Educational Laboratory Pump System Setup – pQ Open Loop Control

Mihailo Bjekić, Vojislav Vujičić, Marko Šućurović, Marko Rosić, Miroslav Bjekić

***Abstract*—In this paper, an educational laboratory pump system setup, realized in the Process Engineering Laboratory of the Faculty of Technical Sciences in Čačak, is described. Starting from the acquired pump system characteristics *p*=f(*Q*) and the characteristic of the throttle valve, mathematical equations were derived. The system is controlled in an open loop by calculating the desired frequency of the variable speed drive and the angle position of the throttle valve based on the desired pressure and flow.**

***Index Terms*— Educational laboratory setup, pQ open loop control, pump system.**

I. Introduction

A pump system was designed in the Process Engineering Laboratory of the Faculty of Technical Sciences in Čačak (Fig. 1), previously described in detail in [1]. The system is intended to be used by students of electrical engineering and mechatronics. The system is modular with a possibility of easily changing the system configuration for different laboratory exercises.

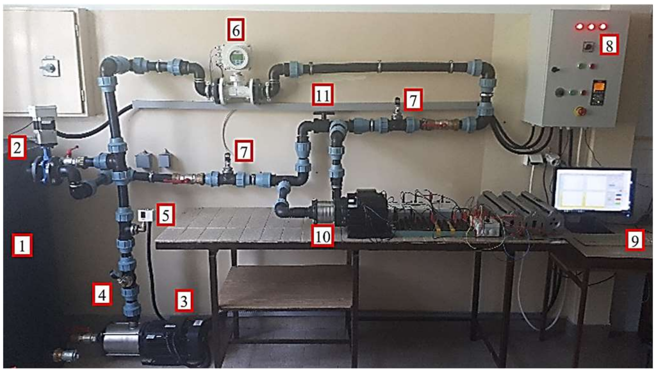

Fig. 1. Pump system realized in the Laboratory for Process Engineering of the Faculty of Technical Sciences in Čačak.

Pump system, shown in Fig. 1, consists of 11 important individual components. The water tank with the capacity of 400 l (1) supplies the system with water. The throttle valve (2) is turned by a step motor with a resolution of 3200 steps per rotation. The pump (3) has the power of 4 kW.

Mihailo Bjekić is a PhD student at the School of Electrical Engineering, University of Belgrade, 73 Bulevar kralja Aleksandra, 11020 Belgrade, Serbia (e-mail: mihailobjekic@gmail.com).
Vojislav Vujičić is with the Faculty of technical sciences, University of Kragujevac, 65 Svetog Save, 32000 Čačak, Serbia (e-mail: vojislav.vujicic@ftn.kg.ac.rs).
Marko Šućurović is with the Faculty of technical sciences, University of Kragujevac, 65 Svetog Save, 32000 Čačak, Serbia (e-mail: marko.sucurovic@ ftn.kg.ac.rs).
Marko Rosić is with the Faculty of technical sciences, University of Kragujevac, 65 Svetog Save, 32000 Čačak, Serbia (e-mail: marko.rosic@ftn.kg.ac.rs).
Miroslav Bjekić is with the Faculty of technical sciences, University of Kragujevac, 65 Svetog Save, 32000 Čačak, Serbia (e-mail: mbjekic@gmail.com).

Analogous barometer (4) is used for monitoring the pressure in the system. There is also a pressure switch in the system (5). For measuring the flow in the pipeline, electromagnetic flowmeter is used (6). Pressure measurement is done using two pressure sensors (7). For the pump control, frequency converter with scalar control is mounted in the electric cabinet (8). Flow and pressure sensors provide current signals proportional to the measured values to the acquisition card. Pump system control is done using a standard PC which runs a dedicated LabVIEW program (9). The system also has a pump (10) which can be used in a pump as turbine (PAT) mode by closing the valve (11).

The described setup allows for the students to perform following laboratory exercises:

1. Introduction to the pump system components and connecting the components into a functional system [1];
2. Characteristics of the pump system (Fig. 2) [2];
3. Pressure and flow control [1];
4. PAT (Pump as turbine) system analysis and determining the efficiency of each individual element [3];
5. Acquiring the characteristic of the throttle valve with the step motor (Fig. 3) [4].

