ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering

Tome XII [2014] – Fascicule 2 [May]
ISSN: 1584-2665 [print]; ISSN: 1584-2673 [online]
a free-access multidisciplinary publication of the Faculty of Engineering Hunedoara

1. Gencho Stoykov POPOV, 2. Anka Hristova KRASTEVA, 3. Boris Zvezdov KOSTOV, 4. Donka Ilieva IVANOVA, 5. Kliment Velikov KLIMENTOV

OPTIMIZATION OF THE ENERGY CONSUMPTION OF A PUMP SYSTEM USED FOR INDUSTRIAL WATER SUPPLY

1. University of Ruse, BULGARIA

Abstract: In this paper the possible variants for the ensuring of the required flow rate in an existing pump system, where the consumed energy should be minimal, have been investigated and analyzed. As a result of the theoretical research a concrete configuration of parallel working pumps ensuring the best balance in terms of the energy consumption and time used for the water's transportation has been given.
Keywords: a pump system, energy efficiency, genetic algorithm

1. INTRODUCTION

After the accession of Bulgaria to the European Union some new responsibilities related to the effective use of energy and water resources have been introduced. In addition, the introduction of the market economy has led to new concerns in the process of their planning and exploitation. Because of the continuous increase in the price of electric energy, it has become necessary to create some mathematical models to analyze the energy consumption in industrial pump systems, so that adequate decisions for their effective use, can be taken. For an existing pump system, consisting of parallel working pumps, the most significant energy savings can be achieved by the ensuring of an optimal work regime. Nowadays, genetic algorithms are widely used to find solutions to different optimization problems [1]. A genetic algorithm can be used as an alternative method for optimization of a given process where the classical methods are not appropriate or in the case that the objective function is interrupted, non-differential, stochastic or strongly nonlinear. The main purpose of this work is to investigate and analyze the possible variants for the ensuring of the required flow rate in a given pump system, where the consumed energy should be minimal.

2. A PUMP SYSTEM – THE OBJECT OF THIS RESERACH

In this research an existing water supply system, whose main purpose is to ensure the necessary volume of water used to cover the technological needs of a concrete company, has been investigated. The system's work process can be divided in two stages: (1) the transportation of water from the exhaustive wells to the "buffer" tank (100 m^3), whose function is to compensate the difference between the overall flow rate ensured by the drilling pumps (Ist level) and the flow rate taken by the pumps in IInd level; (2) the transportation of water to the two main tanks, each of which has a capacity of 2000 m^3 (fig.1). The drilling pumps (same type) p_1, p_2 and p_3 (Pleuger submersible pump), produced by „FlowServe", are located at different altitudes and distances from each other, as their main working parameters are respectively: flow rate - Q=50 l/s; head - H=250 m; motor's power - P_M=190 kW; speed – n=2880 min^{-1}. In IInd level there are four pumps of the same type. Three of them – p_4, p_5 and p_6 (70M32x6) are produced by "Vipom" – p_6 is being used just in emergency situations: Q=69.5 l/s; H=192; P_M=250 kW and n=1500 min^{-1}. The pump p_7 (DURCO) is produced by „FlowServe": Q=62.5 l/s; H=118; P_M=110 kW and n=3000 min^{-1}.

