Proc. International Conference on Mechanical, Automotive and Mechatronics Engineering (ICMAME 2023)
29-30 April 2023, Dubai, UAE

Control Oriented Model of the Throttle Valve for Pumping Applications

Levon Gevorkov
Power systems group, Catalonia Institute for Energy Research (IREC)
Barcelona, Spain
lgevorkov@irec.cat

José Luis Domínguez-García
Power systems group, Catalonia Institute for Energy Research (IREC)
Barcelona, Spain
jldominguez@irec.cat

***Abstract*—In pumping plants, oil production, and many other industries, throttle valves play a crucial role. Throttle valves are used to control the liquid flowing through them and they are frequently employed as flow control devices. A proposed throttle control simulation approach for centrifugal pumps is presented. A specific stepper motor-based model is designed to offer various possible simulation scenarios. The stepper motor, control system, gearbox, centrifugal pump, liquid tank, pipeline, throttle valve, and sensors are among the model's essential parts. A number of simulations were done in order to examine the proposed model. The modelling demonstrates that the proposed simulation is quite accurate and simple to modify. The electric drive model that has been developed is suitable for the validation of different operation modes of pumping plants that involve throttling.**

Keywords— valves, DC motors, microcontrollers, fluid flow control

I. INTRODUCTION

Based on the latest statistics in the European Union, electric drive systems use about 70% of the total electrical energy generated. Electric drives are among the top consumers of electricity, according to the statistics. For instance, 10% to 40% of the total electrical energy produced is consumed by centrifugal pump systems [1]. As a result of the centrifugal pump systems' large electricity consumption, it is crucial to optimize and modify these systems to reduce energy losses [2-3].

An electro-mechanical system called a centrifugal pump plant is made primarily for industrial use and is used to supply kinetic energy to the fluid moving from the suction side to the discharge side of a pumping plant. The centrifugal pump converts the rotational energy of an impeller into the pressure energy of the liquid that is flowing through the pump. Thus, increasing the kinetic energy of the liquid. The impeller, which provides energy to a liquid flow, is one of the most crucial components of a centrifugal pumping system. To provide fluid flow regulation in a pump system valves also called ball or gate valves are applied [4].

The majority of current pumping applications use throttling valves due to their simplicity and inexpensive price. These valves, however, suffer from the absence of electromechanical actuation and inaccurate control characteristics in most cases [5]. Additionally, their low linearity renders them quite unpredictable when used in closed-loop control applications.

Urban population density is increasing, necessitating the development of larger, more intricate water supply and distribution networks [6-7]. That is the main reason that pumping systems are becoming more and more important. Processes that operate with fluctuating liquid flows typically use centrifugal pumping systems supplied with throttling valves to control the volumetric flow of pumped fluid. The majority of those valves are manually operated, and they are available in a variety of sizes for various uses. Among the different valve types, the ball valves are preferred in automated fluid handling applications because they may rotate from fully closed to fully opened by turning within a small angle, typically operating in first quadrant of the circle (up to 90 degrees). Centrifugal pumps to achieve proper precision and lower electrical energy consumption use different control techniques. Among them are [8-9]:

- Throttling control;
- Rotational speed control.

Electronic throttle valves are being utilized more frequently in the industry due to the need for excellent performance in pumping systems [10] and [11]. The electronic throttle control (ETC) is often a valve powered by an electric motor that controls the flow of fluid through the outlet of the plant. These devices utilize an automated control system or the operator-provided reference opening angle to position the throttle valve. The main objective of the current research is to present the designed electric drive system for the control of the throttle valve. Pressure regulation in compliance with specified technical needs of various operational tasks, as well as pressure maintenance at a reference level, are the goals of the simulation approach for an electric drive.

The key benefit of the current simulation approach lies in the possibility to operate with standardized dynamical building modules, making it simple to adapt to diverse pumping systems with variable parameters. Additionally, the model has a stepper motor actuator control system which brings the possibility to implement control algorithms based on a standard microcontroller like Arduino Uno or a similar types of microcontrollers. A model's control unit enables quite an exact adjustment of a valve angle position. It also aids in achieving the primary objective of the ongoing research, which is to develop a robust, accurate, and flexible simulation approach.

II. THEORETICAL BACKGROUND OF VALVE CONTROL

Fig. 1 shows the key parts of a typical topology of a centrifugal pumping system with throttling valve options.

