

Water Pumping System with PLC and Frequency Control

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Abstract

In this study controlled water pumping system is designed, constructed, and modeled. The programming method of control of pumping flow rate is achieved by means of integrated programmable logic controller (PLC) and frequency inverter (FI). PLC main function is to determine the required flow rate levels and the related time intervals of the flow rate hold time. (FI) is used to control the dynamic change of temperature between various operating points. The designed system shows the capability for full control of pumping flow rate from zero to maximum for any required range of time in case of increasing or decreasing the pumping flow rate. All variables of the system will be changed gradually until reaching their needed working points. The mathematical model of water pumping system with PLC and frequency control is built based on MATLAB-SIMULINK. A test rig built and an experimental study was performed. From the analysis of the experimental starting dynamic characteristics of water pumping system and modeled characteristics, it was noticed that they are very similar.

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Keywords: PLC; Frequency Control; Water Pumping System; Dynamic Characteristics.

1. Introduction

Pumping equipments in the modern manufacturing systems may be used as main parts in many industrial activities, like chemical industries, food industries, etc. The automation of the pumping processes in those industries will certainly lead to improve their performance [1]. In Jordan about 18% of generated electrical power is consumed by three-phase-induction motors driven centrifugal pump in water pumping stations. From the analysis of the working conditions of water pumping systems, it is noticed that there are many problems, which face the work of such systems, as hydraulic hammers, dynamic stresses in mechanical parts, high starting currents in the three-phase-motor driven centrifugal pump, and energy saving problems [2].

A new single-switch parallel resonant converter for induction heating was introduced in [3]. The circuit consists of an input LC-filter, a bridge rectifier, and only one controlled power switch. The switch operates in a soft communication mode and serves as a high frequency generator. A voltage-fed resonant LCL inverter with phase shift control was presented in [4]. It was observed that the control strategy offered advantages in the megahertz operating region, where a constant switching frequency is required. The inverter steady state operation is analyzed using fundamental frequency analyses. A cost-effective high efficiency inverter with phase-shifted pulse

modulation scheme was proposed for medium power (5-30) kW induction heating applications is discussed in [5]. The proposed inverter accomplishes soft switching operation over a wide power regulation range. The actual power conversion efficiency reached was 96.7%.

A control method of reducing the size of the dc-link capacitors of a converter-inverter system was presented in [6]. The main idea is to utilize the inverter operation status in the current control of the converter. This control strategy is effective in regulating the dc-voltage level. Even the dc-link capacitor is arbitrarily small and the load varies abruptly. In [7], a method was proposed to accurately predict the minimum required temperature recovery, considering repeatability and accuracy of the leak detector by investigating the relation between temperature recovery time and applied pressures using PLC system. A methodology was demonstrated to design a PLC program that organizes the relation between the physical inputs and outputs of the pumping tools in manufacturing systems.

In [8], an experimental study was performed to investigate the effect of using two axes tracking with PLC control on the solar energy collected. The two axes tracking surface showed better performance with an increase in the collected energy up to 41% compared to the fixed surface. This study seeks to design, model, and experiment of fully automated water pumping system with PLC and frequency control, where the main PLC function is to control the required flow rate levels and the related time intervals of the pumping flow rate hold time. FI is

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used to control the dynamic change of pumping flow rate between various operating points.

2. Water Pumping System Design and Control

For the purpose of experimentation, the electromechanical system PLC-FI-Three phase induction motor-centrifugal pump pipeline was designed and constructed as shown in figure 1.

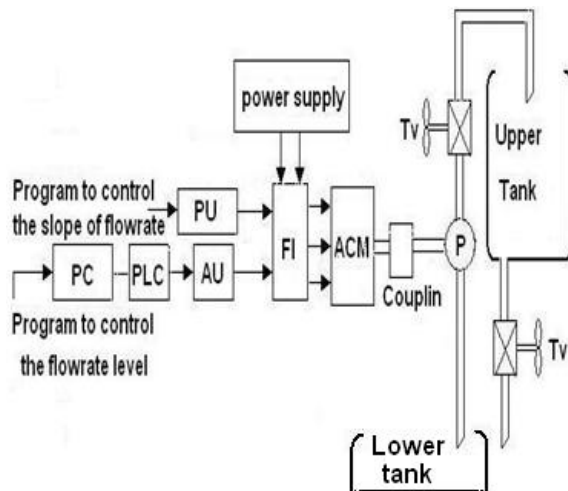


Figure 1. Water pumping system with PLC and frequency control.

