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Evaluation of Efficiency Improvement Potential Applying Proportional Pressure Control for Variable Speed Pumps in Water Supply

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ABSTRACT: *The proportional pressure control of centrifugal pumps may significantly increase the efficiency of water supply systems in terms of both electrical energy consumption and water leakage. The goal of this research is the derivation of the approximation concept for evaluation of the efficiency improvement potential applying the proportional pressure control for variable speed pumps in water supply. The proportional pressure control has been compared with the constant pressure control. For this reason, the energy calculation analyses have been made for certain pumps. The concept for evaluation of the efficiency improvement potential has been derived and experimentally tested. The interaction among the energy consumption, water leakage, and declination of the pump proportional pressure control curve has been found at the specific load profile. Based on the average possible linear declination of the pump proportional pressure control curve (15%) and the average water leakage in network (24%) in Latvia, the conclusions are as follows: 1) 12.2% of annually consumed electrical energy may be saved up in water supply systems applying the proportional pressure control is used instead of the constant pressure control; 2) The annual reduction of the existing water leakage rate may reach 3.7% in water supply networks.*

KEYWORDS: *Control, efficiency, leakage, pressure, pumps, water*

I. INTRODUCTION

Pumps and pumping systems consume about 10% of the total electrical energy produced in the world, and more than half of that may be saved up [1, 2].A lot of scientific papers were dedicated to the energy efficiency investigation in centrifugal pump technology [3, 4, 5, 6, 7, 8]. Some of the research works show the results of the experimental measurements of variable speed pumps. Some of the research works show the theoretical approach on energy calculation for variable speed pumps in water supply systems.

The researches related with the energy efficiency of centrifugal pump technology are as follows:

- Efficiency evaluation of variable speed pumps' operation in water supply systems with a focus on efficiency level at partial load and reduced rotation.
- Measurements of actual parameters of pumping systems and optimization proposals for certain pumping system.
- System reliability and energy efficiency analysis for variable and constant speed pumps.
- Construction and operation analysis of the single stage end-suction centrifugal pump.
- Interaction analysis of pressure and water leakage.
- Measurements and improvement of energy efficiency of pumping stations with a focus on activation order of variable speed pumps.
- Theoretical analysis of variable speed pumps control modes.
- Theoretical analysis of load profiles.

No one research concerns the analysis of the energy efficiency improvement potential of variable speed centrifugal pumps' operation in water supply systems (based on different load profiles and the proportional pressure control).Normally network pumps are operating via the constant pressure control in water supply. The proportional pressure control mode is the most efficient mode of the booster pumps' control in water supply systems. The closer the proportional pressure control curve is to the system curve the higher level of the energy efficiency can be obtained. At the same time, the level of water leakage is being decreased. The proportional pressure control is generally recommended to the systems where the total pressure drop is mostly dedicated to the piping system. Thus the proportional pressure control is advised to be applied in water supply systems with relatively long piping network.

The evaluation of the efficiency improvement potential is very important when applying the proportional pressure control for variable speed pumps in water supply systems. To make an evaluation of the efficiency improvement potential in water supply systems, the proportional pressure control has been compared with the constant pressure control. The energy improvement evaluation concept can be derived taking into account a specific load profile of water supply systems. Various energy calculations have been realized based on the load profile. With the certain research focused on the evaluation of operation of pumping systems, it's possible to substantially increase the total level of efficiency in engineering networks, thus contributing to energy saving in the world.

II. APPROXIMATION CONCEPT FOR EVALUATION OF EFFICIENCY IMPROVEMENT POTENTIAL

The proportional pressure control has been compared to the constant pressure control during the development of the approximation concept for evaluation of the efficiency improvement potential for variable speed network pumps in water supply systems. The proportional pressure control curves are described with the declinations within the range of 0-80% from the head value of the duty point. It is done in comparison with the constant pressure control curve (Fig.1).

