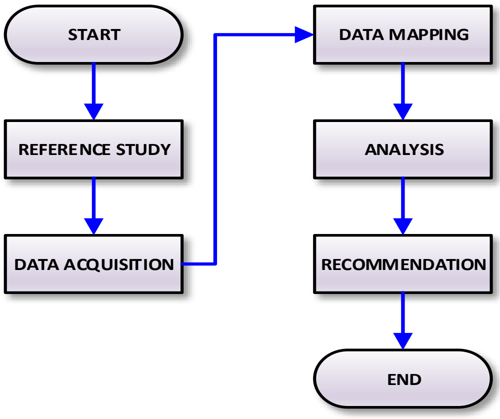

Fig. 4Steps of the research.

After the data collection is complete, then data will be mapped to determine the infrastructure built by PDAM geographically and do the classification of data that has been collected.

Stage analysis is done to draw the theory based on the investigation of each data mapping that has been done before. The theory will be tested and clarified as necessary with the data collected and with the general requirements issued by the Energy and Natural Resource Ministry of Indonesia with respect to energy efficiency in water production. Electrical simulations performed are experiments of adding capacitor (per pumping station) and adding VFD device (on every pump motor) [8].

The final stage of this research is to deliver recommendations related to the results of analysis for each pumping station in PDAM.

IV. Results and Discussions

Pump Units Data

The lists of pumping stations are Wendit 1, Wendit 2, Wendit 3, Mojolangu, Badut, Sumbersari, Istana Dieng, and Supit Urang. As a special case, Wendit 1 and Wendit 3 will be displayed in combination due to the very close location and the power supply from PLN is a single contract (including kWh meter and kVArh meter). Table 1 shows all data of pump unitsin the pumping stations under the management of PDAM.

TABLE IPUMPING STATIONS OF PDAM

ID	PUMPING STATION	MOTORS		MAX. POWER					MAX. PRODUCTION CAPACITY		
		OP.	ALL	PER MOTOR		OPERATING		PF	FLOW	POWER CONS	SEC
				P	Q	P	Q				
				kW	kVAr	kW	kVAr	%	$l \cdot s^{-1}$	$kW \cdot l^{-1} \cdot s$	$kWh \cdot m^{-3}$
C-1-1	WENDIT 1	3	4	200.00	150.00	600.00	450.00	80.00	170.00	1.18	0.33
C-2-1	WENDIT 2	3	4	200.00	150.00	600.00	450.00	80.00	170.00	1.18	0.33
C-3-1	WENDIT 3	4	5	147.00	91.10	588.00	364.40	85.00	110.00	1.34	0.37
C-4-1	MOJOLANGU	2	3	132.00	74.80	264.00	149.60	87.00	100.00	1.32	0.37
C-4-2	MOJOLANGU	2	3	166.00	107.20	332.00	214.40	84.01	110.00	1.51	0.42
C-5-1	BADUT	1	1	15.00	9.30	15.00	9.30	84.99	16.70	0.90	0.25
C-5-2	BADUT	1	1	15.00	9.30	15.00	9.30	84.99	21.70	0.69	0.19
C-6-1	SUMBERSARI	1	1	5.50	3.40	5.50	3.40	85.06	4.70	1.17	0.33
C-7-1	ISTANA DIENG	1	1	15.00	9.30	15.00	9.30	84.99	21.70	0.69	0.19
C-8-1	SUPIT URANG	1	1	15.00	9.30	15.00	9.30	84.99	21.70	0.69	0.19
TOTAL						**2,449.50**	**1,669.00**				

History of Electric Energy Consumption of PDAM

Figure 5 shows the history of electricity consumption used in Wendit 1 PumpingStation, which is based on electricity usage and bill from January 2014 to July 2016.