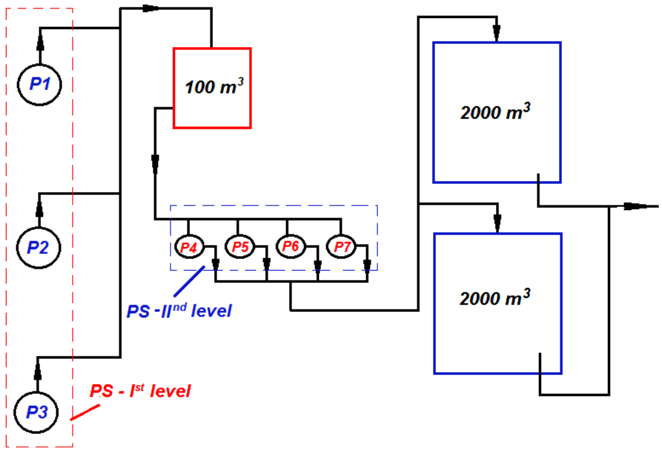

FIGURE 1. A hydraulic scheme of the investigated water supply system

In fig.1 it can be clearly seen that when the drilling pumps transfer water to the "buffer" tank, because of its low capacity (volume), it is necessary for the water to be immediately transported to the two main tanks, i.e. the pumps from both I[st] and II[nd] levels should always be working together.

For the ensuring of the system's optimal work regime (in terms of energy efficiency), it is necessary to determine the work regimes for all the possible combinations of pumps working together and also the cases when a single pump works with the pipe system. However, to do this for the drilling pumps will be more complicated, because they suck water from wells which are located at different altitudes (fig. 2).

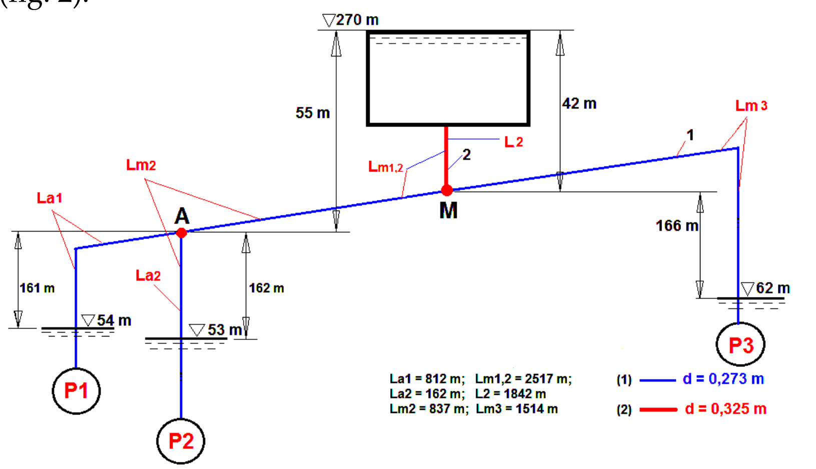

FIGURE 2. A scheme of the location of each of the drilling pumps

According to the company's annual report for the balance of water consumption, the overall quantity of water used in this period is 1401930 m^3, which means that the average daily consumption is equal to about 3840 m^3. Therefore, it can be assumed that the filling of the two main tanks with water will be enough to ensure the daily needs related to the technological processes of the company.

3. AN ANALYTHICAL DETERMINATION OF THE WORK REGIMES

The determination of the pipe characteristic's coefficient "k" and the coefficient of friction λ, can be done according to the method described in [2].

For "n" number of parallel working pumps, each of which is located in a different pump station and having a different altitude, it is necessary for their head characteristics to be brought to a common point. In this case the equation of a pump's head characteristic is (1) and for a concrete value of the head the flow rate can be estimated by (2):

(1) $$H^*_{1,2...n} = (a_{1,2...n} - k_{1,2...n})Q^2 + b_{1,2...n}Q + c_{1,2...n} - h_{1,2...n};$$

(2) $$Q^*_{1,2...n} = \frac{-b_{1,2...n} - \sqrt{b^2_{1,2...n} - 4(a_{1,2...n} - k_{1,2...n})(c_{1,2...n} - h_{1,2...n} - H^*_{1,2...n})}}{2(a_{1,2...n} - k_{1,2...n})}.$$

where $a_{1,2...n}$, $b_{1,2...n}$ and $c_{1,2...n}$ are the coefficients of the head characteristics respectively of pumps 1, 2…n, determined on the basis of the catalogues provided by the manufacturer; $h_{1,2...n}$ – the distance between the levels of the water in the exhaustive well and the beginning of the common pipe, respectively for pumps 1, 2...n.

