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# IMPROVED INTERACTIVE ENERGY SAVING CONTROL ALGORITHMS OF WATER SUPPLY PUMP BASED ON HEAD MEASUREMENT

**Introduction.** At the present time, the problem of energy saving control of water supply systems is being paid increasing attention, owing to the depletion of energy resources and the contamination of drinking water supplies [1]. This attention has resulted in the concept of "intelligent pump" (IP), meaning that the pump's control system identifies its load and parameters, tunes the pump's controller according to the demand, and provides an energy saving algorithm with minimum possible operator intervention. Such complicated problem can be solved using a joint control system of the pump and its induction motor based on a modified frequency converter [2-6]. The novel approach for energy saving of water supply pumps adjusts the pump's velocity to the lowest value suitable while meeting consumers' demand. In the Grundfos Magna IP product, the problem is solved after the pump's operating point is reached by a reduction of the velocity when it is allowed by the consumer (so-called *autoadapt* function) [7]. Another solution was proposed based on a game approach (the interactive control) [8,9]. It considers the pump's control process as a game between consumers striving to satisfy their demand and the system trying to decrease the pump's velocity. As a result, a compromised pump's velocity suitable for both players is reached.

Interactive energy saving algorithms were developed based on flow rate [9] and head [8] measurements. Their drawback is the necessity to have information about the pump's velocity. The velocity signal is obtained from the encoder or from the frequency converter's analog output calculated based on the measured stator voltages and currents. Eliminating the velocity signal makes the system cheaper and simplifies the interactive controller's hardware. The realization of the improved interactive algorithm based on flow rate measurement is presented in [10]. In the paper, the frequency reference signal is used instead of the velocity signal.

**Paper objective.** The objective of the present paper is to modify the interactive algorithm based on head measurement [8] to eliminate the pump's velocity signal, and to present the hardware of the improved interactive controller with experimental results.

**Mathematical representation of the improved algorithm.** The derivation begins from the approach proposed in [10], where the voltage frequency reference signal $U_{rf}$ is used instead of the velocity signal. The information used concerns the motor velocity without load torque (the synchronous velocity) instead of the actual velocity. The difference between the two depends on the motor's load torque and typically does not exceed 3-5%, depending on the rated slip value. Concerning the interactive water supply systems, such error is acceptable because it does not invalidate the conditions of the game generation. The compromised pump velocity is still achievable.

Taking into account the approach mentioned above, the six interactive control laws obtained in [8] are modified as follows

$$U_{rf2}((n+1)T_0) = k\sqrt{\frac{(H(nT_0) - H_{ST})}{(H((n-1)T_0) - H_{ST})}}U_{rf}((n-1)T_0), \qquad (1)$$

$$U_{rf2}((n+1)T_0) = k\sqrt{\frac{H(nT_0)}{H((n-1)T_0) + c}}U_{rf}((n-1)T_0), \qquad (2)$$

$$U_{rf2}((n+1)T_0) = k\frac{H(nT_0)}{H((n-1)T_0) + c}U_{rf}((n-1)T_0), \qquad (3)$$

$$U_{rf2}((n+1)T_0) = \frac{kU_{rf}^2(nT_0)}{U_{rf}((n-1)T_0) + c}\sqrt{\frac{H((n-1)T_0)}{H(nT_0) + c}}, \qquad (4)$$

$$U_{rf2}((n+1)T_0) = \frac{kU_{rf}^2(nT_0)}{U_{rf}((n-1)T_0) + c}\frac{H((n-1)T_0)}{H(nT_0) + c}, \qquad (5)$$

$$U_{rf2}((n+1)T_0) = \frac{kU_{rf}^3(nT_0)}{U_{rf}{}^2((n-1)T_0) + c}\frac{H((n-1)T_0)}{H(nT_0) + c}. \qquad (6)$$

where H is the water head, $H_{ST}$ is the geodesic difference of height of water, $U_{rf2}$ is the stator voltage frequency reference delayed by two sample times $T_0$, n is a positive integer, k is a gain close to but less than one to ensure the correct functioning of the algorithm in the case $H(nT_0)=H((n-1)T_0)$, and c is a small positive constant to prevent division by zero.