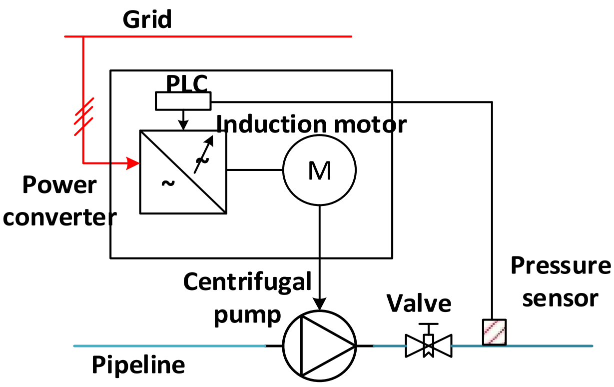

Fig. 1. Structure of centrifugal pumping plant with throttling valve option.

Among the key parts of the centrifugal pumping plant are the following:

- pipeline for liquid transportation;
- centrifugal pump unit;
- variable frequency drive (VFD);
- programmable logic controller (PLC);
- pressure transducer;
- throttling valve.

The shaft of an induction motor is often directly linked to the centrifugal pump. The electric drive system is usually linked to the inverter which controls rotational speed. Mainly the parts of a variable frequency drive (VFD) are an induction motor, a power converter, and a PLC. From the inlet, the fluid moves perpendicular to the rotating impeller of the centrifugal pump. The centrifugal pump's inlet, also known as the suction, is directly connected to a pipeline. The liquid travels toward the discharge side of the pump being driven by the impeller.

The capacity - Q and energy head - H of each centrifugal pumping system serve as its primary hydraulic parameters at a nominal rotational speed. Manufacturers typically include pump-related hydraulic features in their technical descriptions.

The affinity laws are a way to express how various hydraulic characteristics are dependent on one another and rotational speed n. Here index 1 represents the system's starting state and index 2 represents the process variable's final state [12]. The valve regulation technique is typically used to manage the pressure at the constant rotating speed. Throttling offers the potential for pressure management by adjusting the nominal operating point location with the use of a constant-speed valve control on a Q-H plane.

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2}, \tag{1}$$

$$\frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2, \tag{2}$$

The nominal operating point then moves over the pump's specified performance curve at a variable valve position as shown in Fig. 2.

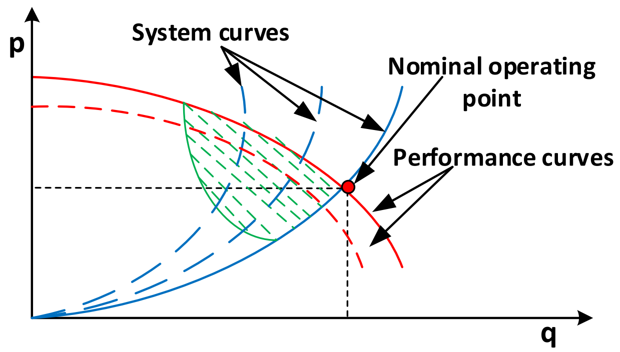

Fig. 2. Valve throttling method for pump's pressure management.

Equation (3) describes the system curve:

$$H(Q) = H_S + C_S Q^2, \tag{3}$$

where H_S – is the static head and C_S – is the coefficient.

Below are the analytical equations for modeling a stepper motor that is used in a simulation:

$$\frac{di_a}{dt} = \frac{U_a + k\omega \sin(D\Theta) - Ri_a}{L} \tag{4}$$

$$\frac{di_b}{dt} = \frac{U_b + k\omega \sin(D\Theta) - Ri_b}{L} \tag{5}$$

$$\omega = \frac{d\Theta}{dt} \tag{6}$$

$$J\frac{d\omega}{dt} = T_{el} - K\omega - T_L \tag{7}$$

where:

- i_b and i_a - are the currents in phases B and A;
- U_a and U_b - are the voltages in phases A and B;
- L - is the inductance;
- k - is an electromotive force constant;
- D - represents the quantity of rotor's teeth;
- ω - represents angular speed;
- Θ - represents the arrangement of the rotor;
- J - represents the absolute inertia;
- T_{el} - represents the electric torque;
- K - represents the absolute friction factor.

