STUDY ON DESIGNING THE AUTOMATIC SYSTEM CONTROLLING PUMP HEAD IN WATER SUPPLY SYSTEMS

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SUMMARY
In a water supply system, water demand always changes over time, affecting head, flow and power of pump. This paper presents the way to design an automatic system controlling head of the pump in order to meet the requirement of water demand changing. This system is integrated several major equipment including PLC S7-200 (Programable Logic Controller), inverter MICNO-KE300, pressure sensor sensor. When water head or flow in the system changes, electrical signal from the sensors are transferred to PLC that controls the inverter to change pump speed. In such the manner, pump head will be changed to the required pre-set head value. Experimental results show that the designed system realized tracking to preset head value with error within permitted. A cost-benefit analysis was also conducted in the case of head to be reduced about 20% compared to the identification value showing that energy can be saved up to 34%.
Keywords: Automatic control, inverter, pump head, water supply system.

1. INTRODUCTION
In water supply systems, the demand for water always changes hourly. During peak hours, much water is used leading the pressure of the system decreases, this affects the water volume of users; On the contrary, during off-peak hours, if the flow is kept as peak hours, the pressure in the pipeline increases easily causing damage to equipment such as valves, locks… even making the pipes break. In order to regulate the flow in the water supply system at different times of use, it is often useful to use several methods such as the construction of water towers and water tanks to regulate the unbalanced water between the supply and demand, and can produce the required water pressure; using the valves on the piping of the pump; adjusting by opening and closing the pumps in the system; or changing the rotational speed of the pump by hydraulic coupling. These methods are limited in terms of manual, labor-intensive, power-consuming, and may cause water hammer in the system and can therefore cause damage to the system. In addition, the pump usually uses induction motor operating at a single speed. Therefore heads and flows of pumps cannot be controlled accordingly to changes of demands. In the world and Vietnam as well, there were a number of studies about pump operation in the water supply system, in order to optimize the operation process, management and repair the water supply system as a union system.

Jingsong Wang and Mietek A. Brdys (2008) optimized the pump operation with a series of scenarios of water requirement changing in one-day cycle by providing water scenario forecasts for next time and using the soft-switching mechanisms between the pump control strategies.

Akayleh *et al.* (2009) used PLC and variable frequency driver (VFD) to control dynamic conditions of pumps such as starting, switching off, or switching from one operational state to another. Using the PLC and VFD will adjust all oscillations in the system smoothly until the desired operating state is achieved. Therefore, hydraulic shock and dynamic effects on mechanical elements in the water supply system can be prevented. Furthermore, the system also avoids dynamic currents in three-phase AC power supplies.

Jiang LinJie *et al.* (2011) used PLCs and Proportional Integral Derivative (PID) controllers built-in frequency correction functions to control system controllers and actuators to maintain pressure in the system. This system saves 54.4% of energy consumption compared to the method of using a damper.

In Vietnam, there were also some researches to optimize the pump operation in the water supply system. Le Chi Nguyen and Nguyen Anh Tuan (2013) found solutions to adjust the rotation of irrigation pump in zones effected tide to ensure that the pumping station receives enough water in the low water source condition by variable frequency devices.

Mai Thi Thuy Duong (2013) studied the application of inverter pumps and compressed air stations in supplying water for some high buildings in Da Nang city. The results showed that the combination of inverter pump and compressed air stations can eliminate the construction of a water tank, reduce the volume of compressed air station, reduce energy costs, extend pump life and, therefore, increase economic efficiency for water supply systems.

In this paper, we design an automatic control system for regulating the pump head of small-scale water supply system using single phase pump. The system is integrated with several major equipment including PLC (Programable Logic Controller), inverter, pressure sensor.

2. RESEARCH METHODOLOGY

2.1. Controlling principle of pump head in water supply system

The relationship between flow, head, power and rotation of a pump is shown in equations from 1 to 3 and figure 1.

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \quad (1) \qquad \frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2 \quad (2) \qquad \frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3 \quad (3)$$

Q_1, H_1, P_1: flow, head and power when pump is working with rotation number n_1;

Q_2, H_2, P_2: flow, head and power when pump is working with rotation number n_2.