The organization of the interactive controller based on equation (4) is presented in Fig. 1. It is similar in the case of equations (1)-(3) and (5), (6). The reference element RE forms the voltage reference $U_{rf1}$ of the frequency converter feeding the pump induction motor. This reference corresponds to the rated value of the motor frequency. It remains constant during the time interval from 0 to $2T_0$. The sample time $T_0$ must exceed the time of the transient response of the system caused by a step change of the frequency voltage reference. The zero-order hold (ZOH) converts the discrete signal $U_{rf}$ into an analog signal. The block 1/z provides a signal delay of one sample time. Zero initial conditions of system operation (H=0, $\omega_m$=0) cause the voltage $U_{rf2}$ to remain zero during a time interval $2T_0$. Then, the value of the frequency voltage reference $U_{rf}$ is defined only by the voltage $U_{rf1}$. After that time, the reference $U_{rf}$ is defined only by the voltage $U_{rf2}$. The frequency reference is limited by the lower value to prevent the pump head from decreasing below the minimum permissible value and by an upper value corresponding to the rated pump motor frequency.

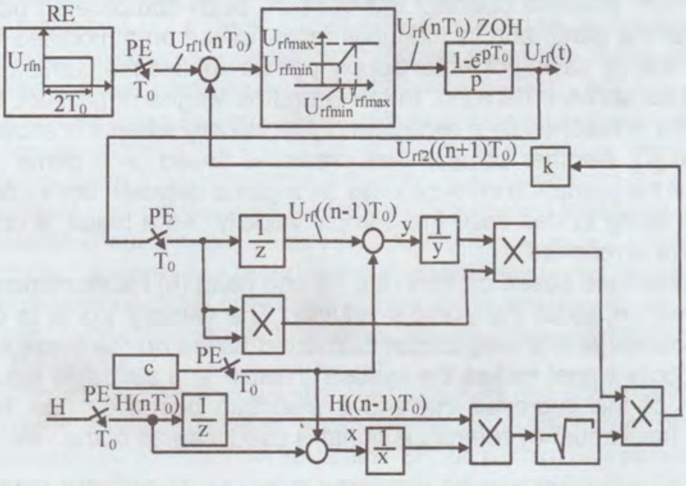

Fig.1. Improved algorithm block diagram

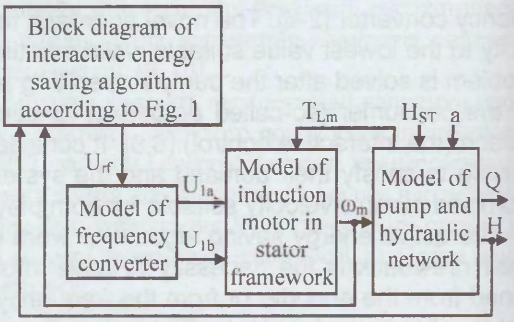

Fig.2. Block diagram of interactive energy saving control system of water supply pump

**Modification of the improved algorithm.** The improved interactive algorithm's operation according to equations (1) – (6) within the electromechanical control system of water supply pump was investigated, based on a Grundfos centrifugal pump CV 125-30 with rated power 90 kW and an induction motor of type 4A250M2Y3 with rated power 90 kW. The model of the system used in the simulation includes the model of the pump with a back vent, the two-phase model of the induction motor in the stator frame, and the frequency converter model with a ramp unit [8]. It is shown in Fig. 2, where $U_{1a}$, $U_{1b}$ denote the motor's stator voltages, $T_{Lm}$ is the load torque of the motor, $\omega_m$ is the motor velocity, Q is the pump flow rate, a is the hydraulic resistance of the network. The parameters of the system were chosen to be the same as in [8]. The parameters of the interactive controller were $T_0$=2 s, k=0.99, $U_{rfmin}$=0. The interactive controllers based on equations (2) and (3) appeared to be insensitive to increasing flow rate. The controllers based on the other laws could not generate an interactive game.