The first and second pair of the above-mentioned equations describe the electrical and mechanical aspects for a proposed model for a permanent magnet (PM) stepper motor, respectively. The developed model does not account for the differences in magnetic linkage as well as the value of induction for both windings.

The following equation for an incompressible liquid describes a ball valve that is used in the simulation [13]:

$$Q = C(\alpha)\sqrt{\Delta P}\,, \tag{8}$$

where Q – is a flow running through a valve, $C(\alpha)$ – is a coefficient that depends on an opening angle that is determining the cross-section of a valve, and ΔP is a pressure differential between the input and output of a valve.

III. ETC Simulation

The "SimPower" simulation toolbox from MATLAB/Simulink environment is applied to create the model of an electric drive system for valve position regulation [14-17]. The model is built up by:

- PM stepper motor unit;
- H bridge drive module;
- a lookup table;
- the modules to convert the signal;
- the direct current measuring tools.

There are two key subsystems in the model. Fig. 3 represents the composition of the created Simulink layout.

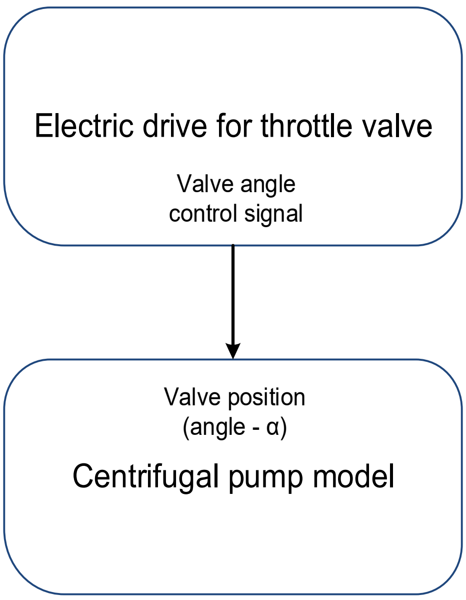

Fig. 3. Sub-blocks of the throttle valve model.

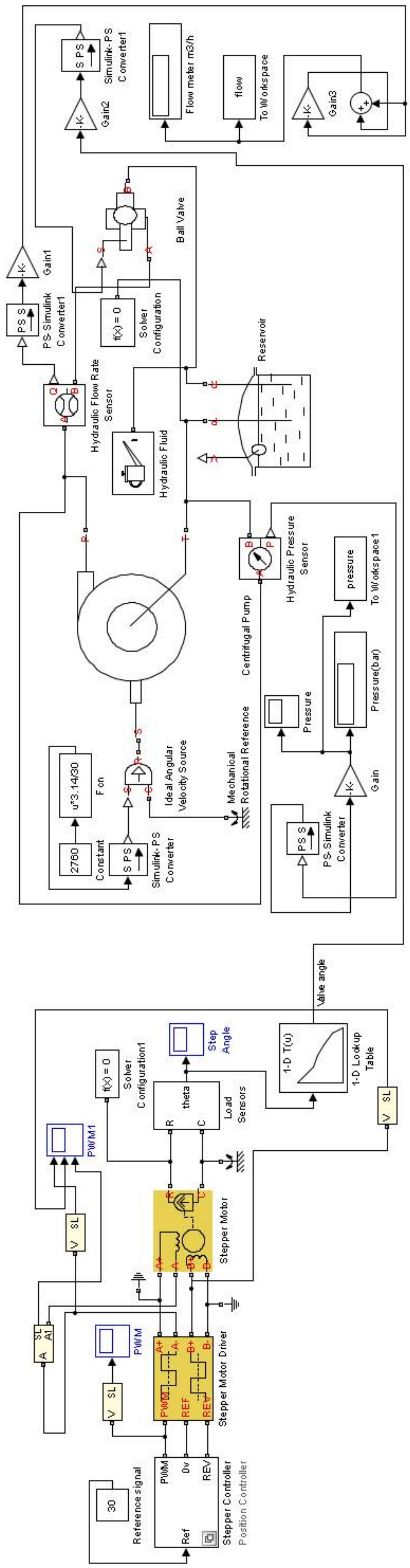

Fig. 4. Stepper motor, control system, and centrifugal pump model.