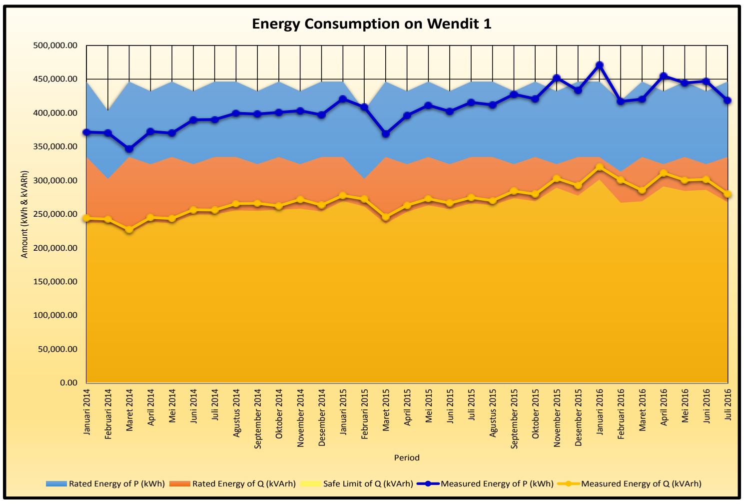

Fig. 5History of electric energy consumption of Wendit I Pumping Station.

History of Water Production of PDAM

Figure 6 shows the history of water production visually. The production of water in Wendit 1 Pumping Station is on average 66.53% when compared to the value it should be. From the plotting formed, the existing trends tend to be constant. As for the SEC produced is still too high, i.e. 0.49 $kWh \cdot m^{-3}$ when compared with the provisions of the Energy and Natural Resources Ministry for a maximum of 0.4 $kWh \cdot m^{-3}$ [9].

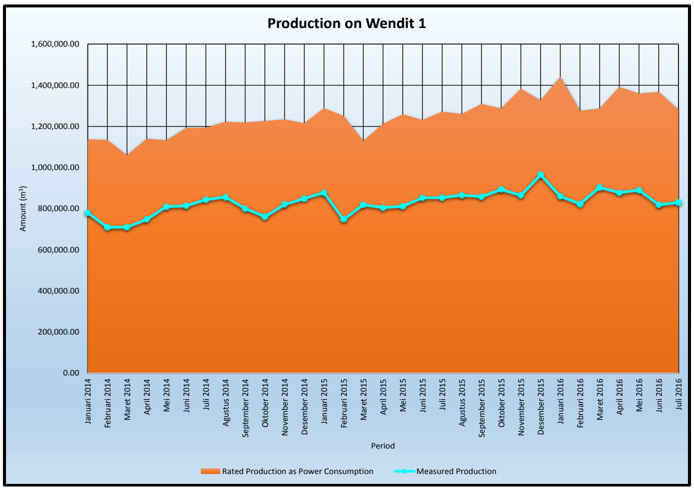

Fig. 6 History of water production of Wendit I Pumping Station.

Measurement Comparison

This chapter will present data validation of kWh meter reading and kVArh meter in Wendit 1, Wendit 2, Wendit 3, and Mojolangu PumpingStation. The four pumpingstations are chosen because there are installation of voltmeters and amperemeters in each pump motor and the data is recorded automatically on the data logger on hourly basis.

TABLE II MEASUREMENT COMPARISON OF WENDIT 1 PUMPING STATION ON JULY 2016

	Data Logger	PLN	Error
Monthly of Active Energy Consumed (kWh)	415,344.96	418,639.10	-3,294.14
Monthly of Reactive Energy Consumed (kVArh)	277,708.04	279,957.93	-2,249.89

The data that can be accessed freely is limited because of the security protocol, so this study selects log on a single month only, i.e. per July 2016 at Wendit 1, Wendit 2, Wendit 3, and Mojolangu Pumping Station. The method for performing these measurements is to add up the multiplication product of the voltage with the current of each pump motor by $\sqrt{3}$ of each measurement period. Since the time of measurement is in hourly basis, then each measurement represents the hour value (h) of kW and kVAr.