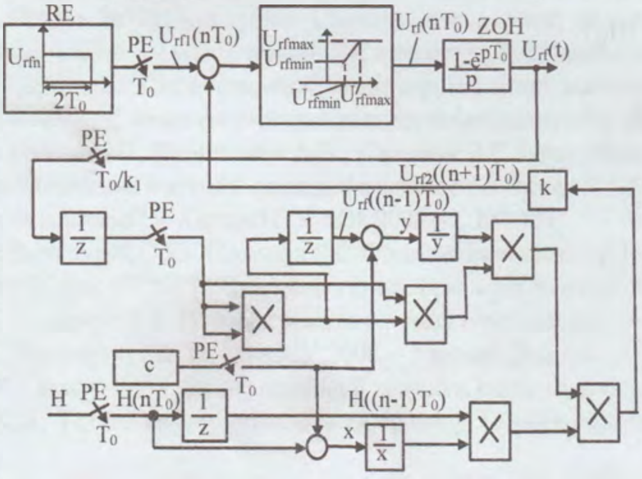

Fig.3. Modified algorithm block diagram

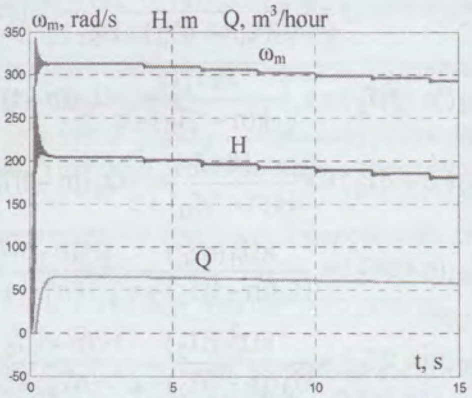

Fig.4. Operation of the system without consumer's response

The simulation results for the controllers based on equations (4) – (6) have shown that the pump velocity references are switched off at time $2T_0$ or $3T_0$. The original variants of the corresponding algorithms [8] are effective. The main difference between them is the use of the frequency reference signal instead of the velocity signal. The frequency reference at the current sample time is used to form the frequency reference for the next sample time. As a result, the frequency reference signal at $2T_0$ or $3T_0$ exists only at that very moment of time and disappears at once without holding by the zero-order hold.

To overcome this obstacle, it was found necessary to include in the improved algorithms a small discrete time delay to deliver $U_{rf}(nT_0)$ from the controller's output to the part realizing the corresponding equations. The block diagram of the modified controller in the case of the equation (6) is shown in Fig. 3, where $k_1$ is a positive integer >>10. The block diagrams for the control laws (4) and (5) are similar.

**Investigation of the interactive pump control system with modified controllers.** The investigation of the modified controllers based on the control laws (4)-(6) was performed for three typical tests: operation of the system without consumers' response to controller action; operation of the system with consumers' stabilization of the flow rate; sensitivity of the controller to increasing flow rate. The choice $k_1$=64 was made. All the modified controllers were found to be effective. The results of the simulations in the case of the law (4) are highlighted in Figs. 4-6.

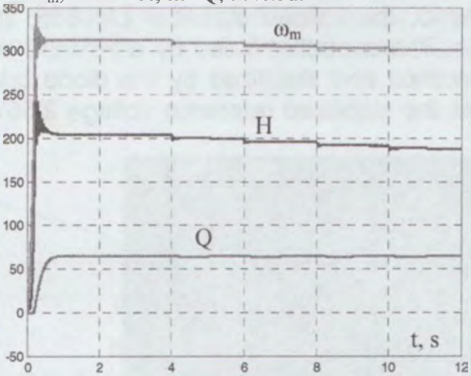

Fig.5. Operation of the system taking consumer's flow rate stabilization into account