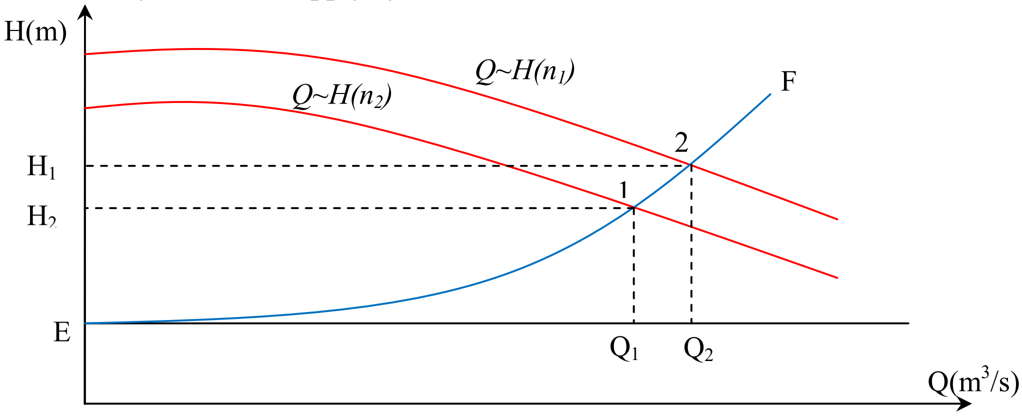

Figure 1. Characteristics of pump when rotation number changes

2.2. Selection of major electrical, sensor and metering equipment in the water supply system

Figure 2. Centrifugal pump DETAX

2.2.1. Pump

The pump used in this study is centrifugal pump DETAX type CMA-100M, single phase, 220 - 240 V power: 0.74 KW, flow: 20 - 100 l/min; Maximum head: 28 m and speed: 2850 r/min (Figure 2).

2.2.2. Inverter

Inverter has a simple operation principle: the input is a one-phase AC power supply, the diode rectifier bridge and the capacitor perform rectification and filter the AC power to a DC source. The IGBT (insulated gate-bipolar transistor) transforms the DC current into a symmetrical alternating current by pulse-width mode (PWM).

Inverter will adjust the rotation speed of the motor by changing the frequency of current supplied to the engine. This "smart" feature helps the device reduce power consumption.

With respect to the selected pump, the inverter is selected to satisfy the condition: Inverter power is larger than the motor pump power so MICNO-KE300 inverter is used in this study. Connecting the inverter input and output MICNO-KE300 to the pump motor as shown in figure 3.

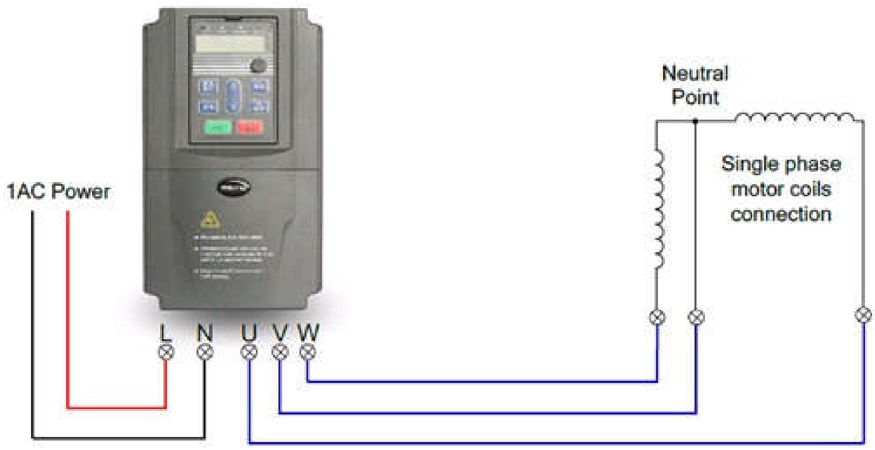

Figure 3. Scheme for connecting MICNO-KE300 inverter with single phase motor

2.2.3. Programable Logic Controller PLC S7-200

Programable Logic Controller (PLC) is widely used in the industry that is the ideal solution for the automation of production processes. A PLC has Input Module block, CPU block (Central Processing Unit) and Output Module block.