All the laboratory exercises can be performed on the same system setup because the system is modular.

All the laboratory exercises are integrated into a single LabVIEW application which enables the user to choose the working mode and allows the acquisition of all necessary mechanical and electrical parameters.

In this paper, a control process (open loop control) by calculating the needed frequency of the variable speed drive and the angle position of the throttle valve, based on the desired pressure and flow, is described. Starting point were the characteristics of the pump system *p*=f(*Q*) (Fig. 2) and the characteristic of the throttle valve α=f(*p*) (Fig. 3).

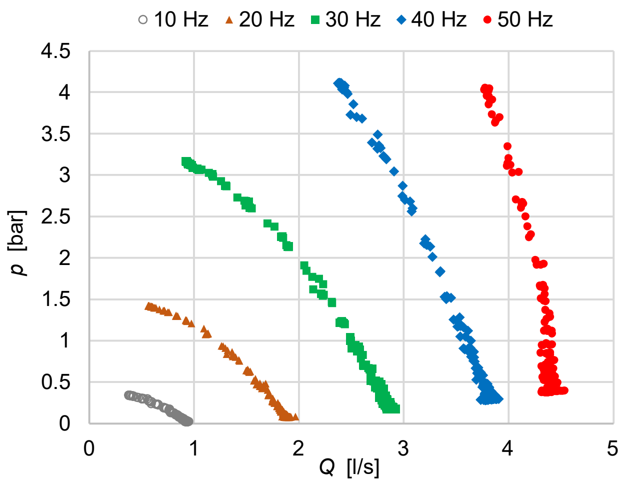

Fig. 2. Acquired characteristics of the pump system for different values of the frequency of the variable speed drive [2].

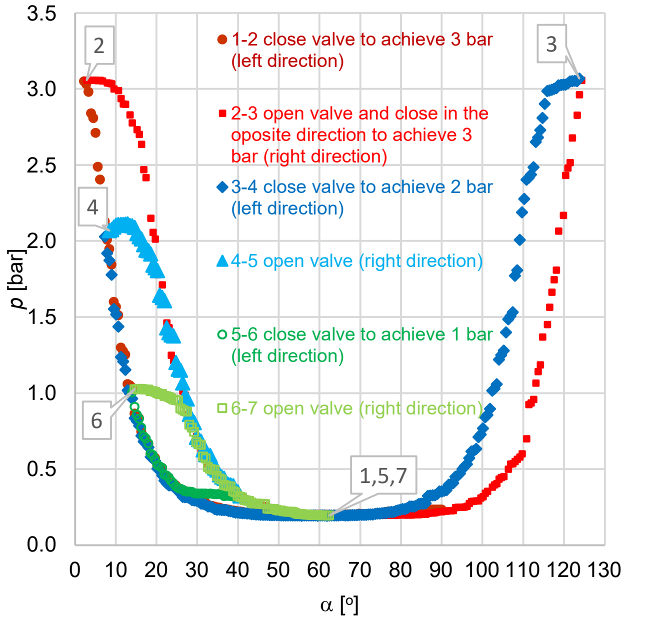

Fig. 3. Acquired characteristic of the throttle valve: pressure and closing angle dependency at the frequency of f=30 Hz. The order of the points is assigned 1-7 [4].

Two sets of analytical equations are derived.

The first set of equations enables calculating the needed frequency of the variable speed drive based on the desired pressure and flow.

Second set of equations calculates the angle position of the throttle valve for the desired pressure.

II. Derivation of Analytical Equations

A. Determining the needed frequency of the variable speed drive for the desired pressure and flow

Fig. 2 shows a set of measured values of p=f(Q) acquired by gradually closing the throttle valve, starting from the totally opened valve, at a constant frequency of the variable speed drive.

A new set of value pairs of pressure and flow must be obtained from the large set of measured pairs. The new set has to contain points on each curve for specific values of pressure in the range 0-4 bar, with a step of 0.5 bar. The new set is shown in Fig. 4.