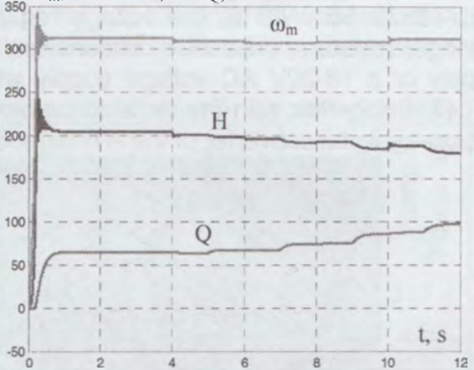

Fig.6. Test of sensitivity of the algorithm to flow rate increasing

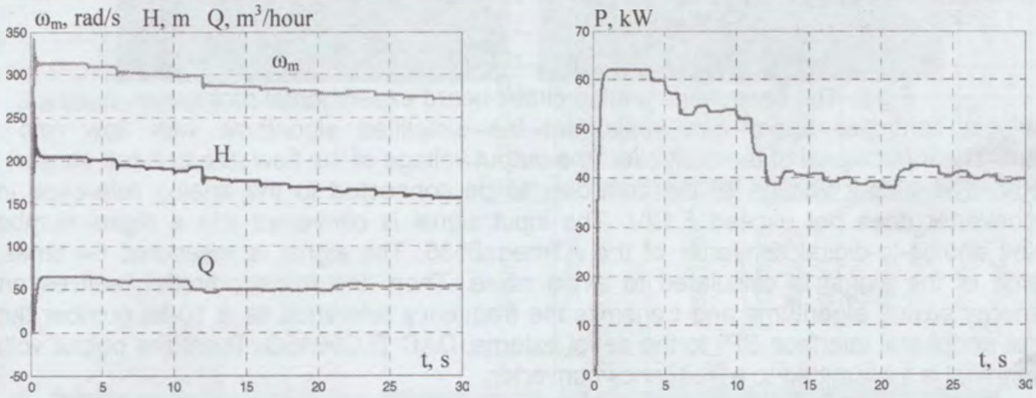

Fig.7. Test of energy saving properties

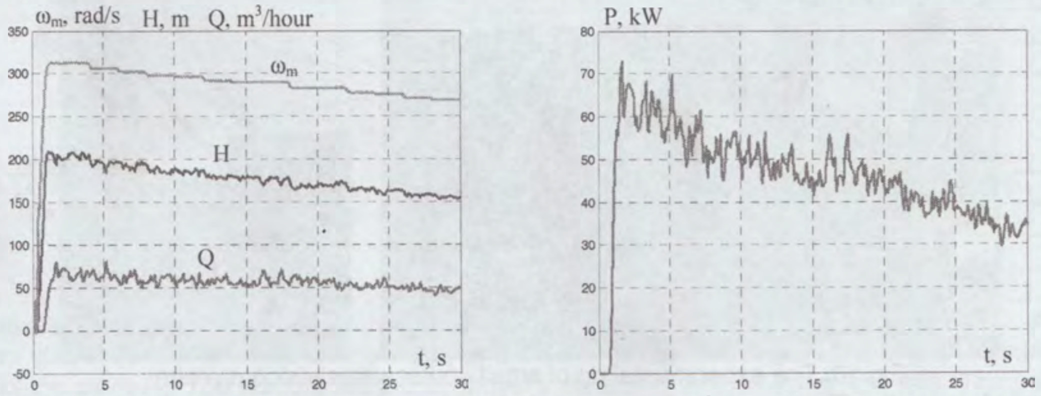

Fig.8. Test with unpredictable behavior of consumers

To evaluate the energy saving properties of the modified algorithms, a test with varying water consumption was done as in [8]. The first four seconds were used to start the system and were not used to evaluate energy consumption. Then, consumers demanded 61 m³/hour from 4 to 10 s; 50 m³/hour from 10 to 20 s and

