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Static head control in pumping system using PID controller

[1]Hadeel Mzahem Mjbel, [2]Ahmed ALKAMACHI, [3]Hisham Hassan Jasim

[1,2,3] University of Baghdad, Al.Khawarizmi College of Engineering, Mechatronics Engineering Department.

Abstract: The main aim of this paper is to focus on the modeling and simulation of a head-controlled water pumping system in a MATLAB/SIMULINK environment. The system is closed loop structure that include a standard PID control strategy to control a centrifugal pump speed in order to obtain a user preset static head. The novelty of this work is the Simscape – based modeling approach of the pumping system which is more practical than equation-based modeling. It is also faster and easier to accomplish the model than the classical modeling methods. The work also makes a control on the system head which is important to safe energy especially in solar powered pumping system. In this work, the centrifugal pump performance is first investigated. The simulation also includes a calculation of the static head for both the pump and the system using the energy equation. Moreover, a classical PID controller is tunned to control a dc motor to drive a centrifugal pump with a required speed to reach a desired static head. The results show an accurate and full control on the system head by adjusting the pump rotating speed.

1. Introduction

A pump running at a constant speed is usually not driving with the best efficiency [1]. The required energy can be saved using a variable speed pump when regulating the flow rate [2, 3]. A commercial centrifugal pump is commonly designed for surplus liquid delivering capacity while most of the actual operation of the pumping system need reduced flow rate [4]. It is common to relay on the affinity laws to make a good estimation for the energy saved using variable speed control when driving the pump. In actual circumstances, the affinity laws give an approximate relationship between liquid flow rate, head and consumed power as pump speed is varied [5]. The affinity laws are:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \quad (1)$$

where Q_1, Q_2 are the pump flow rates for two different operating points. N_1, N_2 are the pump rotating speed for two different working points.

also

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \quad (2)$$

where H_1, H_2 are the pump head for two different operating points.

According to the affinity laws, pump performance efficiency (η_P) is constant and equal [6]

$$\eta_P = \frac{\rho g Q H}{P} \quad (3)$$

where ρ is the liquid density, g is the gravitational acceleration, and P is the pump consumed power.

From Eq 1 to 3, we can conclude that

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \quad (4)$$

which means that there is a significant reduction in the consumed power with the reduction of the pump rotational speed.

Several studies are being performed to model the pumping system for various applications. An irrigation system with a solar pumping system is simulated in Matlab/Simulink in [7]. The authors in [8] proposed a dynamic model of a centrifugal pump using PASS/Hydrosystem software. Tudoroiu etal. describe a simulation for a fuzzy-PID controlled pumping system in a Simulink environment [9]. In [10], an approach for maintaining a constant water flow from a centrifugal pump at a under a constant pressure has been conducted using Matlab/Simulink simulation. Design and analysis of DC pump with a photo voltage panel is demonstrated using MATLAB/Simulink in [11].

In this work, a complete Simscape model for a centrifugal system is presented and a PID controller is proposed to control the centrifugal pump to achieve a desired head. The main advantage of our proposed model is that it includes a standard Simscape and Simulink functional blocks and, therefore, it is easy to modify the block parameters to simulate numerous pumping systems with any specifications. Moreover, the model contains control system for system head adjustment. The main benefit behind the use of Simscape standard blocks is that it results in a high performance and speed of the simulation. Finding a precise and proper values for the controller parameters is also one of the important achievements of using simulation platform.

The paper is organized as follows: In section 2, a complete step by step description for the model is presented. Section 3 includes proposing a suitable controller with their parameters. Moreover, section 4 covers the simulation results and their discussions. The paper is concluded in section 5.

2. The proposed Simscape/Simulink model

The open loop model for a pump system is considered in this section. Simscape blocks plus standard Simulink blocks are used to build the model in Matlab. The blocks are first selected, connected to each other and the parameters are adjusted according to the proposed model. Figure 1 shows a general sketch for the system under consideration, while the overall Simscape/Simulink model including the controller is shown in Figure 2.