Both the design of PLC and frequency controlled pumping system were performed, using an open loop and programming method of control in which stored instructions in memory of PLC was used to control the pumping flow rate. PC is a personal computer which is used to write the control program; then download it to the PLC through communication cable. The PLC is S7-200 type, which has 12 inputs, 8 outputs and 220 VAC supply voltage [9]. The PLC main function is to instruct the analog unit to go on or off and to state the required percentage output and the related hold time intervals. The analog unit function is to transfer the digital output value at the output of PLC into analog value, which ranges from zero to 10 VDC at the output of the analog unit. In the control program, different percentages of output voltage are supplied to the AC motor driven centrifugal pump by the frequency inverter, which is originally stated by the analog unit output, where 0 VDC equals 0% at the output of the frequency inverter and 10 VDC equals 100% at the output of frequency inverter.

FI is a one-phase input, three-phase output with a rated power of 0.95 KVA and a rated output current of 2.5A. ACM is a three -phase induction motor with a rated power of 0.37Kw at 50 Hz, and with a voltage of 240V and current of 1.8A for Δ connection [10]. P is a centrifugal pump which has the following data: flow rate 10-30 L/min, head 14-22m and nominal impeller speed 2900 rpm. P connects the upper and lower tanks with 0.5 inch steel pipes to provide an unlimited water supply for the system. TV is a throttling value which could be used for varying the flow rate manually. A venture meter was used to measure water flow rate, and a stop watch was used to measure the time. The rotational speed of the pump impeller was calculated using the following proportionality equation:

$$Q_a/Q_r = n_a/nr \quad (1)$$

Where:

Q_a : The actual flow rate of water.

Q_r : The rated flow rate of water.

n_a : The actual speed of motor.

nr : The rated speed of motor.

To investigate the system performance during starting towards different input signals, the frequency control laws which represent the frequency function of time, shown in Figure 2, were used. The control laws were started from the base frequency of 10 Hz through the starting time to reach reference frequency of 50 Hz. In case of direct connection to the supply network, the starting time equals zero as shown in curve 1 of figure 2, which represents step signal [11].

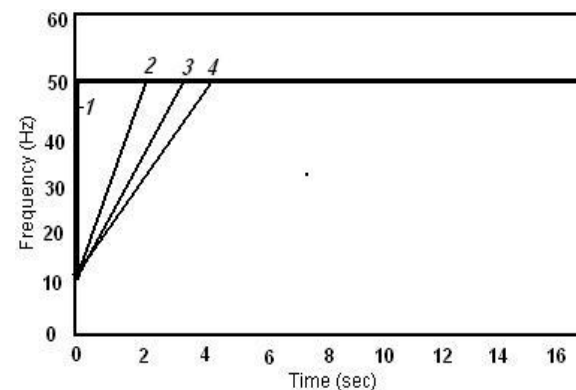


Figure 2. The programmed input frequency of time in case of starting

The curves 2, 3 and 4 in Figure 2, where obtained by using different ramp signals with starting time equal to 2 seconds, 3 seconds, and 4 seconds respectively. According to the different inserted control laws, the output flow rate of the water pumping system in starting condition change as a time function as shown in figure 3.

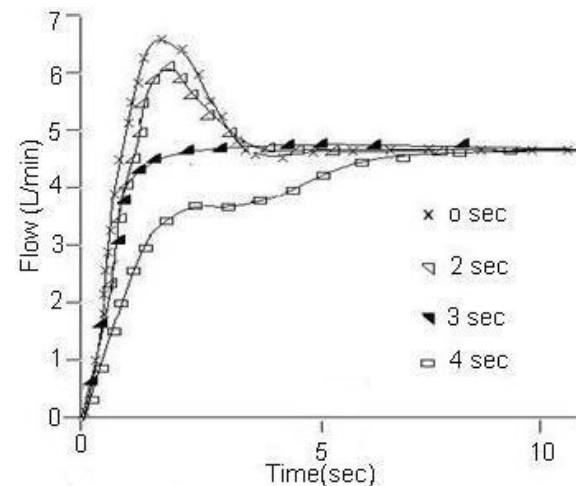


Figure 3. Flow rate vs. time according to the different inserted control laws

According to the different inserted control laws, the output pump speed of the water pumping system in starting condition changes as a function of time as shown in Figure 4.