55 $m^3$/hour from 20 to 30 s and rotated their water taps correspondingly, changing hydraulic net resistance. The specific behavior of consumers was such that they were waiting after the next pump velocity change for half of $T_0$, and then were trying to settle to a desirable value of flow rate. The results of the research for the modified algorithm (6) are depicted in Fig. 7, where P is the pump's power. The energy consumed by the pump from 4 to 30 s was 0.3204 kWh. It gave 11.2% energy saving compared to the head stabilization system operating under the same circumstances. In the cases of the control laws (4) and (5), the energy saving was 10 and 4.3% respectively. The level of energy efficiency of the modified controllers was commensurate with the level of the original algorithms [8].

The modified algorithms demonstrated their efficiency even in the case of unpredictable behavior of the consumers, simulated as the sum of the rated hydraulic net resistance value 0.0243 m/($m^6$/$hour^2$) and a band-limited white noise with sample time 0.1, 1 and 2 s. In all cases, the decreases in pump velocity resulted in energy saving. There were also some periods when the velocity increased temporarily due to the consumers' demand. The test with the noise sample time 0.1 s and the modified control law (4) is shown in Fig. 8.

**Description of the interactive controller.** The controller's two layer printed circuit board experimental prototype is shown in Fig. 9. The controller is realized based on the Atmel microcontroller ATmega 8535. It includes the following auxiliary components: the digital-to-analog converter DAC TLC5615C, the LED indicator RL-T3620 SBAW/D15, the voltage regulator TL431C, the voltage stabilizer LM7805, the diode rectifying bridge, resistors, capacities, buttons and terminals. The controller is fed by a +5V DC stabilized voltage supply or a 18-20V AC voltage supply which is rectified and stabilized by the diode bridge and LM7805. TL431C together with the variable resistor provides the stabilized reference voltage 2.56V for the internal analog-to-digital converter of the ATmega8535.

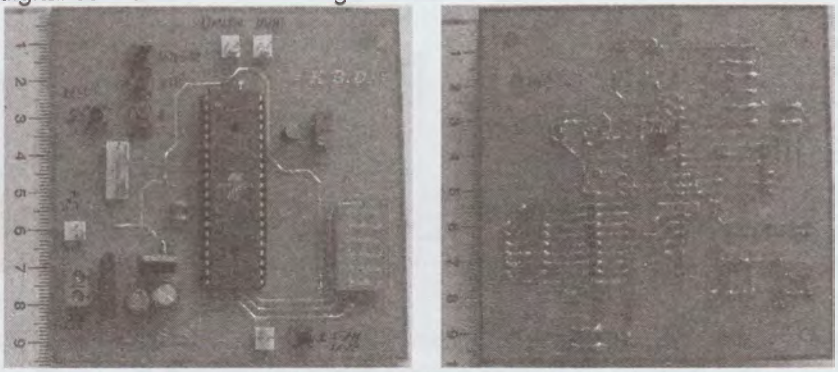

Fig.9. The controller's printed circuit board experimental prototype

The low-cost controller board can implement the simplified algorithms with flow rate or head measurement. The input signal of the controller (the output voltage of the flow rate or head sensor) must not exceed 2.56V. The output voltage of the controller to be connected to the analog reference input of a frequency converter does not exceed 5.12V. The input signal is converted into a digital number by the internal 10-bit analog-to-digital converter of the ATmega8535. The signal is measured 64 times and the average value of the signal is calculated to avoid noise. Then, the microcontroller realizes one of the simplified energy saving algorithms and transmits the frequency reference as a 10-bit number through the internal serial peripheral interface SPI to the serial external DAC TLC5615C. Then, the output voltage from the output terminal is transmitted to a frequency converter.