The Input module function is to receive digital and analog data and convert them into signals for CPU. CPU decides and executes the controlling programs. The Output module transfers the control signals from CPU to analogue, digital data that controls the objects. In this study, we used the Siemens PLC S7-200, which is a PLC for logic control applications, sequential control. Structure diagram of the PLC is shown in figure 4.

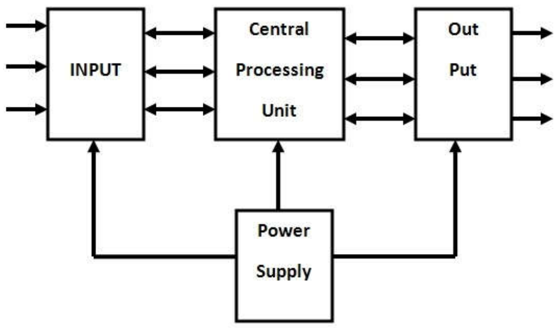

Figure 4. Structure diagram of Programable Logic Controller PLC S7-200

2.2.4. Pressure sensor and pressure gauge

** Pressure sensor*

Pressure sensor is mounted on the pump's flow pipe to monitor the pressure and transfers obtained signals under electrical signals to PLC from which the pump is controlled. In order to match the pressure of the pump, this study used pressure sensor RJ-131, a type of voltage sensor with a range 0 to 1MPa (0 - 10 Bar) shown in figure 5.

** Pressure gauge:* to measure the true value of the pump, we installed an additional pressure gauge on the discharge pipe, next to pressure sensor, measuring range 0 - 5 bar, as shown figure 6.

Figure 5. Pressure sensor RJ-131

Figure 6. Pressure gauge

2.2.5. Rotational speed meter HT-3100 of ONO-SOKKI

To messure the pump speed, the Rotational Speed Meter HT-3100 of ONO-SOKKI as in figure 7 is used in this study.

Figure 7. Rotational speed meter HT-3100 of ONO-SOKKI

2.3. System model and working principle

* *System model*

A basic diagram of a water supply system with automatic head control system installed as shown in figure 8.

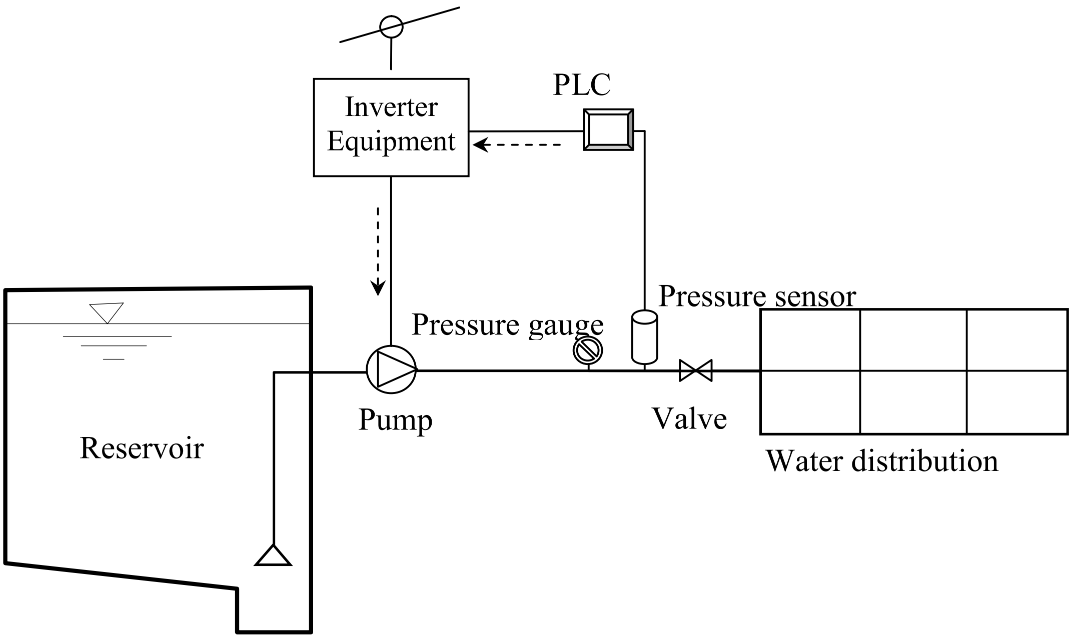

Figure 8. Diagram of a water supply system with automatic head and discharge control system

The real system based on above diagram is installed as shown in figure 9.

