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Engineering approach for cost effective operation of industrial pump systems

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Abstract. Power plants operators are persuaded to operate the main equipment such as centrifugal pumps in economically effective way. The operation of pump sets of district heating network at power plants should be done according to prescriptions of the original equipment manufacturer with further implementation of these requirements to distributed control system of the plant. In order to operate industrial pump sets with a small number of malfunctions is necessary to control the duty point of pump sets in H-Q coordinates, which could be complex task in some installations. Alternatively, pump operation control could be organized in H-n (head vs rpm) coordinates, utilizing pressure transmitters in pressure pipeline and value of rpm from variable speed driver. Safe operation range of the pump has to be limited with system parabolas, which prevents the duty point location outside of the predefined operation area. The particular study demonstrates the engineering approach for pump's safe operation control development in MATLAB /Simulink environment, which allows to simulate the operation of the pump at different capacities in hydraulic system with variable characteristic and to predefine the conditions for efficient simultaneous pump operation in parallel connection.

1. Introduction

According to the European Union new policy the member states have agreed on a new strategy for climate and energy objectives in the period from 2020 to 2030. These targets aim is to help the EU to achieve a more competitive, secure and sustainable energy system. The strategy sends a strong signal to the market, encouraging private investments in innovative technologies to achieve at least 27 % energy savings comparing with the business-as-usual scenario [1]. About the third part of the overall worlds electrical energy consumption relates to electric motors with non-variable speed driver, compressor, etc [2]. Rotating equipment engagement with the static driver and consequent flow media parameters regulation via throttling leads to inefficient primary energy resources spending, as well as decreases power plants overall efficiency due to high energy consumption rates for auxiliary equipment operation.

Conventional centrifugal pump connection with variable speed driver (hydrodynamic systems or distributed variable-frequency converter) offers to meet a high energy efficiency, increases system reliability and reduces maintenance costs of pump unit [3,4]. In case of the modernization of the existing pump system or designing of a new unit, in addition to variable speed drivers, the hydraulic system should be built in optimal configuration to reduce possible redundant hydraulic losses. Such problem could be solved utilizing dynamic simulations of the new pipeline at early design stages, which leads to improved efficiency of the whole system [5].

In numerous studies [6–8] was proved the high efficiency of the variable speed converters. Several researchers declared about electrical energy savings by 49 %, utilizing distributed variable-frequency converters in pumps comparing with conventional centrifugal pumps [3].

In the framework of this study are covered hydraulic theoretical aspects of typical operation conditions of centrifugal pumps, as well as provided the concept for the safe pump operation with duty point control in H-n coordinates, which in combination with condition monitoring can extend intervals between maintenance. The practical part of the study proposes the simulation model in Matlab/Simulink environment and analysis of the obtained results.

2. Simulation approach

2.1. Pump operational parameters conversion

In order to perform analysis of the real pump system was built the theoretical model in MATLAB /Simulink environment. As the prototype of the model was used KSB RDLO 400–665 centrifugal pump (for district network purposes) with the nominal capacity 5000 m3/h and developed head 145 m (Figure 1). The minimum allowed capacity for the particular pump, according to the manufacturer on-site test report is 2050 m3/h, but the maximum defined capacity is approximately 6000 m3/h. These values were taken as the constraint points for the system curve calculation.