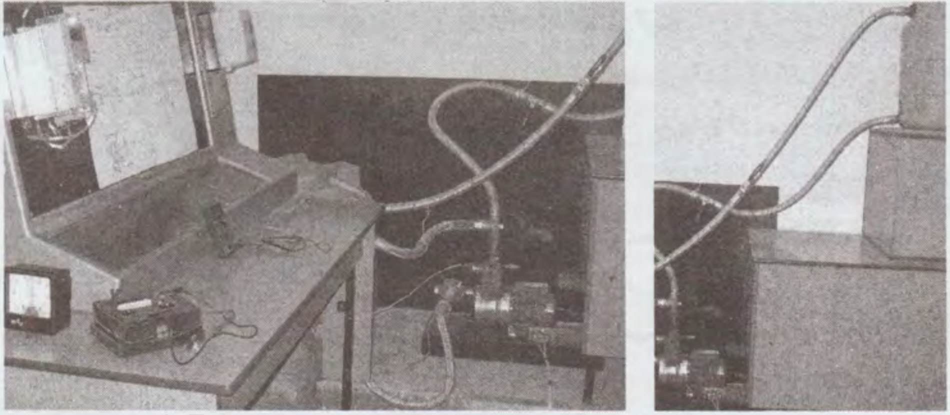

Fig.10. The experimental rig of small power water supply system

**Experimental results.** The experiments were carried out based on the specially-developed laboratory rig of a small power water supply system with two water tanks of 200 liters each (Fig. 10). The system includes also the centrifugal Calpeda MXH 202E pump (with rated power 0.33 kW, voltage 230V, velocity 2800 rpm, and efficiency 42%), driven by a three-phase squirrel-cage induction motor and a frequency converter Lenze

8200 Vector with rated power 0.75 kW. There are also a network of pipes, water taps, a back vent, as well as flow rate and water pressure sensors.

All the necessary measurements were taken using an external digital ammeter and the digital measurement system of the frequency converter. It is possible to pump water from the lower tank to the higher tank, from the lower tank to itself and to do the above operations simultaneously. Water from the higher tank can flow to the lower tank by gravity.

The water pressure sensor MBS3000 has an output current signal proportional to water pressure starting with 4mA, which corresponds to a zero pressure. To simplify the interactive control algorithms, the corresponding output signals of the pressure sensor are used instead of the head values H in equations (4)-(6). All the improved interactive controllers (4)-(6) were found to be effective. Fig. 11 demonstrates the results of the test using the control law (4) with the initial pump operating point $A_1$. It was taken with k=0.95, $T_0$=3 min, the maximum controller's frequency 50 Hz, the minimum frequency 0 Hz. The response of the consumer on the flow rate change was only after the transients caused by the frequency change had subsided. The pump operating points $B_i$ were the results of the interactive controller operation. The points $A_i$ (for i>1) were provided by the consumer to stabilize the flow rate value. Only the steady-state operating pump points connected by lines are shown. The experimental data is presented in Table 1. The controller decreased the pump velocity by 26.6%, while the power consumption decreased by 64 %. Such a good result can be explained by the fact that the geodesic height of water lifting of the experimental rig was less than 1.5 m (only 15% compared with the head of the point $A_1$), which allowed a decrease of the pump velocity in a wide range.

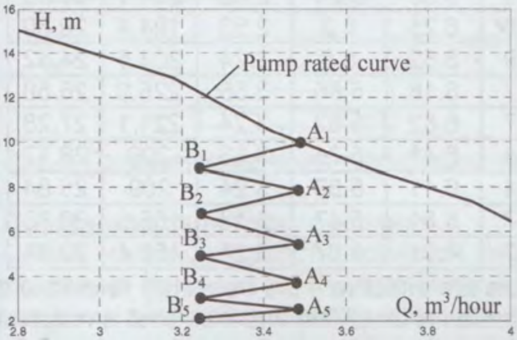

Fig.11. Pump's operating points under the interactive control law (4)