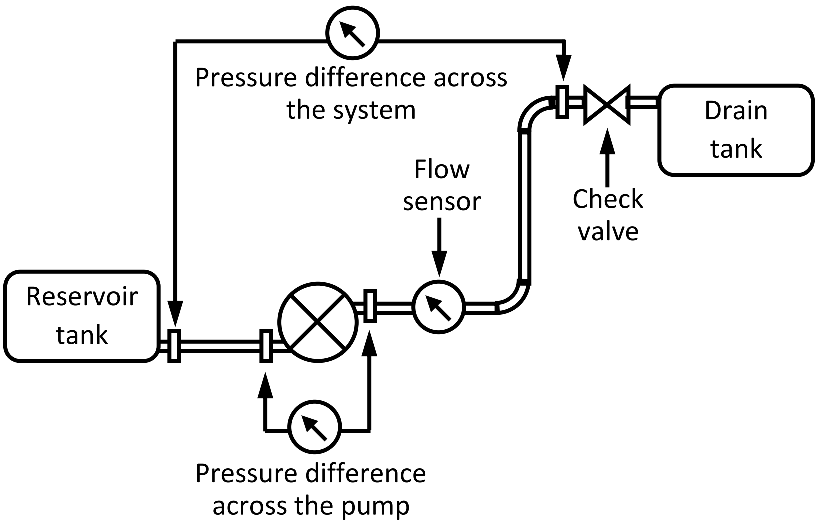


Figure 1: Schematic diagram for a pump system

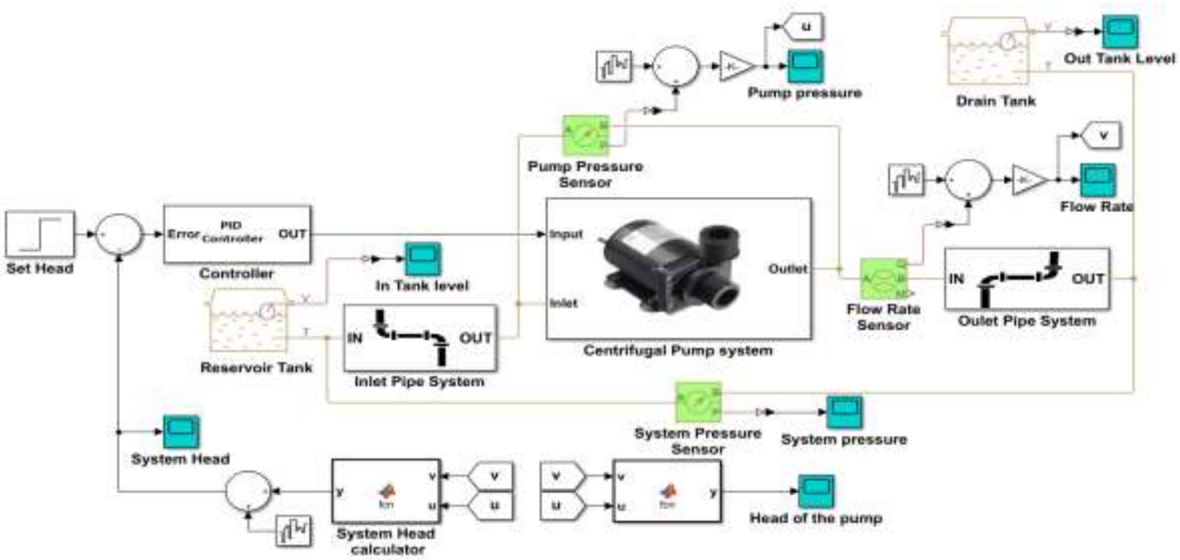


Figure 2: Simscape/Simulink diagram for a pump system

In the following subsections, a detailed drawing and description for each block is presented.