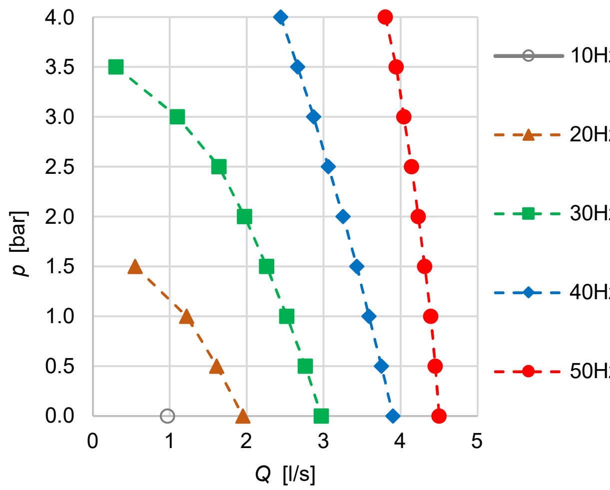

Fig. 4. Pressure and flow dependency for different frequencies of the variable speed drive. Constant pressure value points were chosen.

The new set is obtained to enable constructing a new set of characteristics f=f(Q), at the constant pressure.

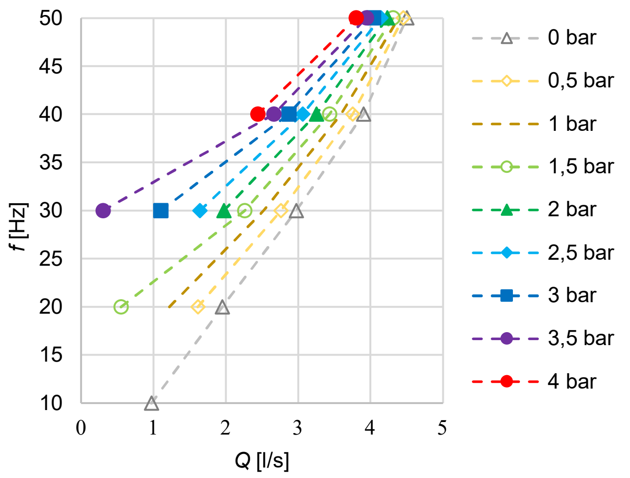

Fig. 5. Characteristics f=f(Q), p=const. Chosen measured points.

An interpolation quadratic function is determined for each of the 9 shown curves:

$$f = k_1 Q^2 + k_2 Q + k_3 \,. \tag{1}$$

The calculated coefficients k_1, k_2 and k_3 are given in the Table I.

TABLE I
COEFFICIENTS k_1, k_2 AND k_3 FOR THE KNOWN PRESSURE VALUES

p [bar]	k_1	k_2	k_3
0	0.7971	6	5
0.5	1	4	11
1	1.06	3.3	15
1.5	1.074	2.728	18.21
2	1.06	2.289	21.38
2.5	1.03	2	24
3	0.99	1.737	26.9
3.5	0.95	1.6	29.51
4	0.9	1.565	32

In the Fig. 6 dependence k_i=f(p) is shown.

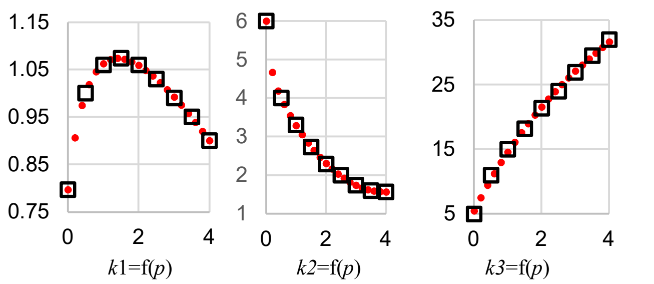

Fig. 6. Calculated coefficients k_1, k_2 and k_3 for pressures in the range 0-4 bar with the step of 0.5 bar (black squares) and values obtained using the interpolation functions (red dots).