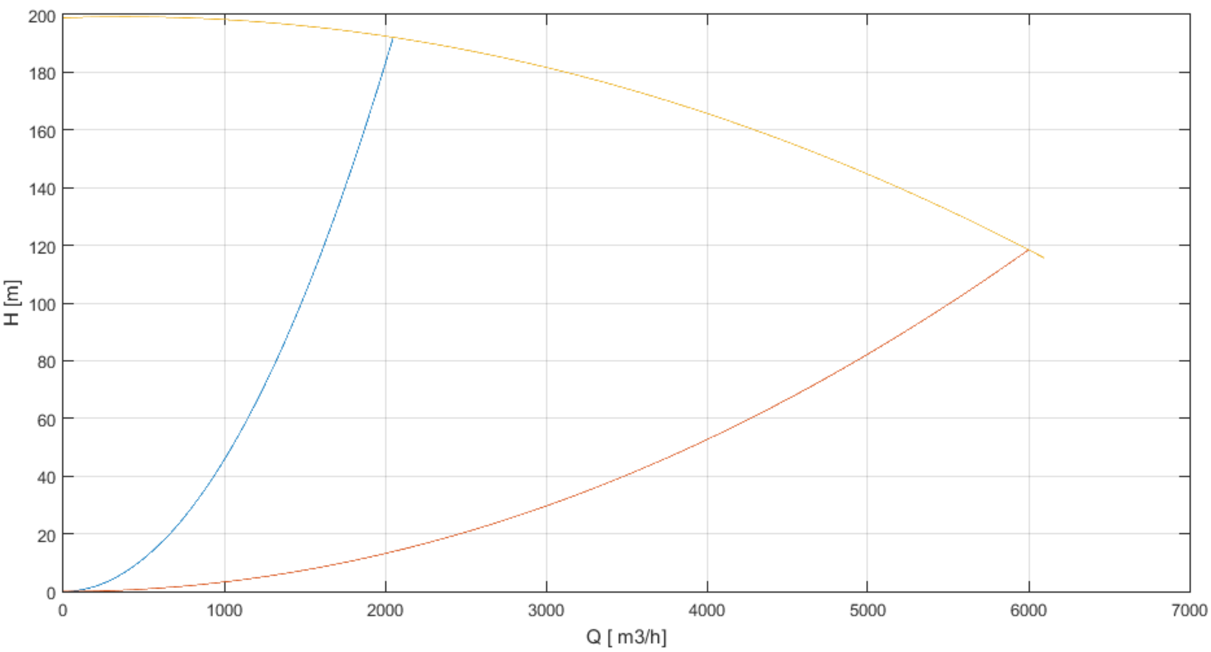

Figure 1. Safe capacity field of industrial centrifugal pump (KSB RDLO 400-665).

The pump operation outside the predefined area (Figure 1) can cause a damage of the pump set. In application with high static head, slowing of pump shaft angular speed can lead to induced vibrations and create performance problems, which are similar to shut-off operation [9]. For industrial pump set operation in predefined capacity range is necessary to control the duty point of the pump. Ordinary, it requires to control the set point of the pump set in H-Q (head versus flow) coordinates, utilizing additional flow meters after each pump.

If the pump sets are utilized in complex hydraulic schemes at power plant where is possible the flow distribution, the separate flow measurement for each unit could be problematic and economically not feasible. In such cases the solution to overcome this problem is the duty point control of pump in H-n (head versus shaft rotations per minute) coordinates, utilizing pressure transmitters in suction and pressure pipelines, and shaft angular velocity from variable speed driver. This approach is based on the coordinates transformation using affinity law formula [10].

$$H_2 = H_1 \times \left(\frac{n_2^2}{n_1^2}\right) = H_1 \times \left(\frac{Q_2^2}{Q_1^2}\right) \tag{1}$$

This formula includes the following parameters: H_1 - rated pressure head (m); H_2 - calculated pressure head (m); n_1 - pump shaft rated angular speed (rpm); n_2 - pump shaft reduced angular speed (rpm); Q_1 - pump capacity at rated shaft angular speed (m^3/h); Q_2 - pump capacity at reduced shaft angular speed (m^3/h). Equation allows to calculate the total head of the pump during the rotation speed changing. Taking into account prescriptions of the industrial pump manufacturer regarding the minimum and maximum allowed pump capacities is possible to calculate the constraint curves at different shaft angular velocities of the pump unit.