2.1 Centrifugal pump and its performance curves

One of the basic characteristics of a pump operation is relationship between the flow rate Q and the head H at a specific pump angular velocity. The total head of a pump depends on the amount of energy that the pump gives to the liquid being transported [12]. Figure 2 shows the Simscape diagram for a centrifugal pump.

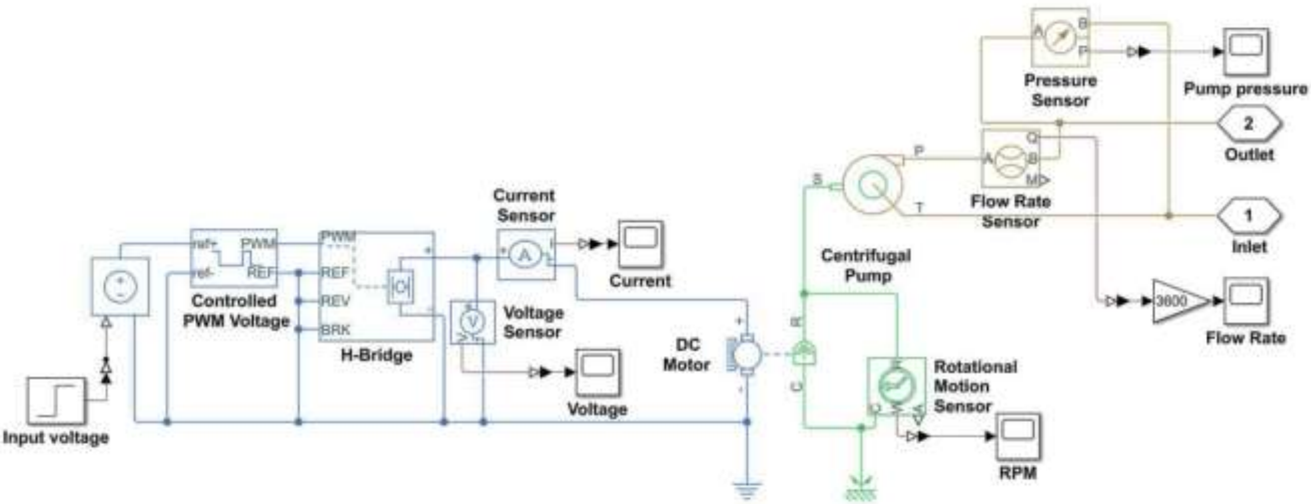


Figure 2: Simscape model for a centrifugal pump

As shown in the figure, the model consists of two main parts as well as some sensors. The first part is the electrical components which includes a 12 to 24 volt DC motor with its pulse width modulation PWM control circuit. The second part is the mechanical centrifugal pump that represents the core of the system. The model has several important sensors that will monitor the DC motor voltage and current, pump rotational speed, liquid flow rate, and the pressure difference across the pump.

In order to determine the performance curve, a gate valve block is added to the outlet pipe line so we can change the valve passage area to control the flow rate and subsequently control the system head. In this way, a curve can be obtained between the flow rate against the system head for a specific pump speed. Head curves for different pump speed (600, 700, 800, 900, 1000, 1100, 1200 rpm) is shown in figure 3. The system curve also plotted on the same figure to determine the intersection points between the head curves and the system curve which will determine the most efficient operating points.