For the purpose of calculating the coefficients for any pressure in the range 0-4 bar, an interpolation function for discrete values of coefficients must be determined. The interpolation coefficients of the new interpolation function are used to determine the coefficients k_1, k_2 and k_3 for any desired pressure in the defined range.

The used rational functions are in the form:

$$k_1 = \frac{pp_{12}p^2 + pp_{13}p + pp_{14}}{p + qq_{11}}, \quad (2)$$

$$k_2 = \frac{pp_{21}p^3 + pp_{22}p^2 + pp_{23}p + pp_{24}}{p + qq_{21}}, \quad (3)$$

$$k_3 = \frac{pp_{32}p^2 + pp_{33}p + pp_{34}}{p + qq_{31}}. \quad (4)$$

The calculated coefficients are shown in Table II.

TABLE II
COEFFICIENTS FOR CALCULATING THE RATIONAL FUNCTIONS
$k_1, k_2, k_3 = F(p)$

i	pp_{i1}	pp_{i2}	pp_{i3}	pp_{i4}	qq_{i1}
1	0	-0.13	1.434	0.735	0.92
2	0.19	-1.46	4.29	0.593	0.1
3	0	0	75.09	36.68	6.66

For the purpose of testing the calculated coefficients, pressure values, in the determined range, with the step of 0.2 bar, are also shown in Fig. 6.

B. Dependence of the angle position of the throttle valve and desired pressure

The used throttle valve is factory constructed to have 10 different positions. The pump system makes use of only 4 positions of the throttle valve, because the change of the angle of the valve, from totally closed to totally opened (from the aspect of the change in pressure achieved by changing the position of the valve) is about 30°. Because of the previous limitations, a change in the throttle valve construction was made. Instead of the hand lever, the valve is closed using a step motor with the resolution of 3200 steps per rotation.

By applying the step motor to the throttle valve, a more precise characteristic of the throttle valve, for different frequencies of the variable speed drive, can be acquired.

The results are shown in Fig. 7.

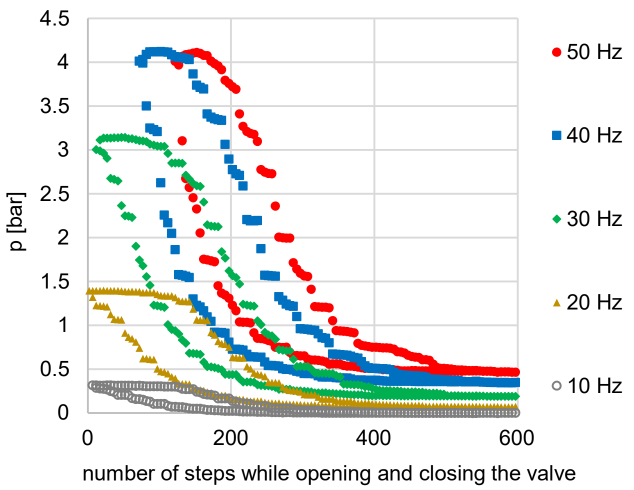

Fig.7. Dependence of pressure and the position of the throttle valve at a constant frequency of the variable speed drive. The valve was firstly closed and then opened.

From the Fig. 7, it can be seen that the characteristics are highly nonlinear with an expressed hysteresis. The existence of hysteresis is the result of the elastic coupling between the step motor and the throttle valve. The elastic coupling creates an idle range of the valve during the change of direction of the turning of the valve.

The problem of hysteresis is overcome by translating the curve of opening of the valve by 104 steps [4]. By translating the curve, both opening and closing curves match.

Opening and closing curves are shown in Fig. 8.