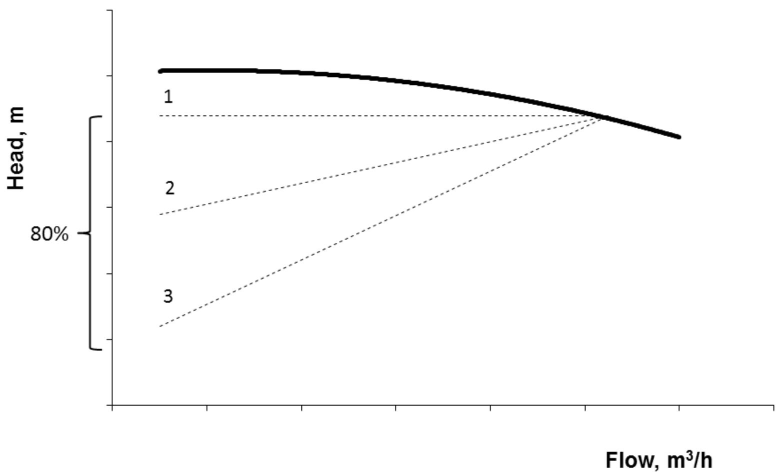

Figure 1 Pumps' control modes (1 – constant pressure; 2-3 – proportional pressure with linear influence)

It was assumed that min 20% of the total head value of the duty point is related to the static head in water supply networks [9]. Then 80% of the total head value of the duty point is related to the friction losses. The energy consumption has been analyzed when the proportional pressure control of variable speed pump comes as an alternative to the constant pressure control for the same system. Equations (1-6) show the relationships among rotational speed, flow rate, head, power and efficiency values when variable speed drive is used for centrifugal pumps [1]:

$$\frac{Q_n}{Q_x} = \frac{n_n}{n_x} \quad (1)$$

$$\frac{H_n}{H_x} = \left(\frac{n_n}{n_x}\right)^2 \quad (2)$$

$$\frac{P_n}{P_x} = \left(\frac{n_n}{n_x}\right)^3 \quad (3)$$

$$\frac{\eta_n}{\eta_x} = 1 \quad (4)$$

$$\eta_{TOT} = \eta_P * \eta_M * \eta_{FC} \quad (5)$$

$$\eta = \frac{P_H}{P_1} = \frac{\rho * g * Q * H}{P_1} \quad (6)$$

The Table 1 shows the change of head values at certain flow components and declinations of the pump proportional pressure control curve within the range of 0-80% [1].

Table 1 Declinations of proportional pressure control curve with linear influence [10]

Flow components / Declinations of proportional pressure control curve	100%	75%	55%	35%	12%
0%	100%	100%	100%	100%	100%
20%	100%	95%	91%	87%	82%
40%	100%	90%	82%	74%	65%
60%	100%	85%	73%	61%	47%
80%	100%	80%	64%	48%	30%

To analyze the consumption of the electrical energy, the load profile of pumping system in water supply has been taken into account. It has been assumed that the annual operation of pumping systems is 3285 hours in public water supply systems [11, 12]. The load profile is divided into five parts with the following flow values: 100%, 75%, 55%, 35% and 12% of the flow rate at the duty point, and each flow component corresponds to the certain duration of operational time:

- 100% → 5%;
- 75% → 9%;
- 55% → 14%;
- 35% → 27%;
- 12% → 45%.

Each flow component corresponds to the certain duration of operational time as a part of the total duration of operation per year (Fig.2).

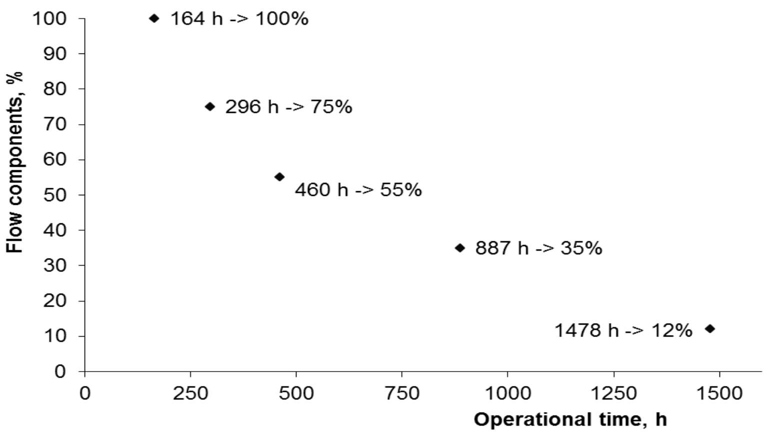

Figure 2 Theoretical load profile of network pumps in public water supply

The energy calculation analyses have been performed for variable speed centrifugal pumps in water supply systems (Table 2). The certain load profile has been used. The calculation principle is shown in Table 2.