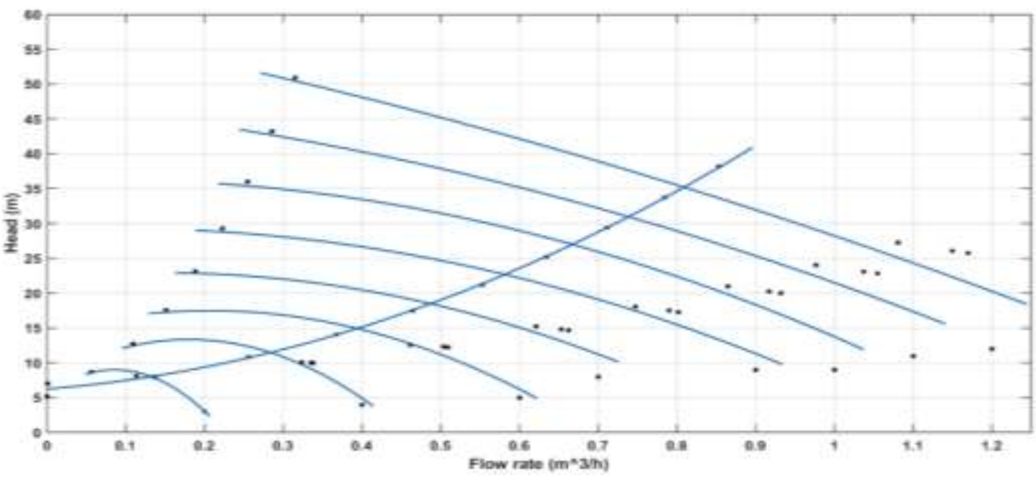


Figure 3: Head curves and system curve plot.

Also, it is important to plot the efficiency vs flow rate relationship. The efficiency is determined by the following formula [13]:

$$\eta = \frac{P_W}{P_E} = \frac{\rho g H Q}{V * I} \tag{4}$$

where P_W is the water power which is the product result of ρ (water density), g gravitational acceleration, H operating head, and Q (the volumetric flow rate). In the other side, the electrical input power P_E is a result of multiplying the motor voltage V by the motor current I.

The efficiency in the above equation represents the total efficiency from the electrical input power to the pump output power which also called wire to water efficiency. Following the formula in Eq. (4), the following curve is obtained as shown in figure 4.

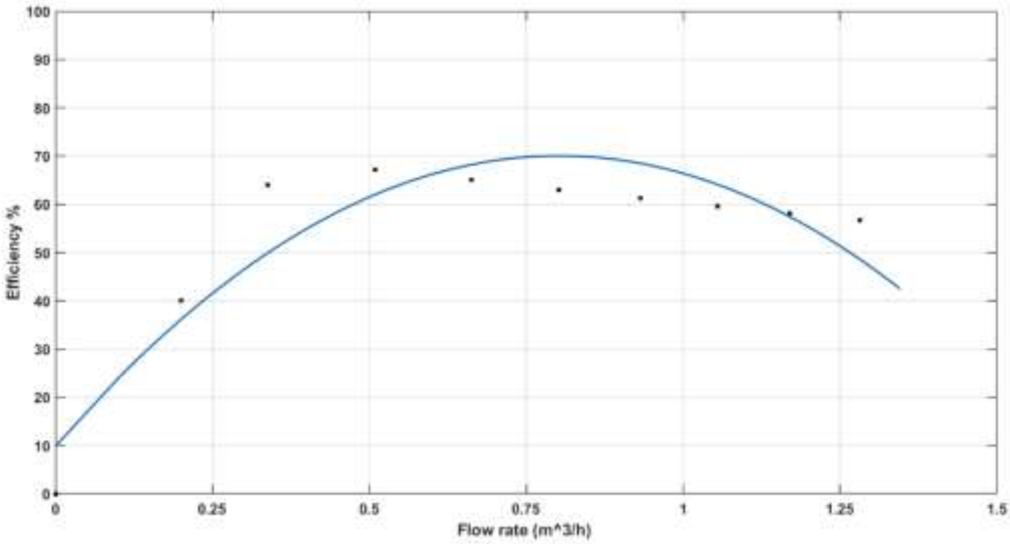
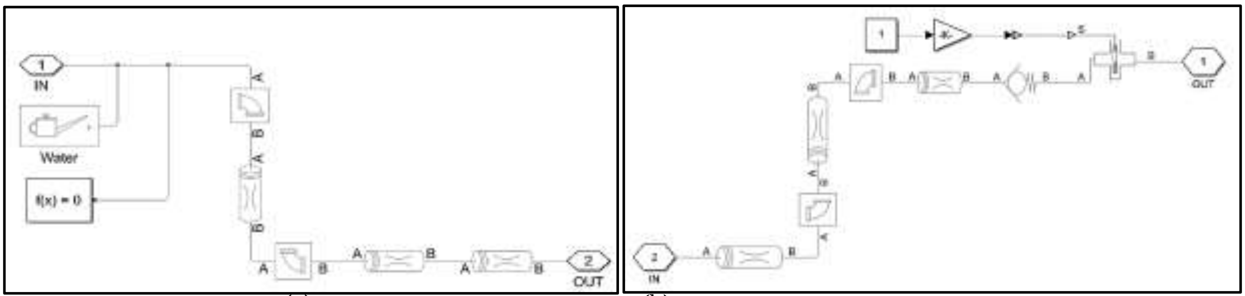