The next step is to select three different values of the head (H', H'', H''') taking places in the interval belonging to the summary head characteristic. Then the relevant flow rates for each of the parallel working pumps can be estimated by (2) and summed, so to achieve the overall flow rates (Q', Q'', Q'''). This can be used for the determination of the coordinates (Q and H) of three points belonging to the summary head characteristic. Finding a solution of (3) first and then using (4), (5) and (6) will ensure the determination of the coefficients (a_0, b_0, c_0) of the equation of the summary head characteristic [3].

$$\begin{cases} H' = a_0(Q_1' + Q_2' + ... + Q_n')^2 + b_0(Q_1' + Q_2' + ... + Q_n') + c_0 \\ H'' = a_0(Q_1'' + Q_2'' + ... + Q'')^2 + b_0(Q_1'' + Q_2'' + ... + Q_n'') + c_0 \\ H''' = a_0(Q_1''' + Q_2''' + ... + Q_n''')^2 + b_0(Q_1''' + Q_2''' + ... + Q_n''') + c_0 \end{cases}; \quad (3)$$

$$b_0 = \frac{(H'' - H''')(Q_{0,1}^2 - Q_{0,2}^2) - (H' - H'')(Q_{0,2}^2 - Q_{0,3}^2)}{(Q_{0,2} - Q_{0,3})(Q_{0,1}^2 - Q_{0,2}^2) - (Q_{0,1} - Q_{0,2})(Q_{0,2}^2 - Q_{0,3}^2)}; \quad (4)$$

$$a_0 = \frac{H' - H'' - b_0(Q_{0,1} - Q_{0,2})}{Q_{0,1}^2 - Q_{0,2}^2}; \quad (5)$$

$$c_0 = H''' - a_0 Q_{0,3}^2 - b_0 Q_{0,3}, \quad (6)$$

where $Q_{01}=Q_1'+Q_2'+…+Q_n'$; $Q_{02}=Q_1''+Q_2''+…+Q_n''$; $Q_{03}=Q_1'''+Q_2'''+…+Q_n'''$. When a_0, b_0 and c_0 are already known, the determination of the work regimes (and the coefficient of efficiency for each of them) can be done, as is described in [3]. The results are given in tables 1 and 2.

TABLE 1. The values of the coordinates (Q, H and η) of the investigated work regimes for the pumps of Ist level

„FlowServe“	P1	P2	P3	P1+P2	P1+P3	P2+P3	P1+P2+P3
Flow rate, [l/s]	54,11	54,356	55,538	103,57	106,912	107,156	153,748
Head, [m]	224,12	222,91	216,64	-	-	-	-
Coef. Of eff., [-]	0,725	0,721	0,68	0,758	0,735	0,734	0,763

	P1+P2		P1+P3		P2+P3		P1+P2+P3		
	P1	P2	P1	P3	P2	P3	P1	P2	P3
Flow rate, [l/s]	51,88	51,689	52,73	54,186	52,958	54,178	50,71	50,89	52,16
Head, [m]	235,9	236,84	231,43	223,81	230,25	223,85	241,9	241	234,4
Coef. Of eff., [-]	0,757	0,76	0,747	0,724	0,743	0,724	0,768	0,769	0,754

TABLE 2. The values of the coordinates (Q, H and η) of the investigated work regimes for the pumps of IInd level

	„Vipom“ – 70M32x6		„FlowServe“
	1 pump	2 pumps	1 pump
Flow rate, [l/s]	92,384	159,762	72,851
Head, [m]	129,63	168,705	122,21
Coef. Of eff., [-]	0,66	0,749	0,692

According to the data given in tables 1 and 2 the following conclusions for the join working pumps from Ist and IInd level can be given:

- If just one of the pumps p_1, p_2 or p_3 is switched on the transferring of water from the “buffer” tank to the two main tanks will be ensured by the pump p_7, whose flow rate has to be additionally reduced by using the frequency method of regulation (the speed has to be reduced with 150 min^{-1}). Therefore the work parameters of p_7 will be changed to: Q=55 l/s (set); H=117 m and η=0,727.
- When two of the drilling pumps work together (p_1+p_2; p_1+p_3; p_2+p_3) to prevent the “buffer” tank to be overflowed it will be enough if just one of the pumps p_4 or p_5 is switched on, as its flow rate has to be regulated by changing the pump’s speed with 130 min^{-1}. The new work parameters of p_4/p_5 will be: Q=105 l/s (set); H=135,4 m and η=0,616.

- In case the three pumps p_1, p_2 and p_3 work together for the subsequent transportation of the water to the two main tanks, it is necessary for the pumps p_4 and p_5 to work together. If this process continues for no more than 4 hours the "buffer" tank will be able to cover the difference between the ensured and transported flow rates and it won't be necessary for the flow rate of each of these two pumps (p_4, p_5) to be reduced. Otherwise, the speed of both the pumps p_4 and p_5 has to be reduced with 35 min^{-1} and the new work parameters will be: Q=154 l/s (set); H=164,5 m and η=0,753.

4. OPTIMIZATION OF THE PUMP SYSTEM'S WORK PROCESS

For the investigated water supply system different combinations of pumps (I[st] and II[nd] level) working together can be ensured. There are four variants, given in tables 3…7, which are used for the establishing of four different optimization problems, and for finding a solution of each of them a genetic algorithm has been used. The selected input parameters of the genetic algorithm are the flow rate, the head and the coefficient of efficiency for each of the pumps (for the given combination), the fluid's density and the gravity acceleration. As for the output parameters the working time and the minimal energy consumption have been selected.

The consumed power P for each of the different combinations of pumps can be determined by using the following equation:

$$P=\sum_{j=1}^{3}P_{1j}+\sum_{q=4}^{7}P_{2q}=\rho g\sum_{j=1}^{3}\frac{Q_{1j}H_{1j}}{\eta_{1j}}+\rho g\sum_{q=4}^{7}\frac{Q_{2q}\,H_{2q}}{\eta_{2q}}, \tag{7}$$

where H_{2q} is the head of the q[th] pump in II[nd] level; H_{1j} – the head of the j[th] pump in I[st] level; η_{1j} – the coefficient of efficiency of the j[th] pump in I[st] level; η_{2q} – the coefficient of efficiency of the q[th] pump in II[nd] level; ρ – the density of water; g – gravity acceleration; j – the number of pump in I[st] level; q - the number of pump in II[nd] level.

The objective function for the first optimization problem (table 3) is:

$$F=n_1\rho g c_g\left(\sum_{j=1}^{3}\frac{Q_{1j}H_{1j}}{\eta_{1j}}+\sum_{q=4}^{7}\frac{Q_{2q}\,H_{2q}}{\eta_{2q}}\right)+n_2\rho g c_n\left(\sum_{j=1}^{3}\frac{Q_{1j}H_{1j}}{\eta_{1j}}+\sum_{q=4}^{7}\frac{Q_{2q}\,H_{2q}}{\eta_{2q}}\right) \tag{8}$$

where c_g is the daily price of the energy and c_n – the night price of the energy.

It is considered that n_2=8 hours. In the two bracketed parts of the formula, according to the selected variant, j can take values 1, 2 or 3; 1 and 2, 1 and 3, 2 and 3; 1, 2 and 3, as for q the values can be 4; 4 and 5; or 7.