The created model's two primary sub-blocks are shown in Fig. 3. The ideal angular velocity source from the Simulink library is found in the second block, which enables the pump's reference speed to be set. This functional unit responds to incoming pulses by producing speed. Additionally, this module includes a mechanical pump unit and standard blocks for measuring hydraulic characteristics, shown in Fig. 4. Special converter blocks included in measuring tools translate the examined numerical quantities to physical units. Then the obtained data may be utilized for graphical representation after being later saved in memory.

The electric motor's windings are connected in a way that allows it to function as a bipolar motor with a serial winding connection. In Fig.5, the winding circuit of ST6018L3008-B PM stepper motor from Nanotec PLUG&DRIVE company is displayed. The technical characteristics of the simulated motor can be found in [18].

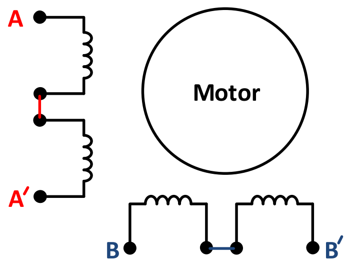

Fig. 5. ST6018L3008-B permanent magnet stepper motor and its winding connection.

IV. Simulation Results

Once all of the stepper motor's settings have been loaded into the model, the simulation was conducted. The definition of simulation execution time is one second. The stepper motor turns the throttle valve to the appropriate position in accordance with the reference signal, thereby regulating the pressure in the centrifugal pump system. Several hydraulic characteristics were measured in order to evaluate the centrifugal pump system's performance curve during throttling control.

The voltage of the stepper motor's two windings is estimated to be around 12 V, and the winding current does not exceed 2.5 A, according to the simulation findings given in Fig. 6.

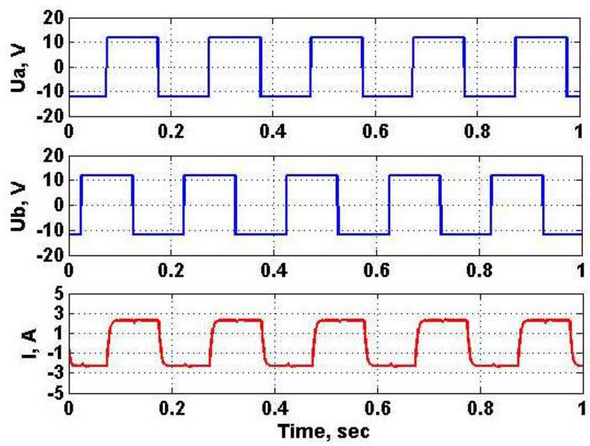

Fig. 6. Electrical characteristics.

According to Fig. 7, the pressure is at its highest and the flow is at its lowest points during the throttling process that approaches 90 degrees.

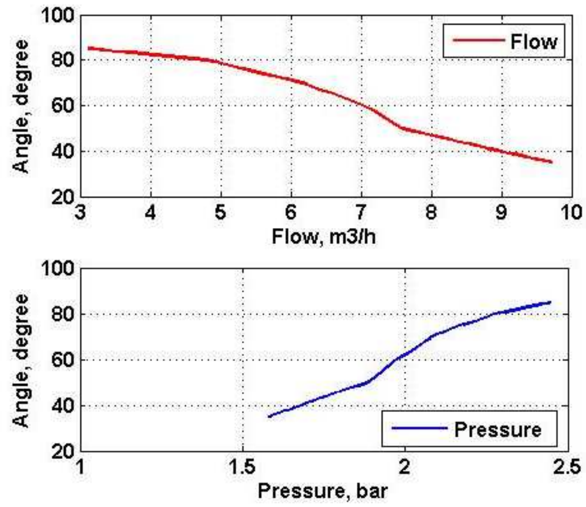

Fig. 7. Dependence charts for valve angle/flow and valve angle/pressure diagrams.

The designed electric drive can open the valve in less than 1.5 seconds, as shown in Fig. 8. It is not required to adjust the angle so quickly when operating under real-world circumstances, and the experimental centrifugal pump setup's primary operating range is between 60° and 85°.