Figure 9. Automation system controlling pump head and discharge

* *Working principle of water supply system with inverter*

When operating the water supply system, the inverter-controlled pump will be started up until the pre-set pressure is reached and inverter equipment will keep pump speed stably. In the case pressure in discharge pipe changes due to varying demand, the membrane of the pressure sensor will be changed in accordance with the change in pressure. PLC will process this change and give the proper control signal to inverter in order to control pump speed to meet the pre-set pressure of the water supply network.

As water consumption in system increases or pressure decreases lower than the setup pressure limit, PLC controls the inverter to increase current frequency to the pump to increase pump speed. Accordingly, pressure increases until the pre-set pressure is reached. In contrast, as pressure in the system increases higher than the setup pressure limit, PLC controls the inverter to reduce current frequency to pump motor to adjust pump speed to be reduced. Therefore, pressure in the system will be reduced until the preset pressure value.

With this design, the system will monitor water pressure in discharge pipe and controls pump speed to maintain the required pressure range automatically.

3. RESULTS AND DISCUSSION

3.1. Control program

The basis for determining pressure stability problem:

- Pressure sensing range: 0 - 10 bar;
- Control input of inverter is in the range of 4 - 20 mA;
- Largest pump head: 2.8 bar.

The target of the problem is to maintain a certain pressure range (suppose that the range is 2.0 - 2.5 bar corresponding to the output signal from 7.0 to 8.0 mA of the RJ-131 sensor). If the pump head smaller than 2.0 bar, i.e. corresponding output current is smaller than 7.0 mA, PLC controls inverter to increase frequency, then pump head will be increase to the preset pressure range accordingly, and vice versa if pump head greater than 2.5 bar.

Programing the problem by using the Micro/WIN program as shown in figure 10.

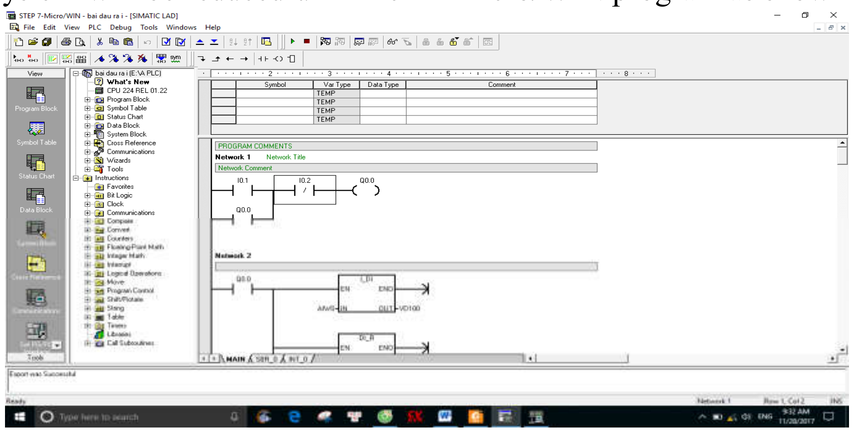

Figure 10. Control program

Running the program with S7-200 software as shown in figure 11.