The objective function for the second optimization problem (table 4) is:

$$F=n_1\rho g c_g\left(\sum_{j=1}^{2}\frac{Q_{1j}H_{1j}}{\eta_{1j}}+\frac{Q_{2q}\,H_{2q}}{\eta_{2q}}\right)+8\rho g c_n\left(\sum_{j=2}^{3}\frac{Q_{1j}H_{1j}}{\eta_{1j}}+\frac{Q_{2q}\,H_{2q}}{\eta_{2q}}\right)+n_2\rho g c_n\left(\sum_{j=2}^{3}\frac{Q_{1j}H_{1j}}{\eta_{1j}}+\frac{Q_{2q}\,H_{2q}}{\eta_{2q}}\right) \tag{9}$$

In the first bracket, according to the selected variant, j can take values 1 or 2, as for q this value can be just 7. In the second and third brackets, j can take values 2 or 3, as for q this value can be just 7.

The objective function for the third optimization problem (table 5) is:

$$F=n_1\rho g c_g\left(\sum_{j=1}^{3}\frac{Q_{1j}H_{1j}}{\eta_{1j}}+\frac{Q_{2q}\,H_{2q}}{\eta_{2q}}\right)+8\rho g c_n\left(\sum_{j=1}^{3}\frac{Q_{1j}H_{1j}}{\eta_{1j}}+\frac{Q_{2q}\,H_{2q}}{\eta_{2q}}\right)+n_2\rho g c_n\left(\sum_{j=1}^{3}\frac{Q_{1j}H_{1j}}{\eta_{1j}}+\frac{Q_{2q}\,H_{2q}}{\eta_{2q}}\right) \tag{10}$$

In the first bracket, according to the selected variant, j can take values 1 and 2; 2 and 3, as for q this value can be just 4. In the second and third brackets, according to the selected variant, j can take values 1 and 3; 2 and 3, as for q this value can be just 4.

The boundary conditions used in solving of the different optimization problems can be described by the equations (11) and (12):

$$n_1\sum_{j=1}^{3}Q_{1j}-n_2\sum_{q=4}^{7}Q_{2q}\le V_b, \tag{11}$$

where n_1 and n_2 (for the selected combination of pumps) are respectively the number of hours when the pumps in I[st] and II[nd] levels work together (tables 3…6); Q_{1j} – the flow rate of a pump in Ist level; Q_{2q} – the flow rate of a pump in II[nd] level; V_b - "buffer" tank's volume:

(12) $$n_1 + n_2 = V_p / \sum_{q=4}^{7} Q_{2q},$$

where V_p is the overall volume of the two main tanks; $\sum_{q=4}^{7} Q_{2q}$ - a sum of the flow rates ensured by the different combination of parallel working pumps in II[nd] level (tables 3...6). The results are given in tables 3...5.

TABLE 3. A combination of pumps used in the first optimization problem and the values of the energy consumed in each of the variants

A combination of pumps		A number of working hours	Relative energy consumption	Relative price
I[st] Level	II[nd] Level	-	-	-
p_1	p_7	20,20	0,431	0,535
p_2	p_7	20,20	0,432	0,543
p_3	p_7	20,20	0,447	0,56
p_1+p_2	p_4	10,58	0,488	0,572
p_1+p_3	p_4	10,58	0,497	0,5805
p_2+p_3	p_4	10,58	0,498	0,583
$p_1+p_2+p_3$	p_4+p_5	7,05	1	1

TABLE 4. A combination of pumps used in the second optimization problem and the values of the relative price of the energy consumed in each of the variants

A combination of pumps		A number of working hours in I	A number of working hours in II	Relative price
I sub-combination	II sub-combination	-	-	-
p_1+p_7	p_2+p_7	12, 00	8,19	0,612
p_1+p_7	p_3+p_7	11,96	8,24	0,618
p_2+p_7	p_3+p_7	11,82	8,57	0,621

TABLE 5. A combination of pumps used in the third optimization problem and the values of the relative price of the energy consumed in each of the variants