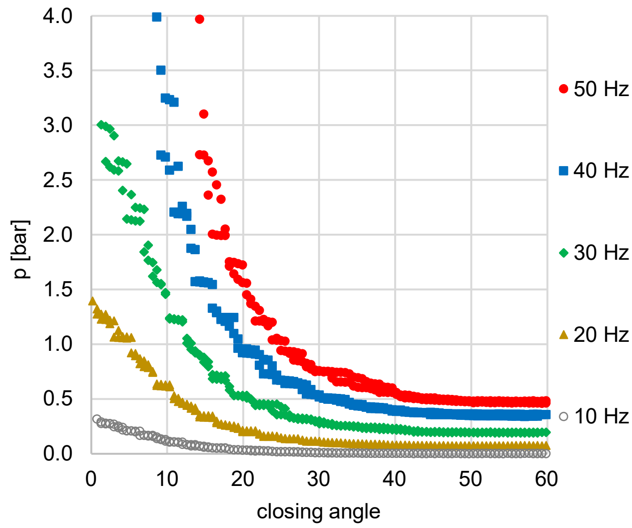

Fig. 8. Dependence of pressure and angle position of the throttle valve at the constant frequency of the variable speed drive, obtained by translating the closing curves by 11.7°.

As in the previous case of deriving the analytical equations from a large set of data, a new set of values was obtained. The new set of values is shown in Fig. 9.

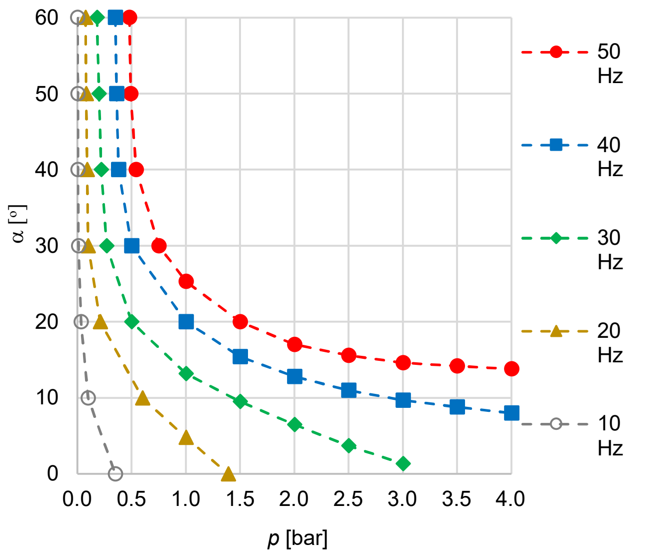

Fig. 9. Dependence of angle position of the throttle valve and pressure, at the constant frequency of the variable speed drive.

A rational interpolation function, with coefficients t_1, t_2, t_3 and j_1, is chosen because it provides satisfactory results with minimal number of coefficients.

$$\alpha = \left(t_1 p^2 + t_2 p + t_3\right) / \left(p + j_1\right) \quad (5)$$

The calculated coefficients are shown in Table III.

TABLE III
COEFFICIENTS t_1, t_2, t_3 AND j_1 FOR THE DESIRED FREQUENCY

f	t_1	t_2	t_3	j_1
10	-38.71	12.62	0.3134	0.004
20	-12.24	17.1	-0.2466	-0.059
30	-6	18	-1	-0.15
40	-2.729	18.46	-2	-0.27
50	-1.568	18.92	-2.715	-0.3738

In the Fig. 10 dependence of coefficients t_1, t_2, t_3 and j_1 is shown.

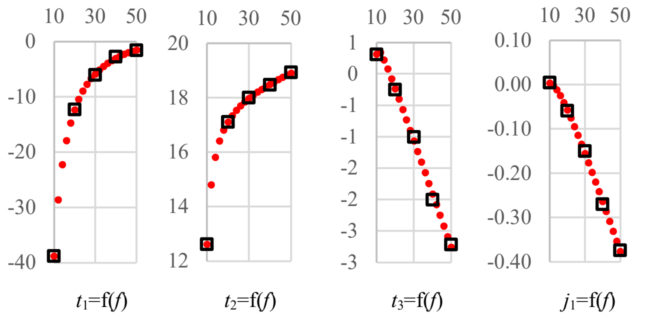

Fig. 10 Coefficients t_1, t_2, t_3 and j_1 for the frequencies 10-50 Hz (black squares) and values obtained by using the interpolation function (red dots).