Table 2 Energy calculation (proportional pressure control/constant pressure control)

Flow component, %	100	75	55	35	12
Head value, %	$100\text{-}\Delta_1$	$100\text{-}\Delta_2$	$100\text{-}\Delta_3$	$100\text{-}\Delta_4$	$100\text{-}\Delta_5$
Operational time, h/year	164	296	460	887	1478
Power (P_1), kW	A_1	A_2	A_3	A_4	A_5
Energy consumption, kWh/year	B_1	B_2	B_3	B_4	B_5
Energy consumption, kWh/year	ΣB_n				

The comparison of the consumed energy has been performed after the energy calculation analyses of various variable speed centrifugal pumps. The amount of the consumed energy at different declinations of the pump proportional pressure control curve has been compared with the amount of the energy consumed at the constant pressure control mode (Table 3).

Table 3 Comparison of consumed energy at different declinations of proportional pressure control curve

Declination of proportional pressure control curve, %	Difference in consumed energy (proportional pressure curve vs. constant pressure curve), %
0	$1-\Sigma B_0/\Sigma B_0$
20	$1-\Sigma B_{20}/\Sigma B_0$
40	$1-\Sigma B_{40}/\Sigma B_0$
60	$1-\Sigma B_{60}/\Sigma B_0$
80	$1-\Sigma B_{80}/\Sigma B_0$

The calculation of annual energy consumption for variable speed network pumps has been carried out. It has been done at the certain declinations of the pump proportional pressure control curve: 20%, 40%, 60% and 80% from the head value of the duty point (Fig.3).

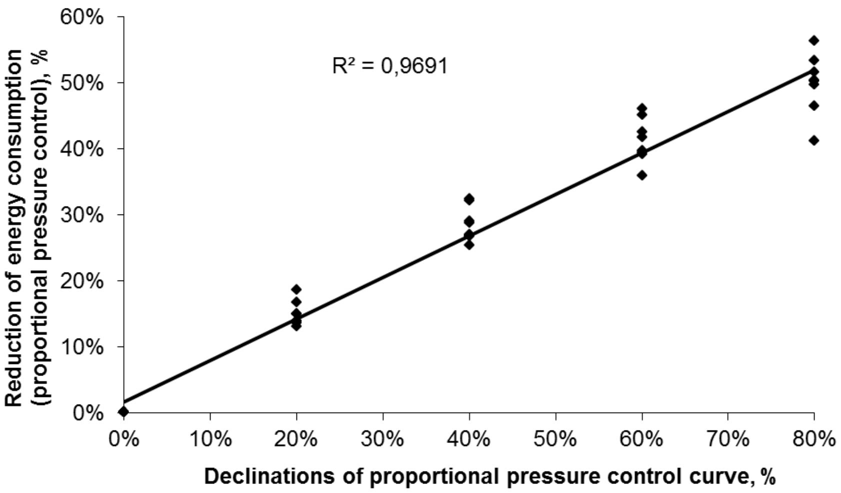

Figure 3 Reduction of energy consumption applying proportional pressure control (vs. constant pressure)

Based on the calculation of the annual energy consumption for network pumps, the regression equation has been derived. The regression equation (7) of the linear trend type ($y = a_0 + a_1 * x + \varepsilon$) and the respective coefficient of determination (R^2) has been derived (using trendline in Excel):

$$y_1 = (0.63 \pm 0.02) * x + 0.02 \pm 0.01 \qquad (7)$$

The Equation (7) can be used as a tool for evaluation of the potential reduction of the energy consumption of variable speed network pump in water supply. The proportional pressure control is used with the declinations within the range of 0-80% (at the given load profile).As a load profile is a variable then the equation is being changed accordingly. The potential reduction of the energy consumption has been estimated in comparison with the constant pressure control, if the value of the duty point remains invariable. Water leakage may significantly be decreased as well, if the proportional pressure control has been applied for variable speed pumps in water supply networks. The calculation of the water leakage has been performed for various variable speed centrifugal pumps in water supply systems. The certain theoretical load profile has been applied (Table 4).

Table 4 Calculation of water leakage index (proportional pressure control/constant pressure control)

Flow component, %	100	75	55	35	12
Head value, %	$100\text{-}\Delta_1$	$100\text{-}\Delta_2$	$100\text{-}\Delta_3$	$100\text{-}\Delta_4$	$100\text{-}\Delta_5$
Operational time, h/year	164	296	460	887	1478
Water leakage index	C_1/C_{100}	C_2/C_{100}	C_3/C_{100}	C_4/C_{100}	C_5/C_{100}
Water leakage index with influence of flow/time components	C_{Qt1}	C_{Qt2}	C_{Qt3}	C_{Qt4}	C_{Qt5}
Water leakage index with influence of flow/time components	ΣC_{Qtn}				

The calculations of the water leakage indexes have been performed. The decrease of the water leakage has been determined at different declinations of the proportional pressure control curve (Table 5).