According to Figure 1, the developed head at the minimal recommended continuous flow for the particular pump is 192.1 m, but at the maximal capacity 118.5 m. Taking this developed head as the constraint points at the nominal 1490 RPM and putting these values in equation 1. is possible to reverse head-flow pattern to the aforementioned H-n coordinates. At Figure 2 are presented results of this transformation substituting developed head (H) in meters with differential pressure (P) in bars.

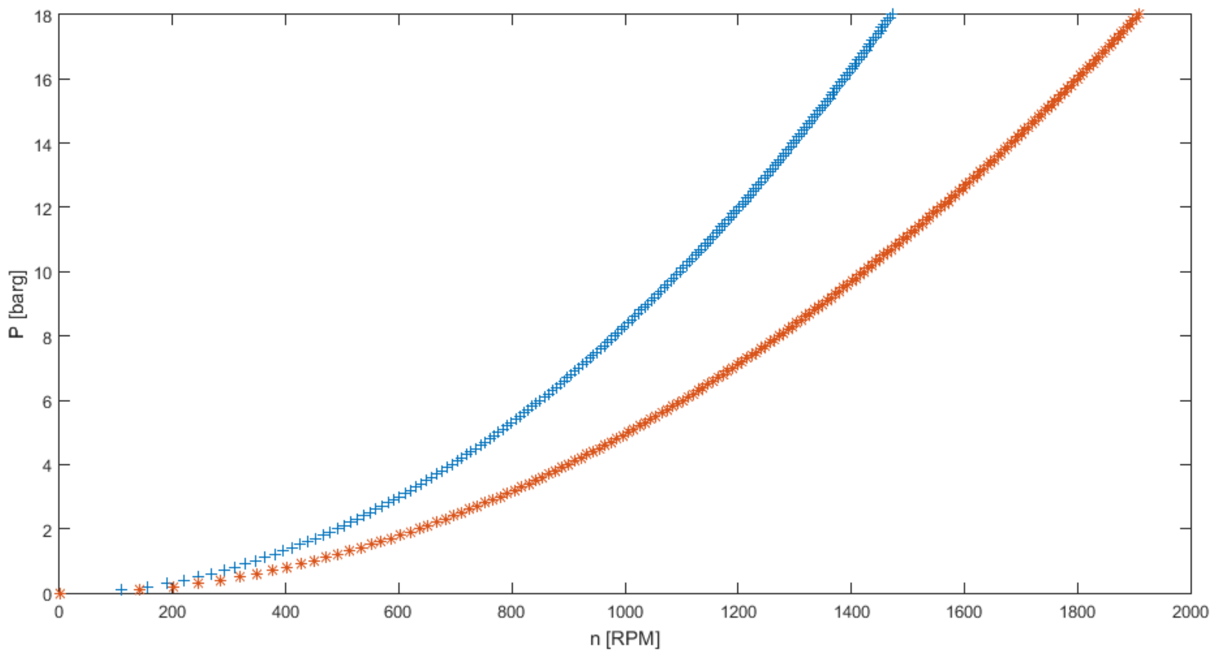

Figure 2. Centrifugal pump typical operation field in P-n coordinates.

The control algorithm of operation point should be integrated into distributed control system of the power plant and the main task of the approach is a pump operation prevention outside the mentioned limits. The measured values of the differential pressure and angular shaft velocity should lie between

Figure 2, red and blue lines. At the moment of the start-up, the pump passes critical operation area, which briefly could be neglected.

2.2. Characteristics of the model

The experimental setup was built in MATLAB /Simulink, utilizing advantages of control systems and hydraulic systems simulations in one package, which allowed to use the delicate internal control algorithm [11]. The model (Figure 3) consisted from predefined blocks, as well as custom made blocks. The model was equipped with all main parameters scope for simulation progress monitoring. Such models should accurately represent physical processes in transient and steadystates regimes, covering all operation conditions [12]. All main measured parameters and signals from the control blocks were logged in separate file for further analysis of simulation process.