A rational interpolation function is determined for the calculated values, the coefficients of the interpolation function are rr_{i1}, rr_{i2}, rr_{i3} and ss_i, where the index i represents the index of the coefficient t_i.

$$t_1 = \frac{rr_{11}{}^2 f + rr_{12} f + rr_{13}}{f + ss_1} \quad (6)$$

$$t_2 = \frac{rr_{21}{}^2 f + rr_{22} f + rr_{23}}{f + ss_2} \quad (7)$$

$$t_2 = \frac{rr_{31}{}^2 f + rr_{32} f + rr_{33}}{f + ss_3} \quad (8)$$

$$j_1 = \frac{rr_{41}{}^2 f + rr_{42} f + rr_{43}}{f + ss_4} \quad (9)$$

The calculated coefficients are shown in Table IV.

TABLE IV
COEFFICIENTS FOR CALCULATING THE RATIONAL FUNCTIONS
$t_1, t_2, t_3, j_1 = F(f)$

i	rr_{i1}	rr_{i2}	rr_{i3}	ss_i
1	-0.025	6.313	-322	-3.238
2	0.0287	17.69	-139	-6.777
3	-0.085	2.238	-13.4	-8.521
4	-0.012	0.231	-1.07	1.367

The accuracy of the analytical interpolation functions was tested by calculating the values of the coefficients t_i and j_i (i=1-3) for 5 times more datapoints (marked by red dots) and comparing them in Fig. 10.

In the end, after deriving the interpolation functions, it is possible to write a program that will, for the two input parameters (desired pressure and flow), give the needed frequency of the variable speed drive and the **opening** angle position of the throttle valve.

$$f, \alpha_{close} = f(p, Q) \quad (10)$$

$$\alpha_{open} = \alpha_{close} + 11.7^o \quad (11)$$

The calculated values are shown on the characteristic p=f(Q), in Fig. 11.

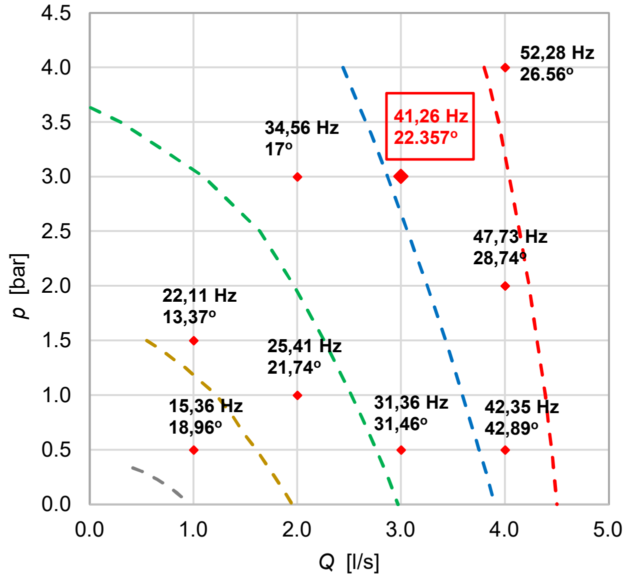

Fig. 11. An example of the calculated values of frequency and the **opening** angle position of the throttle valve, for the desired pressure and flow.

III. LABORATORY EXERCISE PROCEDURE

The procedure for the laboratory exercise "Open loop pump system control based on the desired pressure and flow":

1. The throttle valve is led into the totally closed position using the induction sensor as the reference;
2. Desired values of pressure and flow are inputted into the LabVIEW program. The program calculates the needed values of frequency and the **closing** angle position of the throttle valve α_{close};
3. The throttle valve is opened with an angle position $\alpha_{open}=\alpha_{close}+11.7°$, because the analytical equations were derived from the closing curve of the throttle valve;
4. The pump system is started with the calculated frequency of the variable speed drive.