Table 5 Comparison of water leakage at different declinations of proportional pressure control curve

Declination of proportional pressure control curve, %	Difference in water leakage rate (proportional pressure curve vs. constant pressure curve), %
0	$1-\Sigma C_{Qt0}/\Sigma C_{Qt0}$
20	$1-\Sigma C_{Qt20}/\Sigma C_{Qt0}$
40	$1-\Sigma C_{Qt40}/\Sigma C_{Qt0}$
60	$1-\Sigma C_{Qt60}/\Sigma C_{Qt0}$
80	$1-\Sigma C_{Qt80}/\Sigma C_{Qt0}$

The Torricelli's equation (8) can be used to determine the decrease level of the water leakage in piping systems by decreasing the head value of the pump [13]. The discharge coefficient "0.6" has been applied to Torricelli's Equation to more accurately model the flow through an orifice. The coefficient stands for the flow of fluid through a sharp edged orifice:

$$C = \sqrt{2 * g * H} * 0.6 \tag{8}$$

The calculation of the decrease of annual leakage rate in water supply networks has been carried out. It has been done at the certain declinations of the pump proportional pressure control curve: 20%, 40%, 60% and 80% from the head value of the duty point (Fig.4).

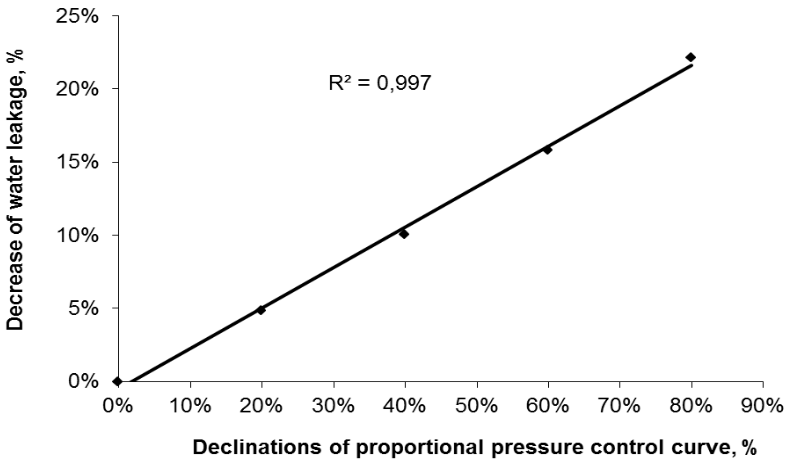

Figure 4 Annual decrease of water leakage from current water leakage rate applying proportional pressure control (vs. constant pressure)

Based on the calculation of the decrease of annual leakage rate in water supply networks, the regression equation has been derived. The regression equation of linear trend type ($y = a_0 + a_1 * x + \varepsilon$) and the respective coefficient of determination (R^2) has been derived (using trendline in Excel):

$$y_2 = (0.28 \pm 0.01) * x - (0.5 \pm 0.4) * 10^{-2} \qquad (9)$$

The Equation (9) can be used as a tool for evaluation of the potential reduction of the water leakage of the existing leakage rate in piping system at different declinations of the pump proportional pressure control curve. As a load profile is a variable then the equation may be changed accordingly. The potential reduction of the leakage has been estimated in comparison with the constant pressure control, if the value of the duty point remains invariable.

III. VERIFICATION OF APPROXIMATION CONCEPT FOR EVALUATION OF EFFICIENCY IMPROVEMENT POTENTIAL

The measurements have been done in the public water supply system (the second stage boosting station) of the town Jaunolaine in the beginning of 2012. The second stage boosting station is located not far from Riga city (20 km). The water supply system supplies drinking water to 2000 inhabitants in a town.

The water supply system is described with the following parameters:

- The drinking water consumption is 131400 m3/year,
- The daily drinking water consumption is 360 m3/day,
- Max drinking water consumption per hour is 36 m3/h,
- The pressure value after a boosting station is 3.5 bar ≈ 35 m,
- The water leakage in network is ~20%,
- The load profile (Fig.5).