Table 1. Results of test with the control law (4)

| Point | Voltage frequency Hz | Head, m | Pressure Sensor, mA | Flow Rate, m³/hour | Pump Power, W | Pump Efficiency % |
|---|---|---|---|---|---|---|
| $A_1$ | 50 | 9.93 | 6.65 | 3.49 | 345.4 | 27.4 |
| $B_1$ | 47.5 | 8.81 | 6.35 | 3.24 | 286 | 27.23 |
| $A_2$ | 47.5 | 7.83 | 6.09 | 3.49 | 297 | 25.13 |
| $B_2$ | 44.8 | 6.75 | 5.8 | 3.24 | 213.4 | 27.95 |
| $A_3$ | 44.8 | 5.47 | 5.46 | 3.49 | 213.4 | 24.43 |
| $B_3$ | 42.4 | 4.87 | 5.3 | 3.24 | 188.1 | 22.90 |
| $A_4$ | 42.4 | 3.75 | 5 | 3.49 | 189.2 | 18.87 |
| $B_4$ | 39.8 | 3 | 4.8 | 3.24 | 158.4 | 16.73 |
| $A_5$ | 39.8 | 2.51 | 4.67 | 3.49 | 160.6 | 14.9 |
| $B_5$ | 36.7 | 2.13 | 4.57 | 3.24 | 123.2 | 15.33 |

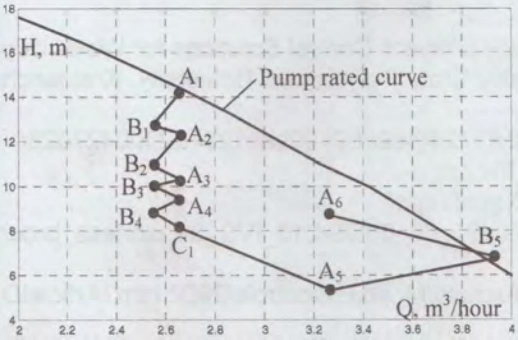

Fig.12. Pump's operating points under the interactive control law (5)

Table 2. Results of test with the control law (5)

| Point | Voltage frequency Hz | Head, m | Pressure Sensor, mA | Flow Rate, m³/hour | Pump Power, W | Pump Efficiency % |
|---|---|---|---|---|---|---|
| $A_1$ | 50 | 14.25 | 7.8 | 2.66 | 330 | 31.37 |
| $B_1$ | 47.5 | 12.75 | 7.4 | 2.55 | 270.6 | 32.78 |
| $A_2$ | 47.5 | 12.37 | 7.3 | 2.66 | 272.8 | 32.96 |
| $B_2$ | 45.8 | 10.95 | 6.92 | 2.55 | 209 | 36.45 |
| $A_3$ | 45.8 | 10.31 | 6.75 | 2.66 | 209 | 35.85 |
| $B_3$ | 45.37 | 10.05 | 6.68 | 2.55 | 204.6 | 34.17 |
| $A_4$ | 45.37 | 9.48 | 6.53 | 2.66 | 204.6 | 33.69 |
| $B_4$ | 44 | 8.85 | 6.36 | 2.55 | 195.8 | 31.44 |
| $C_1$ | 44 | 8.10 | 6.16 | 2.66 | 195.8 | 30.06 |
| $A_5$ | 44 | 5.32 | 5.42 | 3.27 | 204.6 | 23.21 |
| $B_5$ | 48.8 | 6.75 | 5.8 | 3.95 | 330 | 22.05 |
| $A_6$ | 48.8 | 8.7 | 6.32 | 3.27 | 325.6 | 23.82 |

The results of the experiment under the control law (5) are presented in Fig. 12 and Table 2. At first, the consumers stabilized the flow rate at the value of the point $A_1$, and then the consumers' demand was the flow rate of the point $A_5$. The test proved the controller's sensitivity to increasing flow rate. The point $C_1$ was only an intermediate point settled by the consumers before changing the flow rate demand. At first, the pump velocity decrease was 12% (from the point $A_1$ to $B_4$) resulting in 41% energy saving. Then, the new consumers' demand increased the pump velocity for 10.9%. The consumed power at point $A_6$ was 59.1% higher than at $A_5$. This value would be less than the power consumed by the pump if the operating point belonged to the pump rated curve with the flow rate equal to the flow rate of point $A_5$.