The automation part of the parametric model included the main proportional-integral-derivative (PID) controller, supplementary PID controller, maximum and minimum values comparators, process switches, and frequency converter block for the signal conversion from PID controllers. In the considered model the PID controller constantly monitored the controlled and reference signals [13]. On this basis it generates a control signal, which subsequently is converted in frequency converter block. The hydraulic part of the model included industrial centrifugal pump with real characteristics, utilizing 1–D pump characteristics in P-Q and N-Q coordinates with spline interpolation method for different non-reference angular shaft velocities. The model included following hydraulic auxiliary elements: pipe resistive blocks and pressure regulators for flow control in defined range, imaginary reservoir for suction and pressure side connection of the pump unit, block with the properties of the hydraulic liquid, pressure sensors in the suction and pressure lines, flow rate sensor in pressure line for flow monitoring during the simulation and separate solver block.

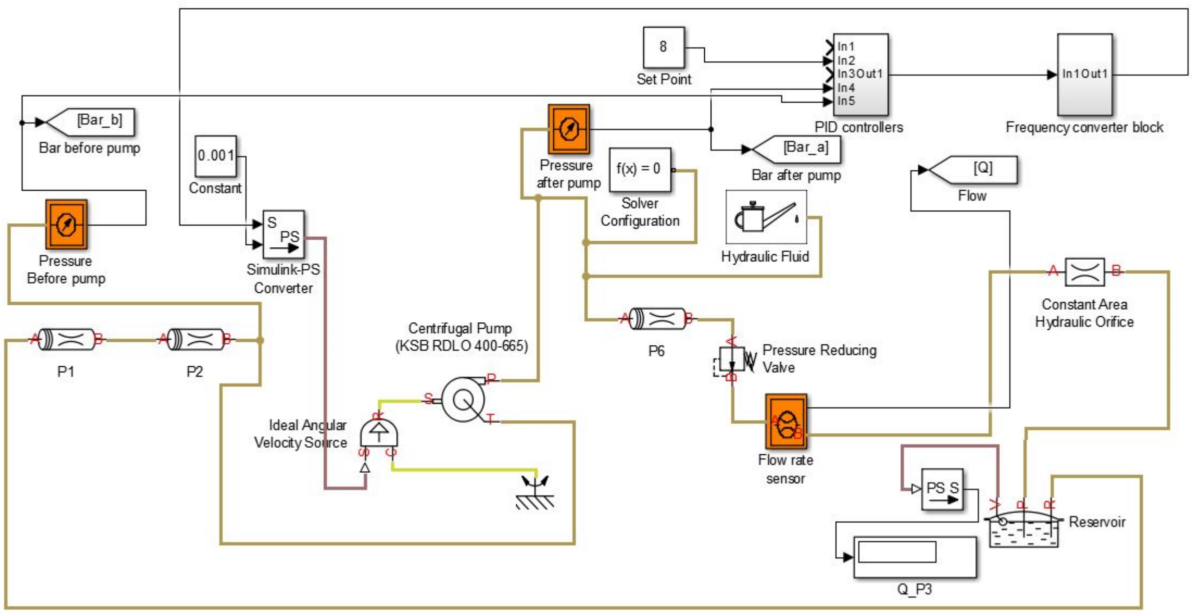

Figure 3. Scheme of the simulation model in MATLAB/Simulink.

The output saturation of the PID controller was predefined, taking into account the nominal shaft angular velocities of the pump. The supplementary PID regulators received its set point with transport delay from special function block for the better simulation performance. The output signals were connected to the logger for the subsequent graphical data analysis in MATLAB. As shown on the Figure 4 during the simulation eight signals were registered with the defined simulation step.