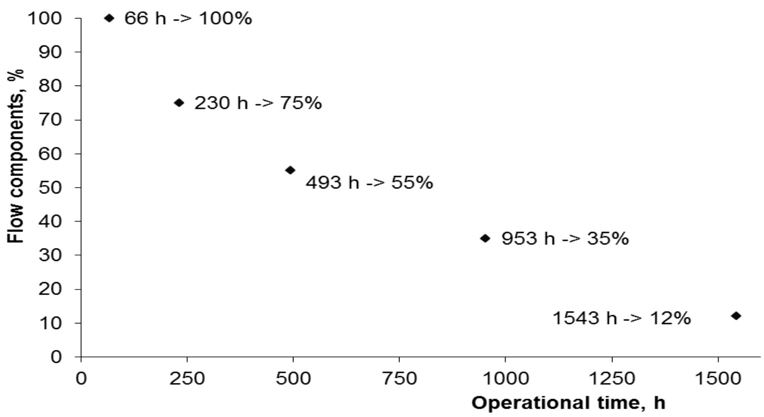

Figure 5 Load profile of network pumps in public water supply system

The pressure boosting station is described with following parameters:

- The boosting station consist of 5 pumps (1 – drinking water pump, 2 – firefighting pumps, 2 – stand by pumps),
- All the pumps are with built-in frequency converters for variable flow,
- Each pump is with the nominal flow/head: 45 m^3/h @ 60 m,
- Each pump has a motor of P_2=11 kW,
- Each pump has the maximum efficiency (BEP) of 64.8 %,
- The pumps are controlled via the constant pressure control: 35 m after the boosting station,
- The control panel of the booster station allows controlling the variable speed pumps via the constant pressure or proportional pressure (Control MPC-E).

The following working parameters have been measured during the analysis of the comparison of the constant and proportional pressure control:

- Flow value per hour (m^3/h),
- Pressure value (bar),
- Power value (W),
- Electrical energy consumption (kWh).

The following tools have been used during the analysis of the pump control modes:

- Energy meter (accuracy: ±0.1%),
- Ultrasonic flow meter (accuracy: ±0.5-2%),
- Thickness meter (accuracy: ±1% + 0.02 mm),
- Pressure sensors (accuracy: ±2%),
- Registering equipment (data logger, accuracy: ±0.2% at 20ºC).

Each of the parameters has been measured every 30 minutes during one month (29 days).The measurements have been done in two steps by using a monitoring program – each pump control mode has been tested during a month. The proportional pressure pump control has been realized at the declination of 15% of the pump proportional pressure control curve. This value of the declination has been chosen in order to provide a constant pressure level at the distal end-user across the day-night period. A constant pressure level at the critical end-user has been provided at both minimal and maximal flow rates. The hydraulic friction losses across the whole network are 5 m or ~15% from the total head value of the duty point. The rest 30 m are related to the static head which consists of the maximum building height (12 m), the topography height (3 m) and the pressure value at the critical tap (15 m). The layout of the network is shown in Fig.6.

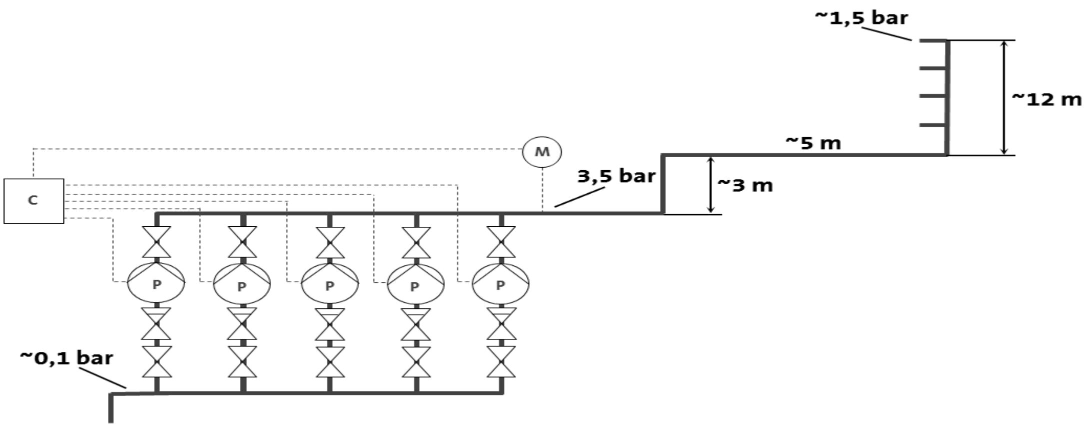

Figure 6 Sketch of public water supply network

The measurements of the head, power and energy values are shown in Fig. 7, Fig.8 and Fig.9.