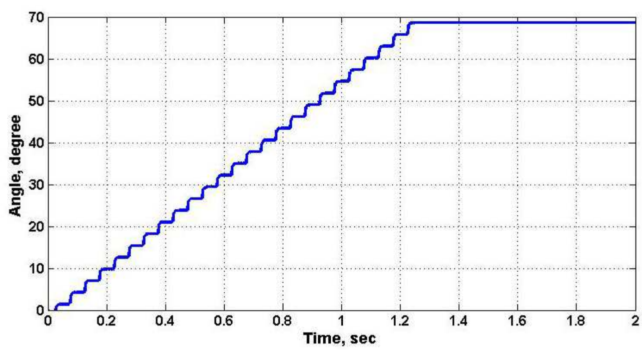

Fig. 8. Time response for valve angle control.

To check the possibility of employing affordable microcontrollers for the electric drive control the ATmega328P was chosen. The simulation was conducted in Proteus Design Suite software [19]. The reference signal from the potentiometer was utilized to control the stepper motor's position, Fig. 9. On the Arduino Uno board platform, analog input *A0* is where the input reference signal is attached. The reference valve angle is then processed by the program and the control signal is generated through ports *A1*, *A2*, *A3*, and *A4* to the L293D integral motor control driver. The motor driver is interfaced with the bipolar-stepper motor and can control both the number of steps and rotational direction. By altering the polarity of a motor's input voltage connected to inputs *S1*, *S2*, *S3*, and *S4* the direction in which it spins can be changed. Using an H-bridge is a typical method for accomplishing polarity alternation.

A four-switch dual-channel H-bridge circuit integrated into the L293D has the motor in the middle, creating an H-shaped configuration.

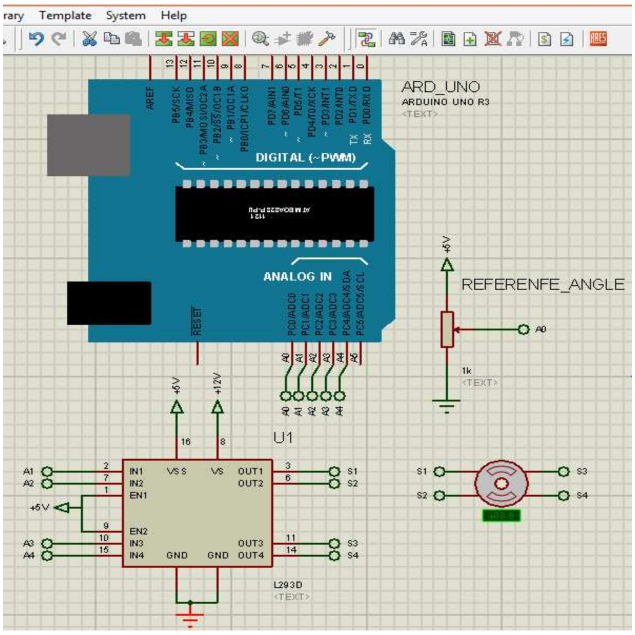

Fig. 9. Control system based on Arduino Uno with motor driver L293D.

V. Conclusion

A stepper motor-based electric drive system model for a throttling valve is designed and presented. The developed concept of the electric drive model can be utilized in pumping applications to maintain pressure and flow. Despite the variety of electric valve types, it is required to design adaptable, precise, automatic, and remote regulation techniques. The proposed approach is suitable for not only pumping plants but also for other hydraulic applications that require pressure or flow maintenance. For maintaining pressure or flow, the suggested approach has a number of benefits. Among these benefits is the option of remote control. The electric drive system's low cost and robust control make it appropriate for small-scale applications. Although, the proposed simulation system is targeting applications that require minimal mechanical forces to regulate the valve position it can be modified to fit other large-scale systems.

Based on the results of the modelling the proposed system demonstrates the capability to maintain the correct level of hydraulic parameters over a wide range. The system can be used to manage the desired hydraulic parameters while at the same time preventing the destruction and damage to the water supply network. Also, simulations in Proteus Design Suite software proved that the control part can be done with the help of affordable and widely available microcontrollers.

Acknowledgment

This project has received funding from the postdoctoral fellowships programme Beatriu de Pinós, funded by the Secretary of University and Research, from the Department of Enterprise and Knowledge (Government of Catalonia), with the grant Nº Ref. 2020 BP 00134.

References

[1] I. J. Karassik and T. McGuire, Centrifugal Pumps, Springer Science & Business Media, 2012, 780 p.

[2] L. Nelik, Centrifugal & Rotary Pumps: Fundamentals With Applications, CRC Press, 1999, p 152.