Tests with the control law (6) were carried out using the starting point $A_1$ which didn't belong to the pump's rated curve (the maximum frequency of the controller was 47.3 Hz). The consumers stabilized the flow rate at two levels. The results are depicted in Fig. 13 and Table 3. The first reduction of the pump velocity by 7.2% (from point $A_1$ to $B_3$) led to a 29.9% decrease in consumed power. The short-time increase of the velocity (from point $A_4$ to $A_5$) by 4.1% increased the power consumption by 8.6%. But then, the velocity dropped by 13.1% (from the point $A_5$ to $A_7$), providing an energy saving of 28.4%.

The control law (6) is preferable among the laws considered because it makes less velocity step changes, reducing the chances of reaching a limit (e.g., the minimum possible frequency of the interactive controller or the situation when the water taps are opened entirely).

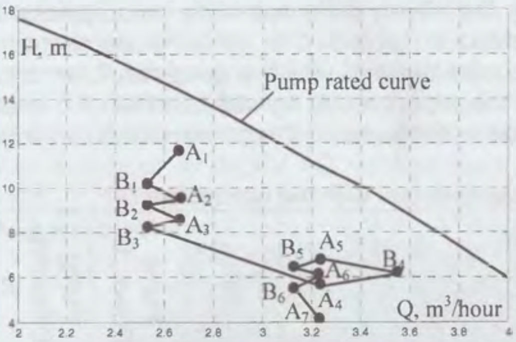

Fig.13. Pump's operating points under the interactive control law (6)

Table 3. Results of test with the control law (6)

| Point | Voltage frequency Hz | Head, m | Pressure Sensor, mA | Flow Rate, m³/hour | Pump Power, W | Pump Efficiency % |
|---|---|---|---|---|---|---|
| $A_1$ | 47.3 | 11.7 | 7.12 | 2.66 | 277.2 | 30.67 |
| $B_1$ | 44.9 | 10.2 | 6.72 | 2.53 | 201.7 | 34.92 |
| $A_2$ | 44.9 | 9.48 | 6.53 | 2.66 | 206.3 | 33.40 |
| $B_2$ | 44.8 | 9.22 | 6.46 | 2.53 | 201.7 | 31.59 |
| $A_3$ | 44.8 | 8.58 | 6.29 | 2.66 | 204.1 | 30.56 |
| $B_3$ | 43.9 | 8.25 | 6.2 | 2.53 | 194.4 | 29.30 |
| $A_4$ | 43.9 | 5.62 | 5.5 | 3.24 | 203.5 | 24.42 |
| $B_4$ | 45.7 | 6.18 | 5.65 | 3.56 | 225.9 | 26.59 |
| $A_5$ | 45.7 | 6.82 | 5.82 | 3.24 | 221.1 | 27.28 |
| $B_5$ | 44.4 | 6.41 | 5.71 | 3.13 | 209 | 26.17 |
| $A_6$ | 44.4 | 6.11 | 5.83 | 3.24 | 209 | 25.84 |
| $B_6$ | 39.7 | 5.51 | 5.47 | 3.13 | 155.5 | 30.23 |
| $A_7$ | 39.7 | 4.01 | 5.07 | 3.24 | 158.4 | 22.38 |

**Conclusion.** The interactive energy saving pump controllers are effective if the frequency reference signal is used instead of the velocity signal. The controllers' realization is simplified and their cost is reduced. It is possible to use the output signals of the pressure sensor in the interactive control laws without transforming them into head values. The operation of the controllers is efficient for any starting pump point unless the head is less than the geodesic height of water lifting. The energy saving level provided by the interactive controllers depends on the possible range of the pump velocity reduction, which itself depends on the head difference between the starting point and the head when the flow rate equals zero. Further research and development of the interactive pump control systems may concern an implementation of the sensorless pump control based only on measurement of the driving induction motor electrical signals.

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