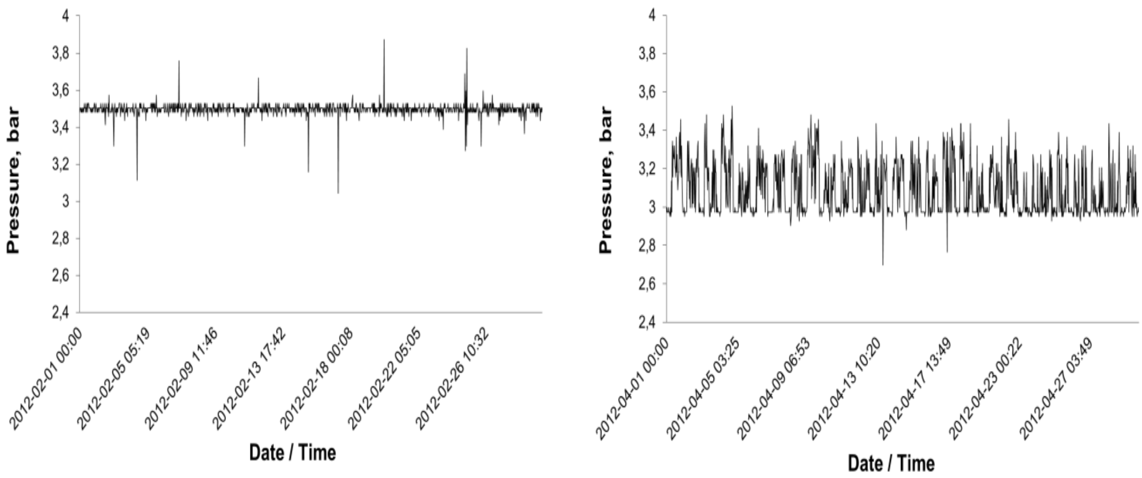

Figure 7 Pressure values (from left: constant pressure; from right: proportional pressure)

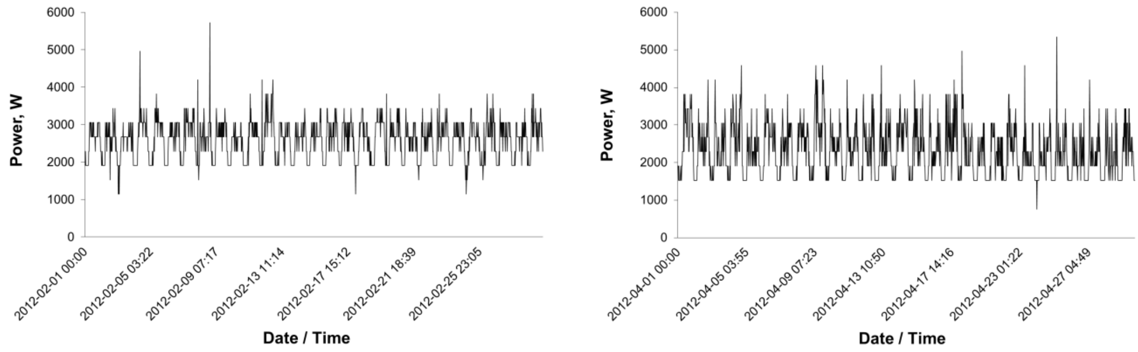

Figure 8 Power values (from left: constant pressure; from right: proportional pressure)

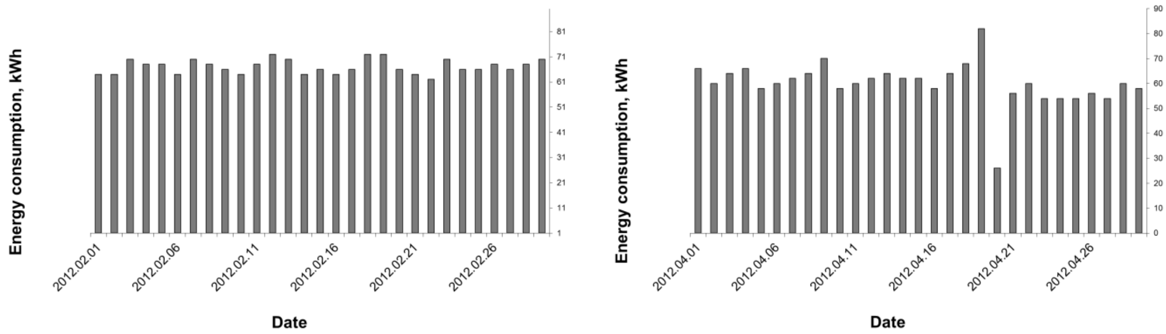

Figure 9 Energy consumption values (from left: constant pressure; from right: proportional pressure)

During the proportional pressure control, the flow value varies from 6 m^3/h up to 33 m^3/h (Fig.10). The measured pressure values after the boosting station vary from 2.9 up to 3.5 bars within the flow range. The pumping station activates “night mode” when the flow value decreases less than 6 m^3/h. The pumps then stop (the pressure values vary from 2.8 up to 3.4 bar at the zero flow).