At Wendit 1, there are data log for pump motor 1, pump motor 2, pump motor 3, and pump motor 4. From data log and PLN measurement, the information as in Table 2 has been obtained.

Simulation Result

Simulation is used to determine how the speed, slip, load, and voltage of each pump motor at the time of starting.Figure 7 shows the simulation of power flow of capacitor mounting at Wendit 2 PumpingStation based on measurement from PLN. In the simulation,it can be seen that the installation of capacitors with 331 kVAr capability will produce active power of 719 kW and 0.49 kVAr of reactive power, with 3 pumps operating simultaneously.

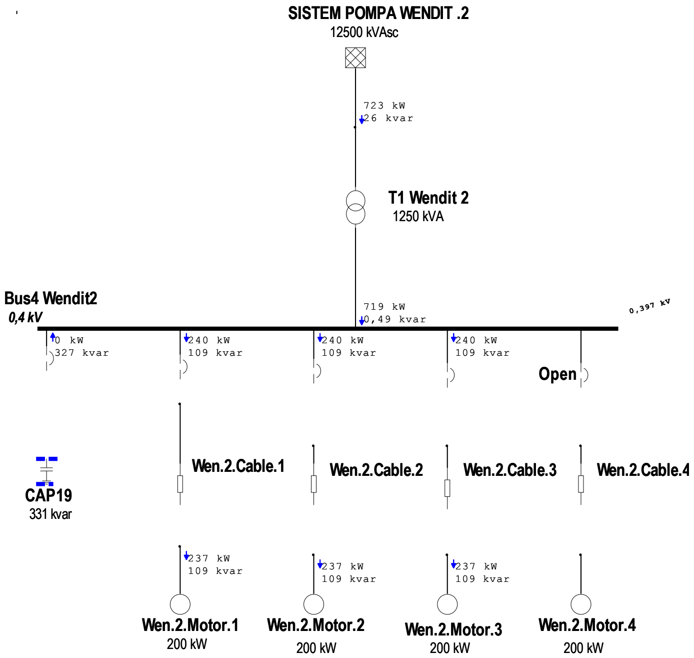

Fig. 7Simulation result of installation of capacitor in Wendit 2.

The motor starting simulation performed at Wendit 2 PumpingStation is based on the normal condition, i.e.three pumpsoperate out of four. Wendit 2 Pumping Station aimsone pump at stand-by, with the remaining pumps operating simultaneously, and one pump taking over every 1,000 hours. Given the conditions above, it will create an event of motor starting. In Table 3 it is shown that the event scenario of motor starting at Wendit 2.

TABLE IIIWENDIT 2 PUMPING STATION MOTOR STARTING EVENTS

TIME (s)	MOTOR ID	EVENT
1.000	WENDIT.2.MOTOR.1	START
5.000	WENDIT.2.MOTOR.2	START
10.000	WENDIT.2.MOTOR.3	START
20.000	WENDIT.2.MOTOR.4	START
25.000	WENDIT.2.MOTOR.1	STOP

The normal conditions occurring at Wendit 2 are described at about 15 s to 20 s, in which the three Wendit 2 pumps operate and one Wendit 2 pump is not operating. The transition in the case of a motor pump turnover at Wendit 2 is at 20 s to 25 s, where the pump motor previously not operational is started, and after the pump reaches stability then the replaced pump is stopped.