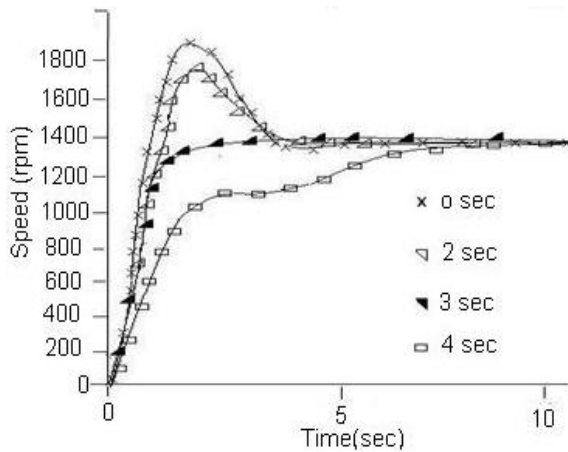


Figure 4. Speed vs. time according to the different inserted control laws.

From the analysis of starting curves in Figures 3 and 4, it can be noticed that in case of starting with step input signal, all output parameters of the water pumping system including speed and flow rate exhibited a high peak value with fluctuation until reaching the rated values. Considering other control laws, the range of vibrations decreased as time increased. Setting the starting time to 3 seconds exhibited very small oscillations that can be neglected. While setting the starting time to more than 3 seconds exhibit no oscillations [12, 13].

Figure 5 shows the variation of programmed frequency function of time. The control law was started from the base frequency of 0 Hz to reach 12.5 Hz with in 10 seconds, after that, the frequency will be stable for 15 seconds, then the frequency will be changed softly from 12.5 Hz to the 25 Hz through 10 seconds, later the frequency will be stable for 15 seconds, then the frequency will be changed softly from 25 Hz to 37.5 Hz through 10 seconds, after that the frequency will be stable for 15 seconds, later the frequency will be changed softly from 37.5 Hz to 50 Hz through 10 seconds, after that the frequency will be stable for 15 seconds, next the frequency will slow down softly to 25 Hz through 10 seconds, after that the frequency will be stable for 20 seconds, then the frequency will slow down softly from 25 Hz to 0 Hz through 10 seconds.

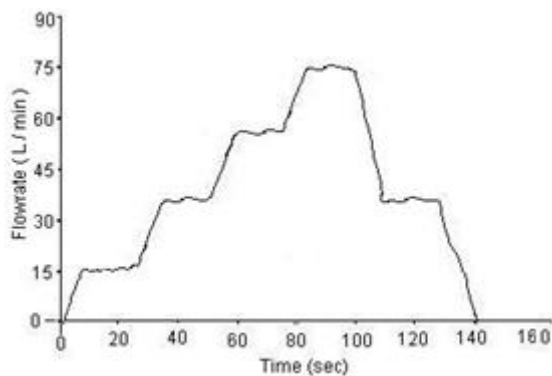


Figure 5. Input frequency vs. time

According to the control law, shown in Figure 5, the experimental output flow rate and experimental pump

speed of the water pumping system are shown in Figure 6 and figure 7.

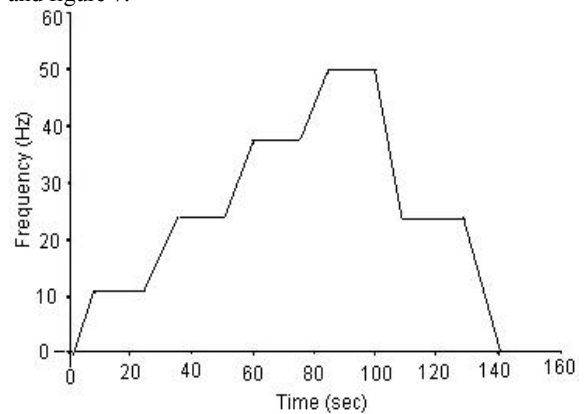


Figure 6. Flow rate vs. time.

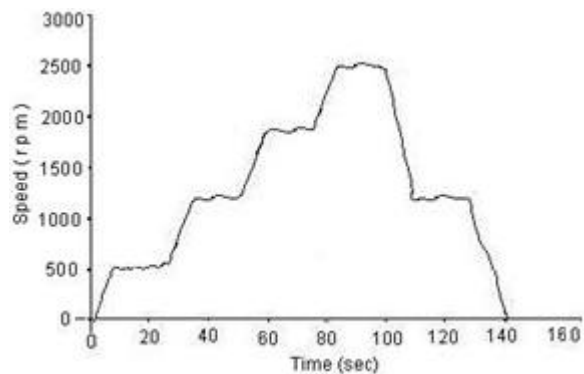


Figure 7. Pump speed vs. time.