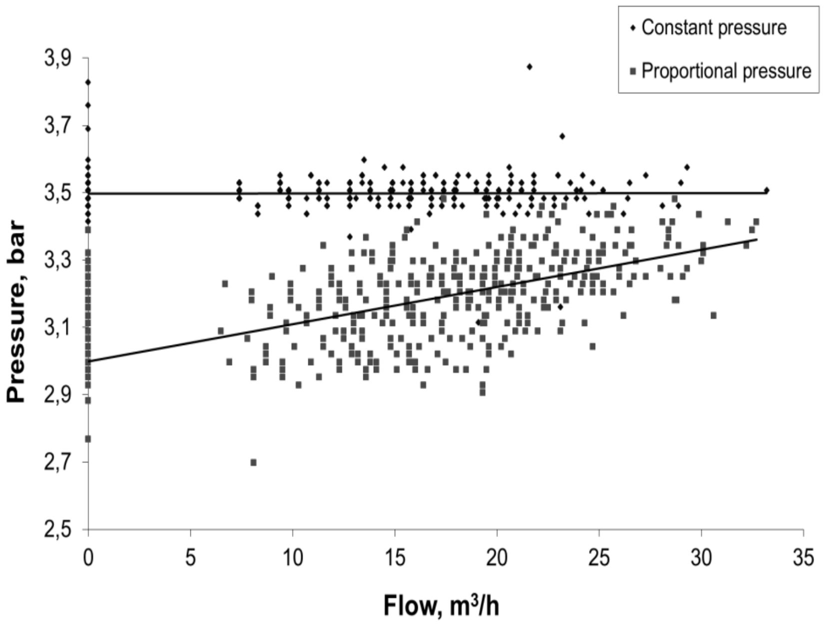

Figure 10 Pressure and flow values applying constant and proportional pressure control

The real measured savings of electrical energy is 11.7% (the proportional pressure with the declination of 15% has been compared with the constant pressure).By applying the approximation concept for evaluation of the efficiency improvement potential, the calculated savings of electrical energy are 12.1%.The absolute error is ~0.4%, if the approximation concept for evaluation of the efficiency improvement potential is compared to the field measured data.

IV. CONCLUSIONS

As the result, the interaction among the energy consumption, water leakage, and declination of the pump proportional pressure control curve has been found at the specific load profile (Fig.11).

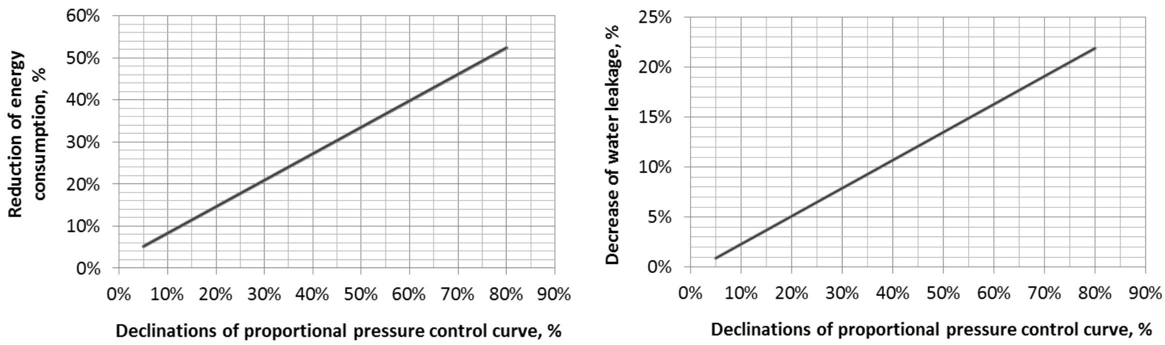

Figure 11 Interaction among energy consumption, water leakage, and declination of pump proportional pressure control curve

This has been found when the proportional pressure control was compared with the constant pressure control. If the pump control mode is known, then the current pump control mode should be considered to be changed (based on hydraulic calculations). If it is possible to change the constant pressure/existing proportional pressure control to the proportional pressure control with the bigger control curve declination, then the potential energy savings may be evaluated using the Fig.11 (see leftwards). If the current water leakage rate is known for the system, then it is possible to detect the potential reduction of the existing water leakage rate using the Fig.11 (see rightwards).In Latvia, the average declination level of the pump proportional pressure control curve is 15% in small towns (up to 10000 inh.), and the average water leakage in the network is 24%.1. About 12.2% of the annually consumed electrical energy may be saved up in water supply systems changing the control of variable speed network pumps from the constant pressure control to the proportional pressure control (the linear declination of the pump proportional pressure control curve is 15%).