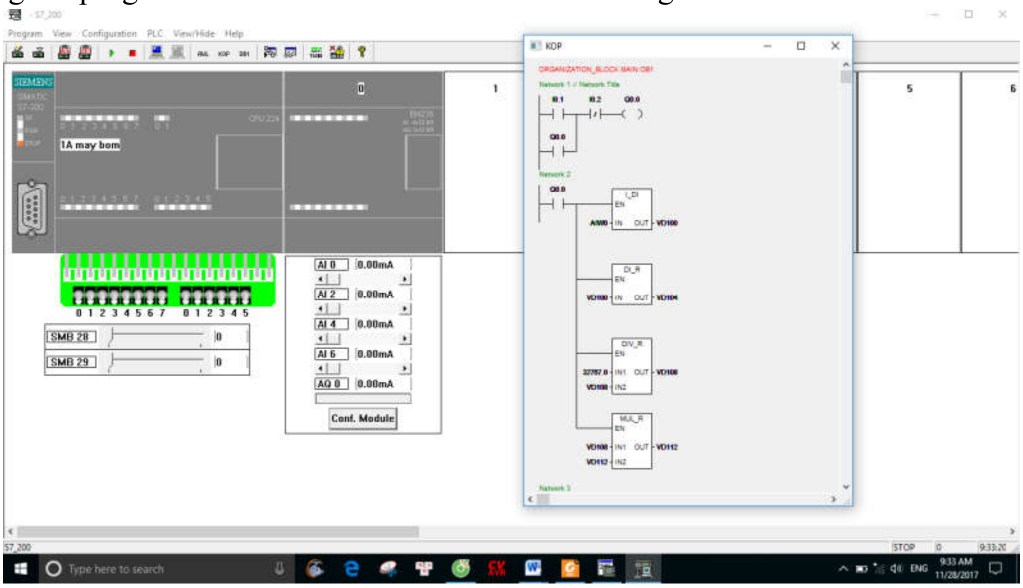

Figure 11. Running the program on Step 7 MicroWIN software

3.2. Results and discussion

Table 1 shows the number of pump rotations, delivery head, discharge of the pump corresponding to obtained current frequency by using inverter.

Table 1. Rotations, delivery head, discharge of the pump corresponding to current frequency

N0	Frequnecy (Hz)	Pump speed (r/min)	Largest delivery head (Bar)	Largest delivery head (m)	Total head (m)
1	20	1192	0.20	2.0	10.0
2	30	1745	0.85	8.5	16.5
3	40	2200	1.60	16.0	24.0
4	45	2336	1.92	19.2	27.2
5	50	2685	2.50	25.0	33.0
6	55	2780	2.80	28.0	36.0
7	60	2910	3.20	32.0	40.0

Relationship between frequency and pump rotation is displayed in figure 12.

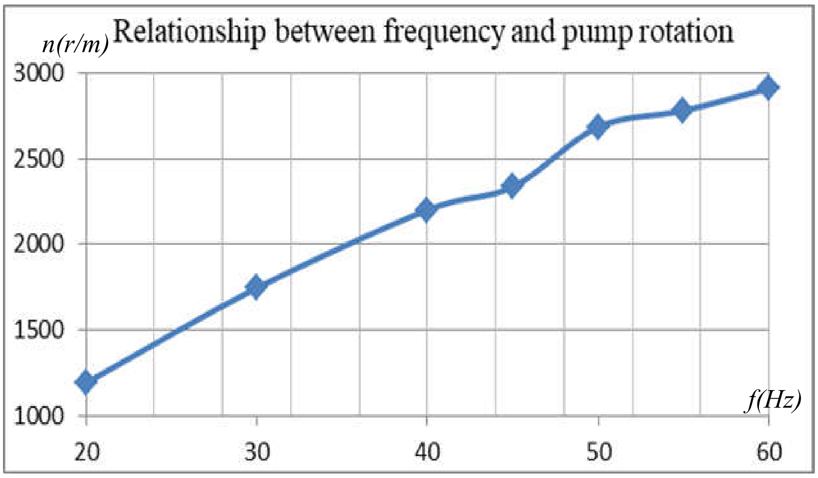

Figure 12. Relationship between frequency and pump rotation

Relationship between delivery head and pump rotation is displayed in figure 13.