Figure 4: Pump wire to water efficiency

2.2 Inlet and outlet pipe system

These to subsystems consist of resistive pipes, elbows, check valve, and gate valve. All the pipes and valves are of circular cross section. The internal diameter is 0.5 inch and the laminar friction constant for Darcy friction factor is 64. The inlet and outlet pipe connections is shown in Figure 5a and b respectively.



(a) (b)

Figure 5: Pump system model: (a) Inlet pipe system, (b) Outlet pipe system

2.3. System head calculator

In our work, it is required to sense the system head so it can be controlled by controlling the pump speed. Bernoulli equation is used to calculate the system head from other system variables. The total head can be calculated using the following equation [14]:

$$H_{sys} = Pressure\ head + Elevation + Kineticterm \tag{5}$$

$$H_{sys} = \frac{\Delta P}{\rho g} + \Delta Z + \Delta \mathrm{H}_{\text{friction loss}} + \Delta \mathrm{H}_{\text{minor loss}} \tag{6}$$

where ΔP is the pressure difference across the system, ΔZ is the change in the elevation, $\Delta \mathrm{H}_{\text{friction loss}}$ is the head difference due to the frictions in the pipes and it is also called Moody-type friction loss, $\Delta \mathrm{H}_{\text{minor loss}}$ is the head difference due to the minor loss which include the loss caused by pipe fittings and valves.

Now, recall equation (6) and substitute $\Delta H_{\text{friction loss}}$ and $\Delta H_{\text{minor loss}}$ with their equivalent expression yield:

$$H_{sys} = \frac{\Delta P}{\rho g} + \Delta Z + \frac{L}{D} * \frac{V^2}{2g} + \sum K \frac{V^2}{2g} (7)$$

where K is the minor losses factor, L is the sum of pipes length, D is the diameter of the pipe, $V^2/2g$ is denoted as velocity head and $V = Q/A$, where A is the cross-section area of the pipe.

Equation (7) is implemented using Matlab function block to calculate the head of the system using two inputs which are the pressure difference and the flow rate.

3. Proportional Integral Derivative (PID) controller

In the previous subsection, the different parts of the open loop system are described. Now, it is required to design a controller that should be able to vary the pump rotational speed so that the system can settle to a definite head. The PID controller governing equation is as follows [15]:

$$u(t) = K_P \left(e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \right) \quad (8)$$

where $u(t)$ is the controller output, $e(t)$ is the error signal, K_P, K_I, and K_D is the proportional, integral, and derivative constants respectively. A PID controller is proposed to do the control task due to its simplicity, stability, durability, and ease of implementation. The PID controller configuration which is considered though our design is shown in Figure 6.