2. The annual reduction of the existing water leakage rate may reach up to 3.7% in water supply systems. It is possible if the linear declination of the pump proportional pressure control curve is 15%. The total annual leakage reduction is 0.9% of the annually delivered water rate in water supply systems, if the network is described with the current leakage rate of 24%.

The following limitations have been taken into account during the research:

- The proportional pressure control mode with linear influence has been chosen;
- Each duty point has been met with the appropriate pump;
- The deviation from the pump efficiency optimum is up to 3% for each duty point;
- The declination value of the pump proportional pressure control curve varies from 0 to 80%.

During the study, the energy analyses of 8 variable speed centrifugal pumps have been realized [10, 15].

NOMENCLATURE

C	Water speed at pipe rupture (m/s)
g	Acceleration of gravity (9.81 m/s^2)
H	Pump head (m)
n	Pump rotational speed (RPM)
P_1	Pump motor input power (kW)
P_H	Power delivered to pumped liquid (kW)
Q	Flow rate (m^3/s)

R^2 Coefficient of determination

x Declination of pump proportional pressure control curve (%)

y_1 Reduction of energy consumption (proportional pressure control vs. constant pressure control) (%)

y_2 Decrease of water leakage from current water leakage rate (proportional pressure control vs. constant pressure control) (%)

η_P Efficiency of pump (%)

η_M Efficiency of motor (%)

η_{FC} Efficiency of frequency converter (%)

η Efficiency of complete pump unit: pump and motor (%)

η_{TOT} Total efficiency of complete pump unit with frequency converter (%)

ρ Density of pumped liquid (kg/m^3)

REFERENCES

[1] P. Giribone, R. Beebe, And G. Hovstadius, System Efficiency (A Guide For Energy Efficient Rotodynamic Pumping Systems) (Brussels: Europump, 2006).

[2] S. Trinath, And G. Amitabh, Energy Cost Savings With Centrifugal Pumps, World Pumps, 2009.

[3] E. Durmus Kaya, K. Alptekinyagmur, Suleymanyigit Et Al, Energy Efficiency In Pumps,Energy Conversion And Management, 49, 2008, 1662–1673.

[4] K.J. Astron, And B. Wittenmark,Adaptive Control(Reading: Addison Wesley, 1995).

[5] F. De Paola, And M. Giugni, Leakages And Pressure Relation: An Experimental Research,Drinking Water Engineering And Science, 5, 2012, 59–65.

Marchi, A.R. Simpson, And N. Ertugrul, Assessing Variable Speed Pump Efficiency In Water Distribution Systems,Drinking Water Engineering And Science, 5, 2012, 15–21.

[6] Moreno, A. Carrion, P. Planells Et Al, Measurement And Improvement Of The Energy Efficiency At Pumping Stations,Biosystems Engineering, 98, 2007, 479 – 486.

[7] D. Kaya, And F. Cankakılıc, Energy Conservation Opportunity In Vsd System – A Case Study,World Energy Engineering Congress Proceedings, Texas, Usa, 2004.

[8] R. Palgrave, Troubleshooting Centrifugal Pumps And Their Systems(Oxford: Elsevier Ltd., 2003).

[9] Grundfos Management A/S, Grundfos Webcaps (Computer Aided Product Selection), 2010. Available At Http://Net.Grundfos.Com.

[10] Vdma (Verband Deutscher Maschinen- Und Anlagenbau - German Engineering Federation), Working Group Load Management, 2013. Available At Http://Www.Vdma.Org.

[11] Butk Consortium, Grant Agreement Eie/06/010/Si2.443504, Calculation And Reporting Of Co2 Emission And Savings Attributable To Lighting,Epta Environmental Consultants – Engineers, Athens, 2007.

[12] College Of Engineering (Wayne State University), Torricelli's Theorem And The Orifice Equation, 2002. Available At Http://Www.Eng.Wayne.Edu.

[13] N. Bidstrup, Differential Pressure Controlled Pumps,Ashrae Winter Conference, Seminar: Fundamental Pump Selection And Control, Dallas, Texas,2013.

[14] Wilo Se, Wilo-Select Online, 2009. Available At Http://Www.Wilo-Select.Com.