Frequency inverter, according to the different incoming instructions of PLC through analog unit, operates the three-phase motor with the required percentage of voltage and frequency. Parameter unit is a type of programmer which is used to program the ramp up and ramp down time between each two controlled levels. So, frequency inverter has two types of commands:

1. Type of commands supplied by the PLC to the analog unit then to the frequency inverter to state the required level of flow rate and the hold time interval.
2. Type of commands supplied by parameter unit to control the ramp up and ramp down time to make a soft transition conditions between various operating levels.

It can be noticed from the curves in Figure 6 and Figure 7 that the experimented system shows the capability for full control of flow rate and pump speed from zero to maximum for any required range of time in case of increasing or decreasing the flow rate and pump speed. All variables of the system will be changed gradually until reaching their needed working points [14, 15].

3. Mathematical Model of the System

The mathematical model of water pumping system with PLC and frequency control will be done by using MATLAB-SIMULINK graphical interface Figure 8.

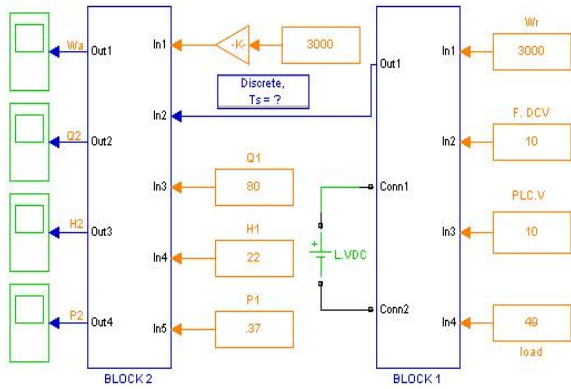


Figure 8. Mathematical model of water pumping system with PLC and frequency control.

The mathematical model consists of two blocks each of them has a specific function.

Block 1- The main function of this block is represent the vector control of a variable –frequency induction motor drive, which is available as a built using MATLAB library (see figure.9)[16]. In this block the main input signals are:

- Rated angular speed signal In 1
- Full value of dc controlled voltage signal In 2 ,this value is related of rated frequency of the system.
- PC or PLC voltage signal In 3
- Rated load torque signal In 4

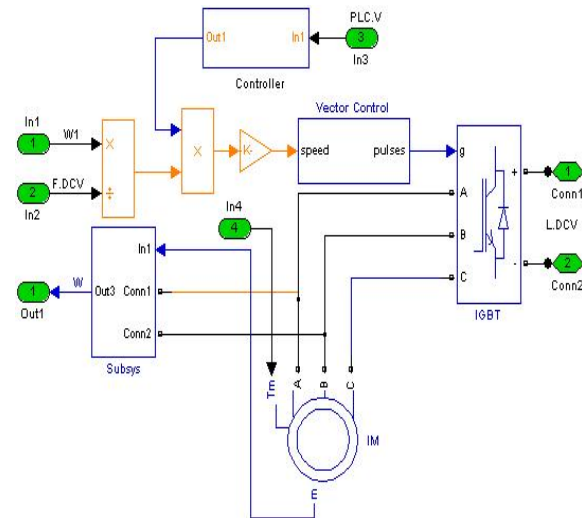


Figure 9. Vector control of a variable –frequency induction motor drive.

Block 2- This block contains the mathematical equations that are responsible for the main equations and relationships of pumping system calculation. The main inputs of this block are the rated of pump system parameters (Q_r, H_r, P_r) and the rated and actual speed values of the induction motor (n_r, n_a) (see figure.10).

Output values of this block diagram are presented as the main system response as follows:

$$Q_a / Q_r = n_a / n_r \tag{2}$$

$$H_a / H_r = (n_a / n_r)^2 \tag{3}$$

$$P_a / P_r = (n_a / n_r)^3 \tag{4}$$

Where:

H_a : The actual head of pump

H_r : The rated head of pump

P_a : The actual power consumption

P_r : The rated power consumption

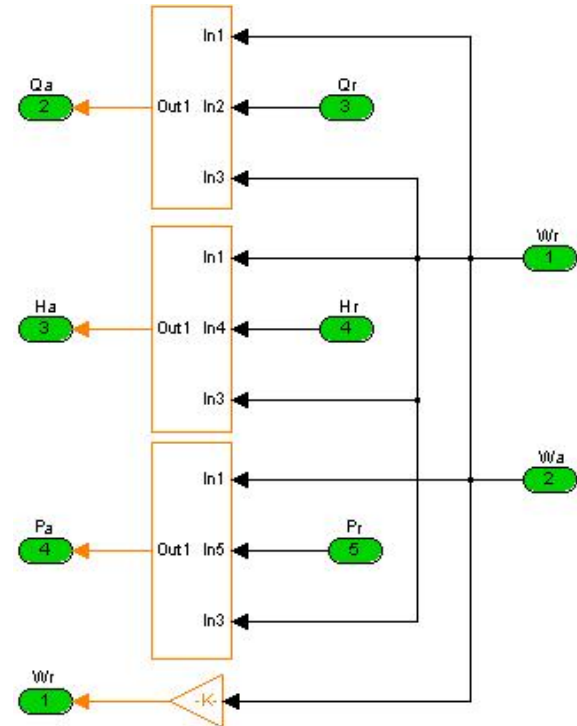


Figure 10. System main equations block.

Output values of this block diagram are presented as the main system response as follows:

$$Q_a / Q_r = n_a / n_r \tag{2}$$

$$H_a / H_r = (n_a / n_r)^2 \tag{3}$$

$$P_a / P_r = (n_a / n_r)^3 \tag{4}$$

Where:

H_a : The actual head of pump

H_r : The rated head of pump

P_a : The actual power consumption

P_r : The rated power consumption

4. System Operation and Test

According to the programmed control law shown in Figure 5 as a relationship between frequency and time, the modeled output flow rate and pump speed of water pumping system are shown in figure 11 and figure 12.

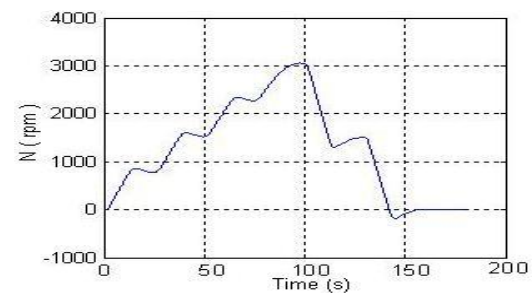


Figure 11. The modeled flow rate.

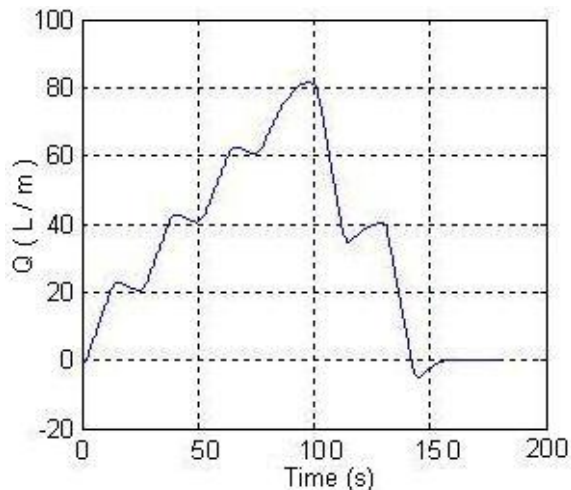


Figure 12. The modeled pump speed

It can be noticed from Figure 11 and Figure 12 that the flow rate and pump speed in modeled system showed the capability for full control from zero to maximum for any required range of time in case of increasing or decreasing.

5. Discussion and Results

PLC and frequency control of water pumping can be used in cases of dynamic conditions, for example starting, breaking, and changing from one operating condition to another. The using of PLC and frequency control of water pumping system will change all variables of the system gradually until reaching the desired operating condition. Consequently, it is possible to prevent hydraulic hummers and dynamic stresses in mechanical elements in water pumping system. Also it is possible to avoid dynamic currents in the three-phase AC machine. From the comparison of the experimental curves in Figure 6 and Figure 7, and the theoretical curves in Figure 10 and Figure 11, it is obvious that they are very similar. This means theoretical model can successfully represents the real behavior of water pumping system with PLC and frequency control.

6. Conclusions

In this work, small capacity water pumping system is designed, constructed and experimented by using PLC and frequency control. The designed system shows the capability for full control of flow rate from zero to maximum for any required range of time in case of increasing or decreasing the flow rate. It can be concluded from the experimentation of the water pumping system that all variables of the system would be changed

gradually until reaching their required operating points. The proposed mathematical model of the system successfully represents the real behavior of water pumping system with PLC and frequency control.

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