The frequency is controlled using a voltage signal 0-10 V, and the angle position of the throttle valve is rescaled, with a coefficient k, into the number of steps of the step motor. The step motor has 200 steps per rotation and a resolution of 16 micro steps, so the coefficient is obtained as:

$$k = \frac{16 \cdot 200}{360} = 8.89 \text{ steps/}^o . \quad (12)$$

The screenshot of the LabVIEW program, during the laboratory exercise, is given in Fig. 12. Five different value pairs of pressure (in bar) and flow (in l/s) are inputted during the laboratory exercise. The values are:

$$(Q,p) = (1,1),\ (2,1),\ (1,4),\ (2,2),\ (3,3)\,. \tag{13}$$

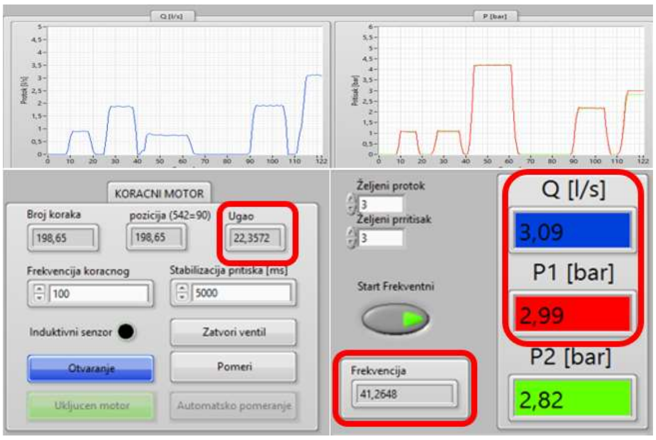

Fig. 12. Screenshot of the LabVIEW program for the input parameters Q=3 l/s and p=3 bar.

For the desired input parameters of Q=3 l/s and p=3 bar, the calculated value of frequency of the variable speed drive is f=41.26 Hz, while the angle position of the throttle valve is α_{close}=22.357°. With the calculated control signals, the achieved values of flow and pressure are Q=3.09 l/s and p=2.99 bar. The position of this operating point is shown on the characteristic p=f(Q), in Fig. 11.

The screenshot is given for the value pair of pressure and flow of 3 l/s and 3 bar. The error of the achieved pressure is 0.3% while the error of the achieved flow is 3%. Considering the accuracy of individual measuring instruments, the accuracy of the interpolation functions, throttle valve characteristic and the characteristics of the entire system, it can be concluded that the achieved accuracy is satisfactory.

IV. Conclusion

In this paper, a procedure for achieving the desired work regime (pressure and flow) of the pump system, in an open loop, is described. The pressure work range is 0.5-4 bar, while the flow work range is 0-4.5 l/s. For the purpose of achieving different work regimes, a throttle valve is used to simulate different loads on the system. Pump characteristic was changed by changing the frequency of the variable speed drive.

Acknowledgment

This study was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, and these results are parts of the Grant No. 451-03-68/2020-14/200132 with University of Kragujevac - Faculty of Technical Sciences Čačak.

References

[1] В. Вујичић, М. Шућуровић, М. Божић, М. Росић, М. Бјекић, "Образовна лабораторијска поставка пумпног система са могућношћу регулације притиска и протока", Зборник радова 63. Конференције за електронику, телекомуникације, рачунарство, аутоматику и нуклеарну технику - ЕТРАН 2019, стр. 321-325, ISBN 978-86-7466-785-9, Сребрно Језеро, Србија, 3-6 Јун,

[2] M. Božić, M. Šućurović, M. Rosić, V. Vujičić, M. Bjekić, , "Laboratory setup for measurements basic pump system characteristic", Proceedings of International scientific conference - UNITECH 2018, Vol. III, pp. 154-158, ISSN: 1313-230X, Gabrovo, Bulgaria, 16-17. Nov. 2018

[3] M. Šućurović, V. Vujičić, M. Bjekić,M. Rosić, M. Bjekić "Power and Efficiency Determination of Pat System Using Laboratory Setup", Proceedings of International scientific conference - UNITECH 2019, Vol. III, pp. 193-198, ISSN: 1313-230X, Gabrovo, Bulgaria, 15-16. Nov. 2019.

[4] B. Vujičić, M. Šućurović, M. Bjekić, M. Rosić, M. Bjekić, "Experimental Determination of the Stepper Motor controlled Butterfly Valve Characteristics", Proceedings of International scientific conference - UNITECH 2019, Vol. I, pp. 35-39, ISSN: 1313-230X, Gabrovo, Bulgaria, 15-16. Nov. 2019.