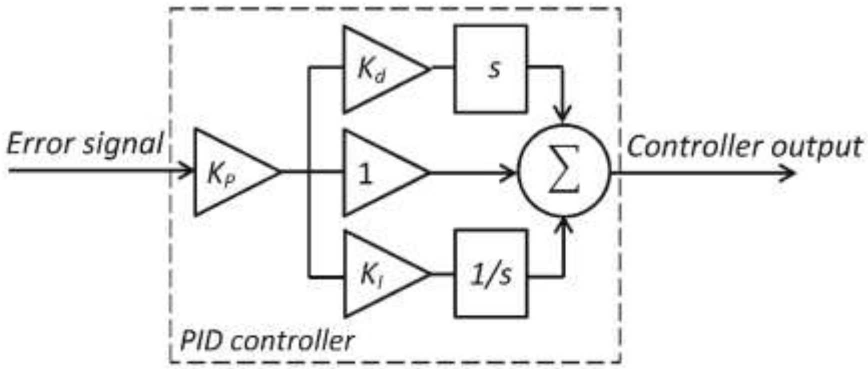


Figure 6: PID controller schematic drawing [16].

Several values for the gain parameters K_P, K_I, and K_D were applied and the response were monitored. It is noticed that the best vales that result in a good response in terms of the settling time, overshoot, and steady state error are $K_P = 49$, $K_I = 0.19$, and $K_D = 0.1$.

4. Simulation results and discussion.

To validate the system model performance, different heads were applied. The model is tested for its capability to follow a desired head scenario. Figure 7 shows the test response for three different heads, while figure 8 shows the corresponding pump speeds.

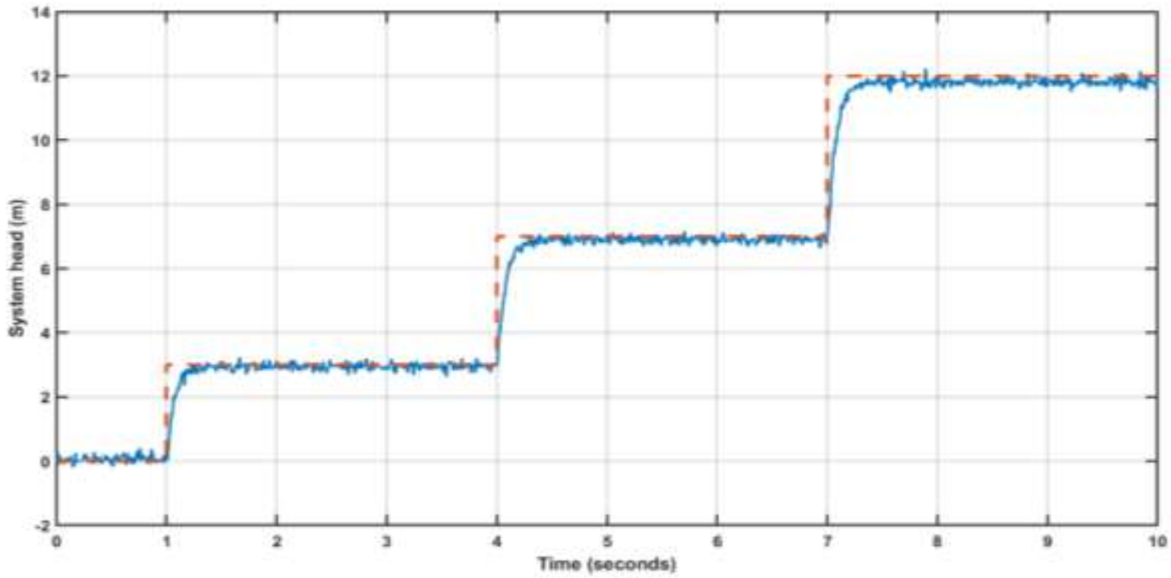


Figure 7: System response to three set heads (3m, 7m, and 12m).