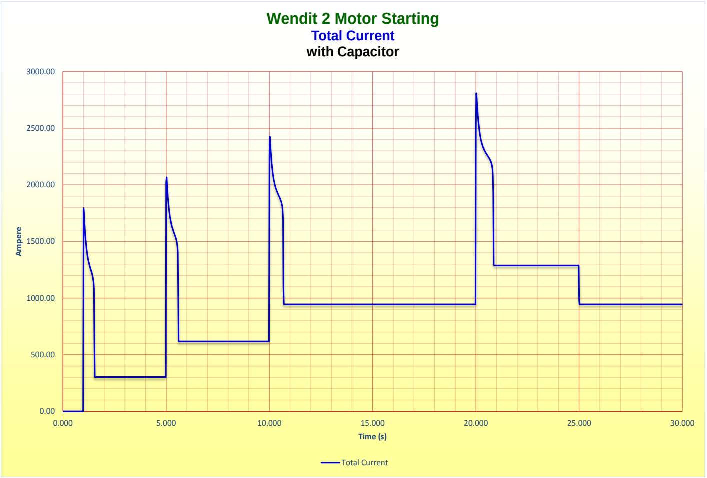

Fig. 8 Motor starting simulation on Wendit 2 shows total current on main bus using capacitor.

Both Figure 8 and 9 using the same scale, therefore it can be directly compared between the installation of capacitors and the use of VFD. As shown in Figure 9, on this installation without using the VFD, the process of starting the pump motor requires a high starting current surge, with the order about six times (600%) higher than the FLA of the motor.

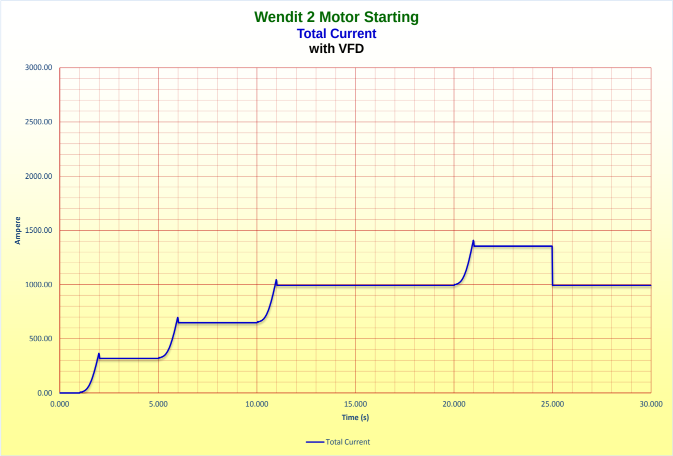

Fig. 9 Motor starting simulation on Wendit 2 shows total current on main bus using VFD.

The first motor of Wendit 2 has a starting current surge of up to 1,778 A, while its own FLA is 308 A. Similarly, it occurs in the installation using capacitors, as shown in comparison when using VFD, as shown in Figure 10, the starting current surge is reduced to only 10%. Starting process using VFD is very different from starting without one. Figure 10 and 11 respectively displayed the ratio of speed and motor slip on one motor at Wendit 2 Pumping Station between VFD using and without VFD. From both plotting, it can be analyzed that without using VFD the motor accelerates to its nominal speed faster than when using VFD, but without using VFD there is a significant large amount of slip at the beginning and it breaksdown in a slower rate. Slip that is not immediately reducedis what makes the current surge so high.

Fig. 10 Motor starting event on Wendit 2 without installation of VFD.

The use of VFD helps to reduce the current surgeon the starting event. The high current surge can result in the active power absorbed beyond the installed power contract, which in turn resulted in excess power on the consumer of PLN. However, as the motorstarting event happensonly once or twicein a month, it does not result in significant losses when compared with VFD procurement investment. Installation of capacitors will further contribute positively to the energy savings under normal conditions.