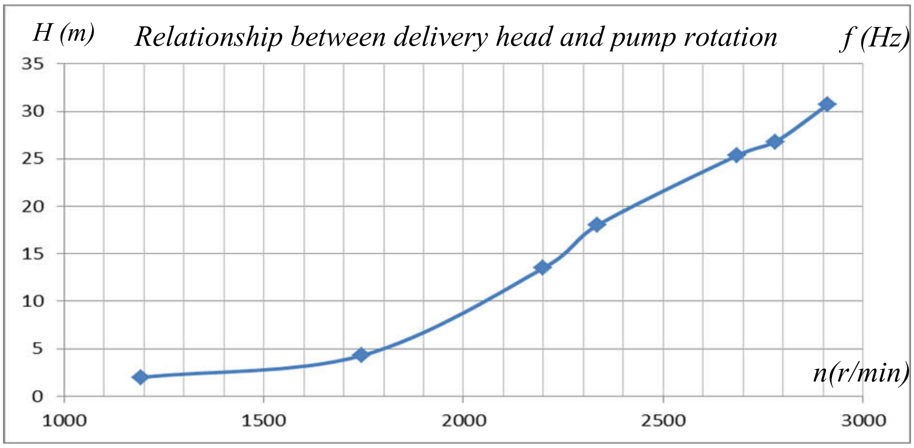

Figure 13. Relationship between delivery head and pump rotation

Relationship between discharge and pump rotation is displayed in figure 14.

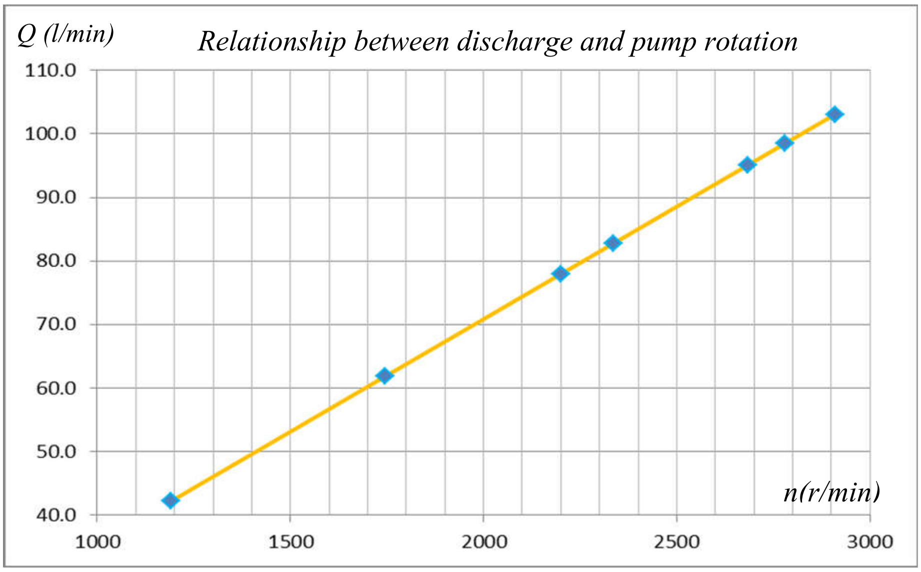

Figure 14. Relationship between discharge and pump rotation

The calculation error between total measured head and calculated head is shown in table 2.

Table 2. The calculation error between total measured head and calculated head

N0	Frequency (Hz)	Pump rotations (r/min)	Measured total head (m)	Calculated total head (m)	Error (%)
1	20	1192	10.0	10.0	---
2	30	1745	19.5	21.4	9.90
3	40	2200	24.0	26.2	9.28
4	45	2336	27.2	27.1	0.52
5	50	2685	34.5	35.9	4.16
6	55	2780	36.0	35.4	1.73
7	60	2910	40.0	39.4	1.39

Table 2 shows that when the pump operates with low frequency range, error between measured head and calculated head is rather high, but it is small when the pump operates with high frequency. This error can be acceptable.

** Calculate the pump power according to pump head, discharge and respective speed*

In table 3, column 3 and 4 are the computed and and measured pump power according to the number of pump rotations. Column 5 shows the corresponding error, it is also quite high when pumps running with low speed, but relatively small in high pump speed.