[3] L. Gevorkov, A. Rassõlkin, A. Kallaste and T. Vaimann, "Simulation Study of a Centrifugal Pumping Plant's Power Consumption at Throttling and Speed Control," 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 2017, pp. 1-5, doi: 10.1109/RTUCON.2017.8124823.

[4] Chern, M. J. and Wang, C. C. (2004). Control of volumetric flow-rate of ball valve using V-port. Transactions-American Society of Mechanical Engineers Journal of Fluids Engineering, 126, pp. 471–481.

[5] L. Gevorkov and V. Vodovozov, "Mixed pressure control system for a centrifugal pump," 2017 11th IEEE International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Cadiz, Spain, 2017, pp. 364-369, doi: 10.1109/CPE.2017.7915198.

[6] D. E. Agthe, R.B. Billings, N. Buras, Managing Urban Water Supply, Springer Science & Business Media, 2013, 277 p.

[7] D. J. Anton, Thirsty Cities: Urban Environments and Water Supply in Latin America, IDRC, 1993, 197 p.

[8] L. Gevorkov and V. Vodovozov, "Study of the centrifugal pump efficiency at throttling and speed control," 2016 15th Biennial Baltic Electronics Conference (BEC), Tallinn, Estonia, 2016, pp. 199-202, doi: 10.1109/BEC.2016.7743763.

[9] L. Gevorkov, J. L. Domínguez-García, and L. T. Romero, "Review on Solar Photovoltaic-Powered Pumping Systems," Energies, vol. 16, no. 1, p. 94, Dec. 2022, doi: 10.3390/en16010094.

[10] X. Yuan, Y. Wang and L. Wu (2008): SVM-based approximate model control for electronic throttle valve, IEEE Transactions on Vehicul Technol, vol. 57, pp. 2747-2756.

[11] Yuan and Y. Wang (2009): A novel electronic throttle valve controller based on approximate model method, IEEE Transactions on Indus Electron, vol. 56, pp. 883-890.

[12] L. Gevorkov and J. L. Domínguez-García, "Simulation Method for Energy Estimation of Variable Speed Pump for Heating System," 2022 IEEE 20th International Power Electronics and Motion Control Conference (PEMC), Brasov, Romania, 2022, pp. 685-690, doi: 10.1109/PEMC51159.2022.9962919.

[13] Kang H-L, Park H-J, Han S-H. Investigation of the Flow Characteristics for Cylinder-in-Ball Valve Due to a Change in the Opening Rate. Applied Sciences. 2022; 12(18):8930. https://doi.org/10.3390/app12188930.

[14] Hoang Le-Huy, P. Brunelle and G. Sybille, (2008). "Design and implementation of a versatile stepper motor model for simulink's SimPowerSystems," 2008 IEEE International Symposium on Industrial Electronics, Cambridge, pp. 437-442.

[15] M. Dashtdar, M. Belik, A. Yadav, S. M. S. Hosseinimoghadam, M. Bajaj and O. Rubanenko, "Improving the Performance of Distance Relay-Based Artificial Neural Network," 2022 IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek), Kharkiv, Ukraine, 2022, pp. 1-6, doi: 10.1109/KhPIWeek57572.2022.9916379.

[16] L. Gevorkov and I. Kirpichnikova, "Model of Solar Photovoltaic Water Pumping System for Domestic Application," 2021 28th International Workshop on Electric Drives: Improving Reliability of Electric Drives (IWED), Moscow, Russia, 2021, pp. 1-5, doi: 10.1109/IWED52055.2021.9376393.

[17] L. Gevorkov, J. L. Domínguez-García, A. Rassõlkin, and T. Vaimann, "Comparative Simulation Study of Pump System Efficiency Driven by Induction and Synchronous Reluctance Motors," Energies, vol. 15, no. 11, p. 4068, Jun. 2022, doi: 10.3390/en15114068.

[18] https://en.nanotec.com/fileadmin/files/Datenblaetter/Schrittmotoren/ST6018/L/ST6018L3008-B.pdf (accessed on 25 February 2023)

[19] S. Shin, S. K. Tirukkovalluri, J. Tuck and Y. Solihin, "Proteus: A Flexible and Fast Software Supported Hardware Logging approach for NVM," 2017 50th Annual IEEE/ACM International Symposium on Microarchitecture (MICRO), Boston, MA, USA, 2017, pp. 178-19.