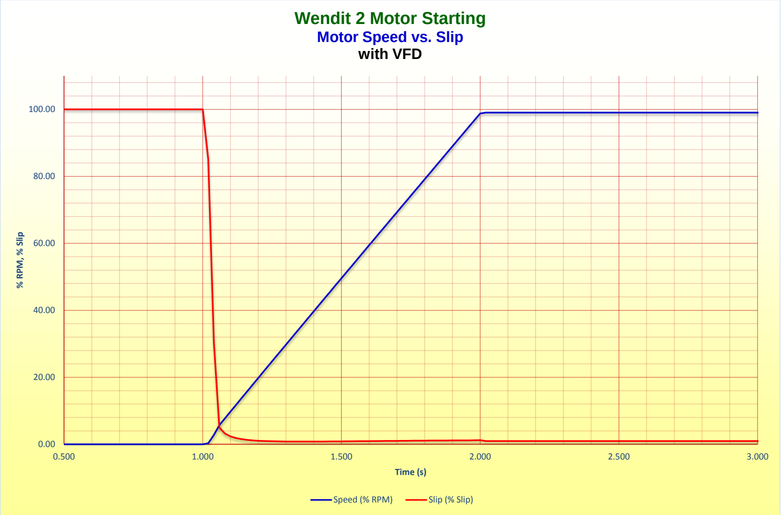

Fig. 11 Motor starting event on Wendit 2 with installation of VFD.

Final Recommendations

From the results of the analysis, there are several recommendations for PDAM, especially for each pumpingstation. Table 4 is the recommendation matrix for each pumping station.

In general, it is recommendedto install data logger for all pumping stations, to install the flow meters (with its data logger) for each point of water send start and receive station, to repair motor for Wendit and Istana DiengPumping Station, to install additional capacitor for Wendit 1 and Istana DiengPumping Station, and to install VFDs for Wendit 1 Pumping Station.

TABLE IVTHE RECOMMENDATION MATRIX

Pumping Station	Data Logger	Flow Meter	Motor Repair	Schedulling	Capacitor	VFD
WENDIT 1	YES	YES	YES	YES	50 kVAr (1000 μF)	YES
WENDIT 2	YES	YES	YES	YES	-	-
WENDIT 3	YES	YES	YES	YES	-	-
MOJOLANGU A	YES	YES	-	YES	-	-
MOJOLANGU B	YES	YES	-	YES	-	-
BADUT A	YES	YES	-	YES	-	-
BADUT B	YES	YES	-	YES	-	-
SUMBERSARI	YES	YES	-	-	-	-
ISTANA DIENG	YES	YES	YES	YES	1 kVAr (20 μF)	-
SUPIT URANG	YES	YES	-	YES	-	-

V. Conclusions

From the results obtained from this study, it can be drawn some conclusions as follows:

1. Difficulty occurs when having to look in detail of the energy consumption of each pump, especially the power factor that should be monitored respectively. Provision of a spare pump will not have a major effect on efficiency improvements when data logging of active and reactive energy consumption per pump is not present. In addition, water production per pump must also be monitored so that the SEC value can be monitored in each pump. Therefore, it is recommended to install data logger in each pump, whichinclude voltmeter, amperemeter, power factor meter, and water flow meter.
2. In the case of Wendit with Mojolangu, no water distribution from Wendit 1 and Wendit 2 to Mojolangu was found, and also from Mojolangu to Tlogomas reservoir and to the customer. This resulted in the inability of SEC in Mojolangu to be independently determined. In addition, water leaks between pump stations and reservoirs are also undetectable. Therefore, it is recommended to install a water flow meter equipped with data logger at each pipeline output point from the pumping station, any pipeline output point from a high water source, or from gravity assist reservoir.
3. The global SEC values are too high, indicating the pump motor or mechanical problem or damaged. Therefore, important recommendations include the replacement or improvement of the pump motor and mechanical so that the actual SEC value will reach the ideal SEC or maximal value of 0.4 kWh·m^{-3}.
4. Capacitor installation is only effective at Wendit 1 and Istana DiengPumping Station, in order to avoid the cost of reactive power excess determined from PLN, with gained efficiency about 64% of active power consumption or equivalent power factor of 84.23%.

5. Installation of VFD is only effective at Wendit 1 and Wendit 3 Pumping Station, if aimed to avoid excessive power cost determined from PLN.

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