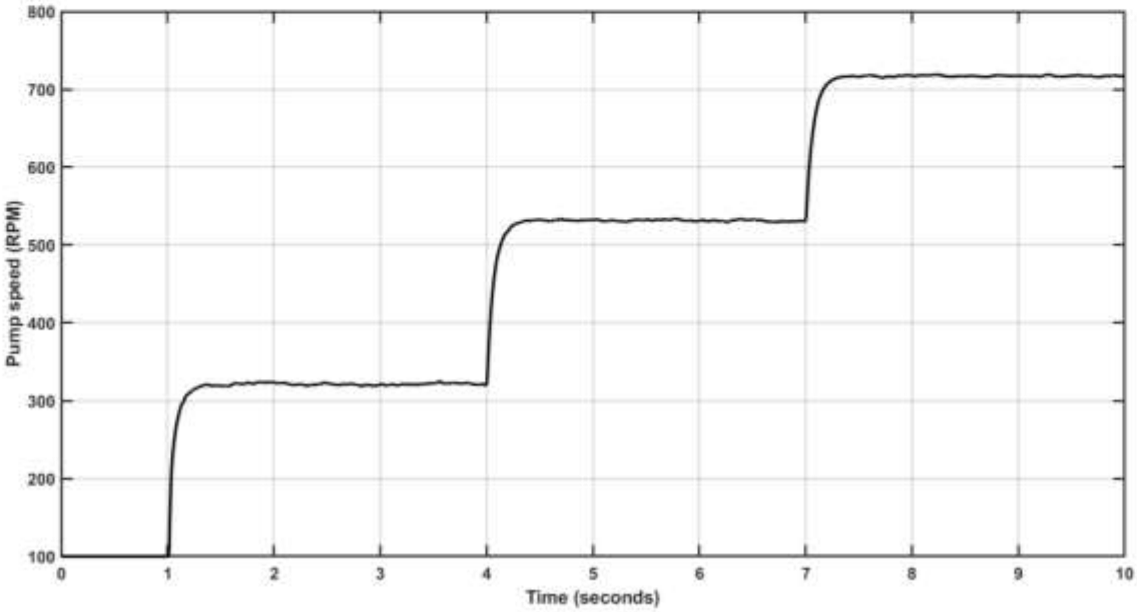


Figure 8: Centrifugal pump rotational speed in RPM.

It can be noticed that the controller did well in tracking the required heads with the existence of sensor noise. There is almost no overshoot and the settling time is 0.2 second only for the three required heads. Also, the pump speeds are in their limits and didn't exceed the nominal speed of 1500 RPM.

Figure 9 shows the system pressure response while tracking the desired heads. The pressure is increased as the required head increased to provide the required force to push up the liquid higher. In the same scenes, Figure 10 shows an increase in the flow rate which is expected due to the increase in the pump rotational speed and system pressure.