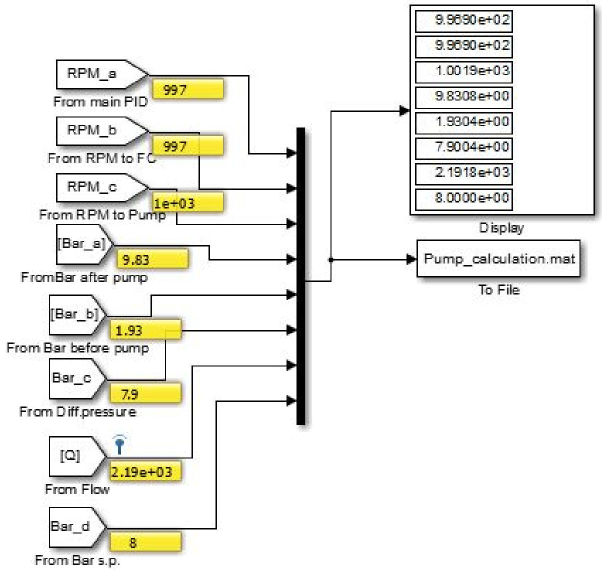

Figure 4. Eight logged signals of the simulation model with enabled value labels.

In the beginning of the simulation, the supplementary PID regulators, which was used to keep the pump unit in safe predefined operation area, was disabled until the rotation speed of the pumps shaft reached minimum 200 rpm. As soon as the rotation speed of the shaft gained the aforementioned value, the simulation process was paused for the activation of the supplementary PID regulator. The manufacturer of the pump unit suggests that operator will take into account the parameters of the system and adjust the operation condition to keep pump in safe area. The model allows to pause the simulation on any progress step and to change the initial set point - differential pressure across the pump. After changing the set point the PID regulator adjusts the speed of the shaft rotation at desired level. Such kind of the simulation would be valuable before the procurement process of the new equipment at design stages, because the manufacturer usually provides the pump characteristics without operation comparison with real system curve.

3. Results

The aim of the theoretical model simulation was the prediction of the duty point varying the set point (pressure difference across the pump), nominal diameter of the main pipe and length of the pipe network. During the simulation process was defined safe limits for the stable pump operation. The simulation results covered following combination of the parameters: the pressure difference was between 15 and 8 bar, the nominal pipe diameter was between DN800 and DN600, and length was varied between 10 and 20 kilometers. Such variation of aforementioned parameters relates to district heating networks of cities. Prior to the model analysis were performed four different simulations with simultaneous data logging. Each logged file included more than 400 000 written numerical performance values for each time step. The simulation was stopped after 400 simulation seconds.

3.1. Parameters analysis of the model

Before the analysis of simulated results was performed the extraction of a large amount of the logged data. In order to compare four simulation results with different pressure across the pump, the developed flow and rotation angular speed was constructed 2D plots in P-Q (Figure 5) and P-n (Figure 6) coordinates and 3D plot in P-Q-n coordinates. This graphical analysis allowed deeply investigate the behavior of the studied hydraulic system and to define the effectiveness of the selected pump (during project design).