Table 3. Computed and measured pump power with corresponding pump speed and their error

N0	Pump speed (r/min)	Computed power (KW)	Measured power (KW)	Error (%)
1	1192	0.086	0.057	34.22
2	1745	0.155	0.178	14.73
3	2200	0.343	0.357	4.16
4	2336	0.440	0.427	2.99
5	2685	0.649	0.649	0.02
6	2780	0.700	0.720	2.81
7	2910	0.815	0.826	1.35

** Calculate economic efficiency*

In the case of using the same pump without inverter, the pump will operate with current frequency of 50 Hz during entire operating time. Therefore, the actual pump speed is n_1 = 2685 r/min, the pump head would be 26.5 m and pump will produce a real power of P_1 = 0.649 KW.

In the case of supposed head needed to be at about 20 m, i.e. the head drop is about 20% compared to the normal head when pump operating with frequency of 50 Hz, PLC will control inverter to adjust current frequency to 45 Hz. Whereby the pump speed will decrease to n_2 = 2336 r/min and power consumption now only is P_2 = 0.427 KW.

So, the power saving would be: ΔP = 0.649 KW - 0.427 KW = 0.222 KW ≈ 34%.

4. CONCLUSIONS

This paper shows the way to install of a water supply system by using PLC S7-200 - integrated inverter MICNO-KE300 and pressure sensor RJ-131 to automatically control pump speed with respect to head or discharge changing. The process of starting and stopping the pump is very smooth. To start, the inverter adjusts current frequency increased gradually, i.e. pump speed also increased gradually until the required head is reached. Then inverter keeps the pump operating at this steady-state. To stop, inverter adjusts current frequency decreased gradually until pump stopped. Accordingly, this can make pump life increase.

The steady head of pump in this study is set in the range of 2.0 - 2.5 bar (20 - 25 m), corresponding to current frequency of about 45 Hz and with the pump speed of 2336 r/min. The result shows that, when using inverter in the system, energy can be saved up to 34%. Hence, in a very large water supply system, the cost will be reduced significantly when using the inverter to automatically control pump speed. This result will be a premise for application to large-scale water supply systems using large-pump three-phase motor.

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NGHIÊN CỨU THIẾT KẾ HỆ THỐNG TỰ ĐỘNG ĐIỀU KHIỂN LƯU LƯỢNG VÀ CỘT ÁP MÁY BƠM TRONG HỆ THỐNG CẤP NƯỚC

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TÓM TẮT

Trong hệ thống cấp nước, nhu cầu sử dụng nước luôn luôn thay đổi theo thời gian làm ảnh hưởng đến cột áp và lưu lượng tại các điểm lấy nước. Bài báo này trình bày kết quả nghiên cứu thiết kế hệ thống tự động điều khiển cột áp của bơm trong hệ thống cấp nước quy mô nhỏ nhằm đáp ứng được các yêu cầu dùng nước thay đổi. Hệ thống là sự tích hợp các thiết bị gồm: biến tần MICNO-KE300, bộ điều khiển lập trình PLC S7-200, các cảm biến suất và một số thiết bị phụ trợ. Kết quả thực nghiệm cho thấy, khi cột áp hoặc lưu lượng nước tiêu thụ thay đổi, tín hiệu điện thu được từ cảm biến sẽ được truyền về PLC dưới dạng tín hiệu điện. Căn cứ vào giá trị tín hiệu điện truyền về và giá trị được thiết lập trước, PLC sẽ điều khiển biến tần thay đổi tần số dòng điện và làm thay đổi số vòng quay của động cơ bơm từ đó sẽ làm thay đổi cột áp bơm cho phù hợp với giá trị yêu cầu của cột áp được thiết lập trước. Khi cột áp ống đẩy giảm xuống quá biên độ dưới, biến tần lập tức điều chỉnh tăng tần số làm số vòng quay của bơm tăng lên, cột áp bơm tăng lên và ngược lại. Sai số giữa tính toán và thực nghiệm có thể chấp nhận được. Nghiên cứu cũng đã tiến hành tính toán hiệu quả kinh tế của hệ thống cho thấy công suất của bơm có thể tiết kiệm tới 34% khi cột áp yêu cầu giảm khoảng 20% so với cột áp định danh của bơm.

Từ khóa: Biến tần, cột áp bơm, điều khiển tự động, hệ thống cấp nước.

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