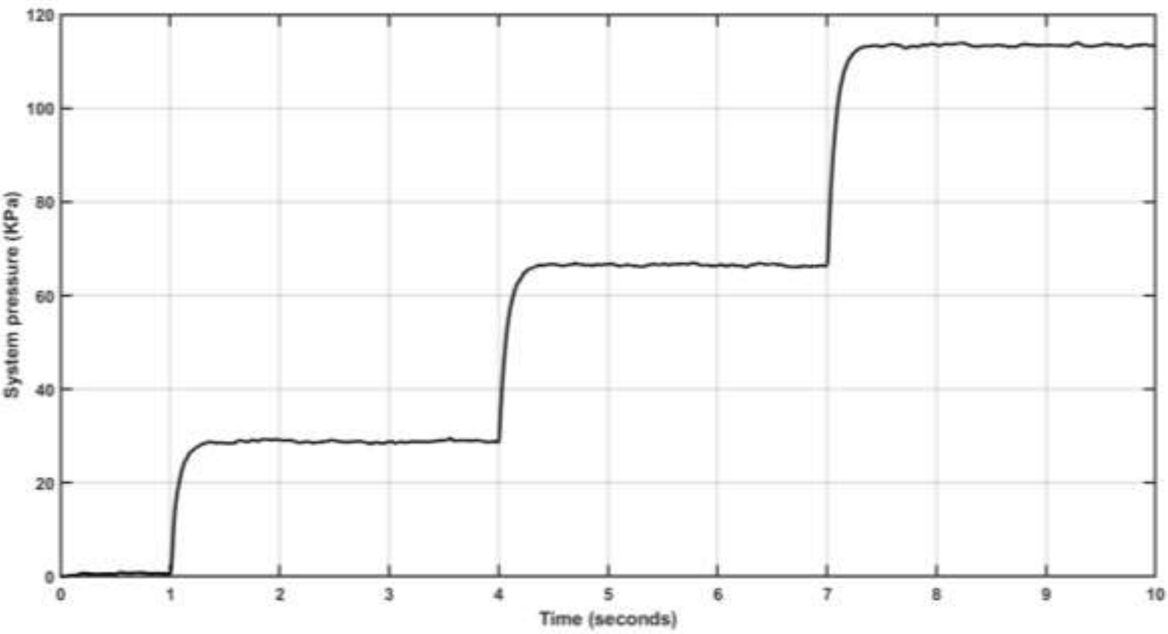


Figure 9: Pressure difference between the inlet and outlet of the system.

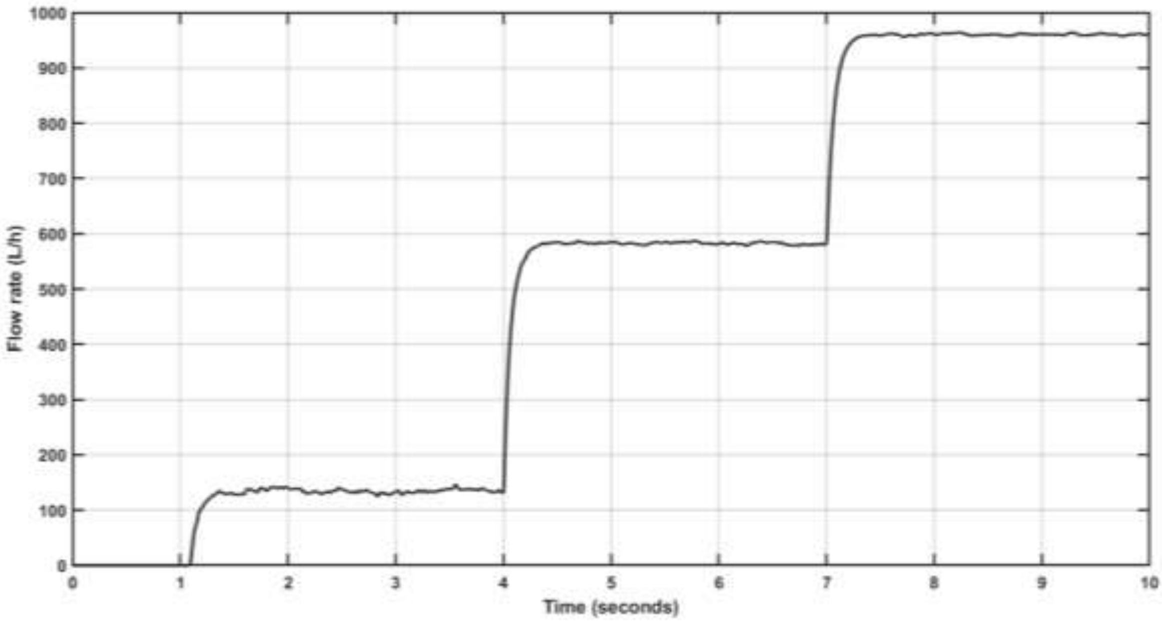


Figure 10: flow rate response plot.

5. Conclusion

In this paper, a comprehensive study and analysis on centrifugal pump system have been conducted using Simscape model in Matlab/Simulink environment. The proposed Simulink module can be used as a raw templet which can be adjusted to study different pump system cases. One of these cases is the control on the head of the system. A desired smooth and accurate system head control has been obtained. The results show that the Simscape based simulation is a good tool to analyze the pump performance and to study the overall system performance.

6. References

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