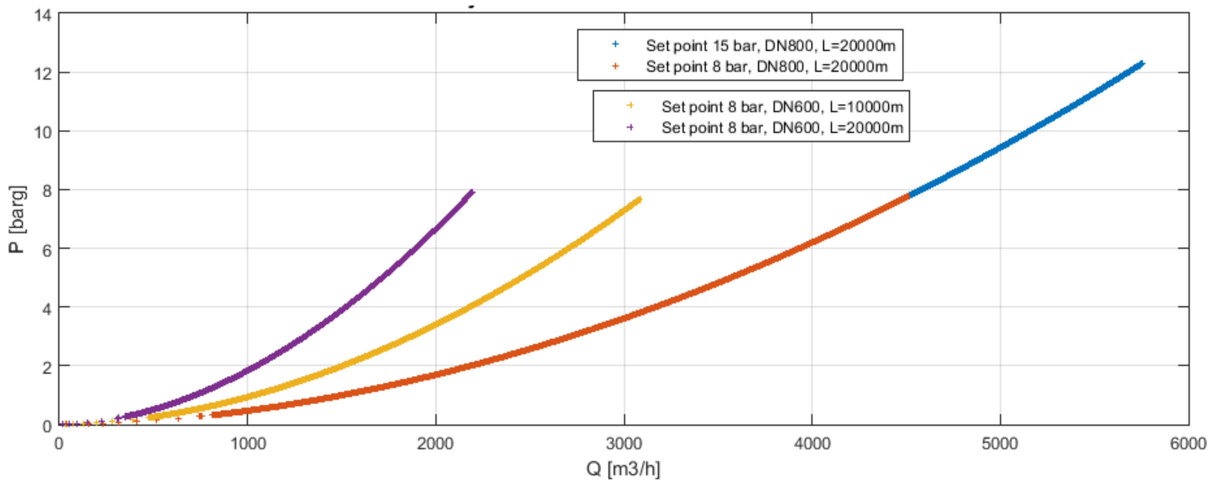

Figure 5. Generated system curves at different initial conditions.

In the Figure 5 are shown systems curves, which could be obtained during the typical operation. These curves are similar to Figure 6 and demonstrate the rigid bond with P-n coordinates. These results confirmed that pump operation point control could be organized in reversed coordinates without data loss. The system curves demonstrate the trajectory of the duty point, varying the set point for the pump unit and keeping hydraulic resistance of the system and dimensional parameters unchanged. In real district network, the operation point of the pump will move along the horizontal direction, which is caused by variable hydraulic characteristics of external heat consumers.

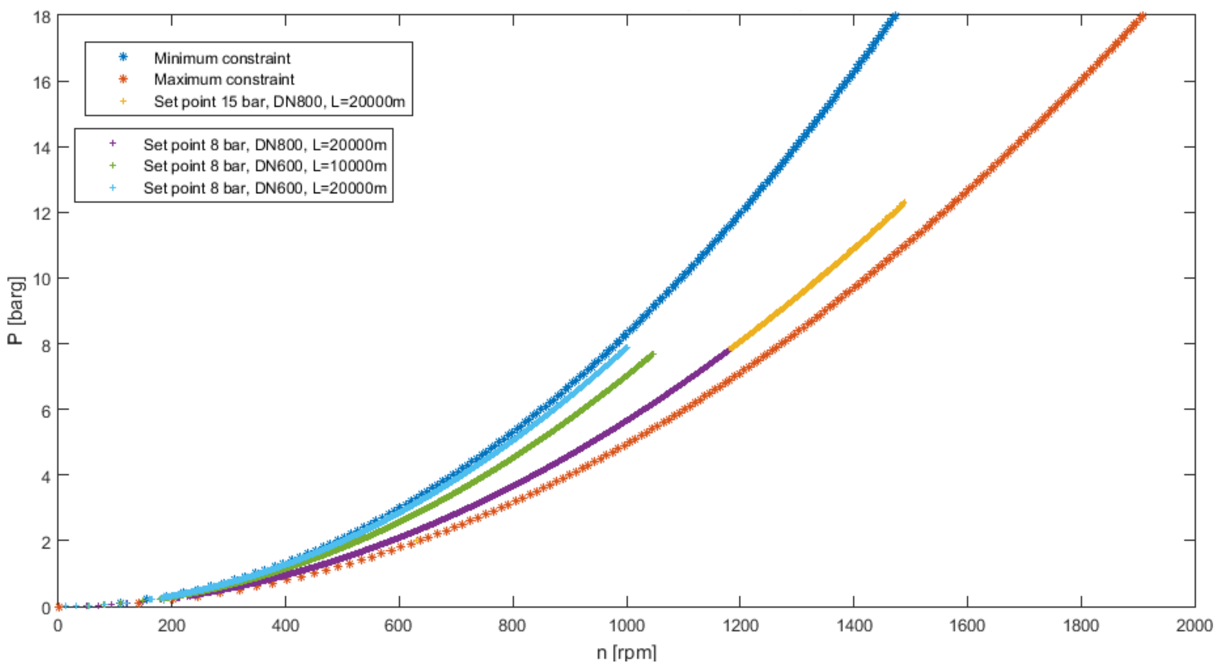

Figure 6. Differential pressure and shaft angular velocity pattern of KSB RDLO 400-665 pump set.

In the showed plot are demonstrated the results of the model simulation according to different conditions. The blue line characterizes the simulation conditions with the set point at 8 bar, the pipe nominal diameter DN 600 and the pipe length 20000 meters. Under these conditions pump set would work near the upper limit. The crossing of upper level would cause non-typical vibrations, flow instabilities and additional probability of the mechanical parts malfunctions.

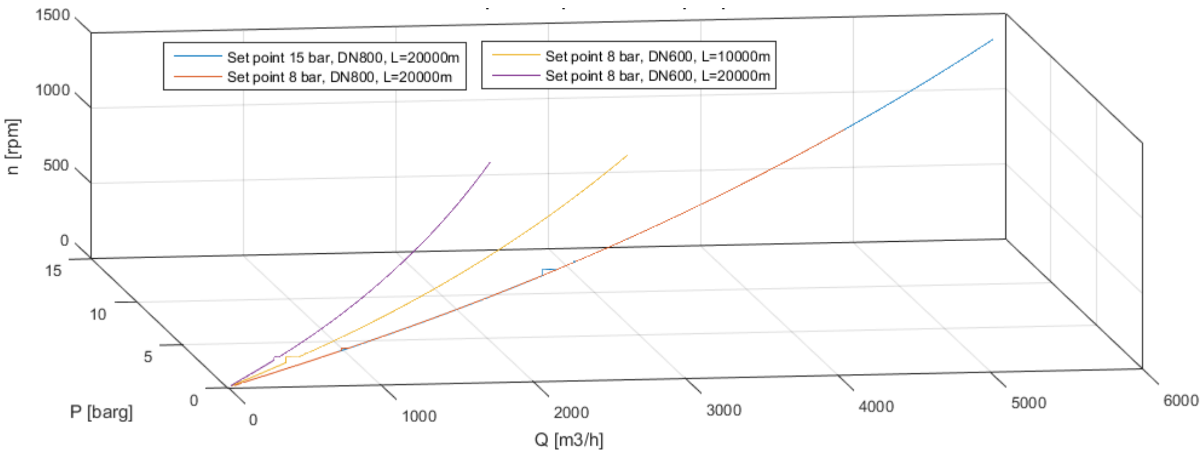

Figure 7. Operation curves of the simulated model in P-Q-n coordinates.

The Figure 7 combines all aforementioned simulation results in 3D plot. Plotted results graphically testify the narrow operation region of the pump, despite the installed variable shaft speed driver. This plot demonstrates the possible operation limits of the pump station and could be successfully utilized for the graphical analysis of pump units with different operation characteristics. Such graphical analysis can simplify selection of the new pump units for seasonal operation at design stage.

4. Conclusions

The analysis of the centrifugal pump set operation, which was conducted in the framework of this study, gave the broad range of the result data. The main concept of this study is a safe operation mode and basic control algorithm development for the centrifugal pumps. The model analysis and simulation in Matlab/Simulink environment allowed to present the simple method for constraint curves modeling and in addition to simulate the typical system curves for the particular centrifugal pump set.

Presented simulation model demonstrates the key points for the new or old pump station retrofitting design. Such model allows to simulate the response of the separate pump unit or a few in parallel connection. Obtained results could be implemented to the distributed control system for the control algorithm enhancement.

Demonstrated engineering approach for the pump operation control in narrow range at H-n coordinates (without additional flow measurement) could be integrated to the hydraulic systems, which utilizes the centrifugal pumps in parallel connection, especially those, which are occupied with variable frequency converters. Such control algorithm could protect the pump sets from unfavourable operating conditions and reduce the maintenance costs.

5. References

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