A combination of pumps		A number of working hours in I	A number of working hours in II	Relative price
I sub-combination	II sub-combination	-	-	-
$p_1+p_2+p_4$	$p_1+p_3+p_4$	2,5	8,07	0,578
$p_1+p_2+p_4$	$p_1+p_3+p_4$	10,5	0,08	0,572
$p_1+p_2+p_4$	$p_2+p_3+p_4$	10,04	0,54	0,572
$p_1+p_2+p_4$	$p_2+p_3+p_4$	2,53	8,06	0,578
$p_2+p_3+p_4$	$p_1+p_3+p_4$	2,11	8,47	0,578
$p_2+p_3+p_4$	$p_1+p_3+p_4$	10,52	0,06	0,575

TABLE 6. A combination of pumps used in the fourth optimization problem

A combination of pumps	
I sub-combination	II sub-combination
p_1+p_7	$p_1+p_2+p_3+p_4+p_5$
p_2+p_7	$p_1+p_2+p_3+p_4+p_5$
p_3+p_7	$p_1+p_2+p_3+p_4+p_5$
$p_1+p_2+p_4$	$p_1+p_2+p_3+p_4+p_5$
$p_1+p_3+p_4$	$p_1+p_2+p_3+p_4+p_5$
$p_2+p_3+p_4$	$p_1+p_2+p_3+p_4+p_5$

It can be seen that if one of the possible combinations of pumps working together has been selected the consumed energy will be minimal in the case when p_1 and p_7 work together and it will be maximal when p_1, p_2, p_3 and p_7 work together. This will happen at the expense of the time used for the filling of the two main tanks, which in the first case is going to be three times longer. Therefore, if the first combination of pumps is selected the water supply will continue during the whole working day which could cause a momentary lack of water (especially for an intermittent water demand schedule). That is why the most appropriate selection of pumps, the combination of p_1, p_2 and p_4, is recommended, because in this case the energy consumption will increase by 14%, but the time for the filling of the two main tanks will be two times shorter.

The energy consumed in each of the investigated variants and its price have been divided by the energy consumption (and its price) when the three pumps p_1, p_2 and p_3 work together, because then we have the highest energy consumption in the system. This gives us the relative price for each variation.

For the ensuring of the required volume of water it can use different combinations of pumps working together (one pump on Ist level and one pump on the IInd level). The analysis of the results (table 4) indicates that the relative price of the consumed energy varies in 1,5% for all the selected combinations of pumps and the working time used for the filling of the two main tanks is almost the same. Therefore, in this case the selection has no impact on the energy consumption.

In this case the water supply is ensured by using two different combinations of pumps working together (2 pumps by Ist and 1 pump by IInd level) the results for the relative price of the consumed energy are similar, which can be seen in table 5. Therefore, in this case the selection has almost no impact on the energy consumption.

In cases of overproduction it will be necessary for a large volume of water to be quickly transported to the two main tanks. Then the influence of the selection of pumps working together (table 6) has to be investigated.

For the ensuring of the required volume of water when the energy consumption has to be minimal it is necessary the daily demand schedule to be known. In this case the most significant energy savings can be achieved if the combination of pumps $p_1+p_2+p_4$ (table 1) is used to work for a given number of hours during the night. After that, p_2 has to be switched off, so just p_1 has to continue working in the system.

CONCLUSION

According to the results found in this research, a combination of pumps working together, to ensure the minimal use of energy to produce the required volume of water, consisted with the working time, has been given.

BIBLIOGRAPHY:

[1.] Krasteva A., Ivanova D., Popov G., Kostov B. Application of a genetic algorithm for analyzing the effective use of electrical energy in working pump systems, Ruse, Bulgaria, 2013

[2.] Popov G., Basis data and criteria for the investigation of the energy efficiency of pipe systems, used to transport fluids, Ruse, Bulgaria, 2009

[3.] Popov G., Kostov B., Klimentov Kl., Effective work regimes of parallel working centrifugal pumps, Thermodynamics, Varna, 2013

[4.] www.vipom.bg

[5.] www.flowserve.com

ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering