Analysis on Issues of Variable Flow Water System

Jinming Yang
Taiyuan University of Technology, Taiyuan 030024, Shanxi, China
e-mail: 237603686@qq.com

Abstract
*   Variable flow water system has played an important role in the field of energy saving with the Electronic Variable Frequency Drive (VFD) widely used in practical projects. How to control the frequency converter to work properly is an essential issue which we must first emphatically solve. The control technology of frequency converter is closely related to characteristics of pumps. Based on the mathmatical a model of pumps with or without inverters, the article discusses some issues in detail, such as inverters configuration, flow rate regulation and overload. These are key issues of control technology of variable flow water system. For those multiple-pump water systems, the engineers may select synchronous frequency conversion control technology or Add-Sub pumps control technology to achieve the maximum energy-saving benefits.*

Keywords: *variable flow, mathematical model of pump, pump overload, water pump inverter, control technology*

1. Introduction
        In recent years, the heating and air conditioning water system began using variable flow technology. Circulation pump motors are driven by inverters to reduce energy consumption, and the advantages that the variable flow technology brings is obvious [3-5].
        Numerous studies conducted by many researchers have identified significant energy savings potential by regulating flow rates to meet process demands. But, characteristics of pumps with Variable Frequency Drive technology are quite different from those of pumps without inverters, and pumps in parallel of multipe-pumps system would make this situation more complex. In other way there are still many issues worth discussing, for example, how to configure inverters for water pumps, how to change system flow correctly, and how to avoid pumps overload? This article will address these issues based on the pump models [10].

2. Mathmatical Model of Pump
2.1. Model of Pump without Inverter
        The basic parameters of water pump include the pump flow and pump head. Under normal conditions we can use the pump characteristics curve to express the model of water pump. The Figure 1 sketches the relationship between pump head with pump flow, the single pump characteristics curve is illustrated with curve 1 and the curve 2 illustrates two parallel pumps characteristics curve in Figure 1. The curve 3 in Figure1 illustrates the pipe system head curve.
        The water pump union operating point is point A under designed operating condition, and operating point of the single pump is point C, Figure 1 below sketches these relationships. When the two pumps all put in operation, the total flow is $2Q_0$ (Q_0 is rated flow of single pump) and flow rate provided by each pump is Q_0 . We can also use formula to express mathematical model of water pump:

$$H = A + B \times Q + C \times Q^2 \tag{1}$$

$$H_n = A + B \times \frac{Q}{n} + C \times \left(\frac{Q}{n}\right)^2 \tag{2}$$

In formula (1) and (2) above, variable is single pump head, variable is the parallel pumps head, is flow rate of water system, and variable is the number of parallel pumps, and are constant coefficients [1].
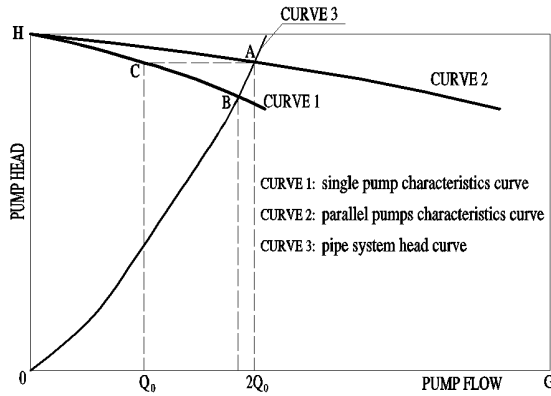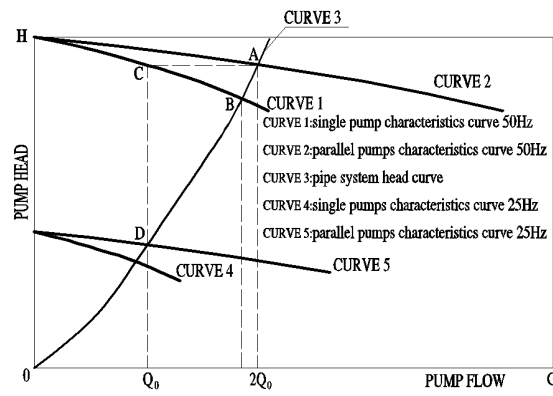

Figure 1. Model of Pump without Inverter

Figure 2. Model of Pump with Inverter

2.2. Model of Pump with Inverter

In order to realize the variable flow technology, the water pump motors are actuated by the inverters. For this reason the mathematical model of the pump with new features would be more complicated.

Similar to the Figure 1, the single pump characteristics curve is illustrated with curve 1 and the curve 2 illustrates two parallel pumps characteristics curve in Figure 2, and the pumps operate under the power frequency. According to the pump law of hydraulic similarity, we can get the different pump characteristics curves under different frequency, and the formula (3) below illustrates the pump law of hydraulic similarity.

$$\frac{f_1}{f_2} = \frac{n_1}{n_2} = \frac{Q_1}{Q_2} = \left(\frac{H_1}{H_2}\right)^{1/2} \tag{3}$$

The mathematical formula of water pump with inverters is still equation (1), but the constant coefficients A, B and C is not the original value. Furthermore, there is a similar equation with different coefficients corresponding to the pump running at any operating frequency.

In Figure 2, curve 4 can be derived based on curve 1 and the curve 5 can be derived based on curve 2. The curve 4 illustrates single pump characteristics curve, the curve 5 illustrates parallel pump characteristics curve, which operating frequencies are all 25Hz.

3. Analysis of Pump Overload
3.1. Pipe System Head Curve

Pump overload is a common fault, which could be caused by many reasons. The unreasonable design and unreasonable operation regulation is the main cause. Prior to the further study of the issue, we learn about the pipe system characteristics. Usually we use formula (4) below illustrates pipe system model [1]:

$$\Delta P = S \times Q^2 \tag{4}$$

In formula (4), ΔP is head loss of pipeline system, S is the pipeline resistance numbers, variable Q is flow rate of pipeline system. We know that variable S is a constant when the pipe network structure does not change. The graphical representation of the characteristics is shown with curve 3 in Figure 1.

3.2. Analysis of Pump Overload

As mentioned above, one of the main cause that cause pump overload is unreasonable operation regulation, the heating or air conditioning water system adopt variable flow technology. The flow rate needs to be regulated by changing numbers of operating pumps or pump operating frequency when the building heating or cooling load changes, especially for those multiple-pumps system.

Takes the Figure 2 above as our discussion objects, the rated flow of water system is $2Q_0$ under designed operating condition when two parallel pumps are all put in operation. The union operating point of two parallel pumps is point A and single operating point of each pump is point C, obviously each pump runs normally with its rated flow Q_0. The point B is operating point of single pump when only one pump is put in operation. The Figure 2 shows that the water pump actual flow is much greater than its rated flow, pump had been overloaded. The pump head exceeds the pipeline system resistance when system flow reduces, and this is the basic reason that causes pump overload [2, 7].

4. Control Technology of Variable Flow Water system
4.1. Inverter Configuration

For single pump system the configuration of inverter is simple, one inverter drives only one pump motor. But for multiple pump system how to configure the inverters? Which method is correct choice, one inverter drives one pump motor or one inverter drives more pump motors? The correct method is that one inverter drives one pump motor, so the number of pumps is equal to the number of inverters. The Figure 3 below shows this principle. In Figure 3 curve 1, 2, and 3 is single pump characteristics curve at different frequency. There are three different situations for water pumps operating at different frequency in parallel. The curve 4 is the union operating characteristics curve of two pumps which operates at the same frequency, and this is an ideal complete parallel mode. Now we decrease frequency of one pump to lower frequency which corresponds to curve 2. The union operating characteristics curve of two pumps which operates at different frequency changes to curve 5, and this is a partial parallel mode. If continue decrease frequency to frequency the value which corresponds to curve 3, we can see the two pumps could not operating in parallel, the pump operating in lower frequency would not work effectively. So it may be unreasonable that one inverter drives more pumps motors.

4.2. Synchronization Frequency Conversion Technology

Now we can assume that the flow rate of the system requirement is changed to 50% of the rated flow, how can we achieve this goal? The easiest method is to use the synchronous frequency conversion technology, that all pumps running at the same frequency. As shown in Figure 2, the operation frequency of all pumps is reduced to $25\,Hz$ and parallel pumps characteristics changes from curve 2 to curve 5, at the same time the union operating point of the parallel pumps changes from point A to point B. All the pumps in parallel by simultaneously changing the operation frequency, just like one pump [8].

4.3. Anti-overload Technology

Synchronous inverter converter is a good technology to meet the needs of the water system with variable flow; it also can effectively avoid the water pump and inverter overload. This technique is suitable for the water system with the small number of pumps. However, when the water system with large number of pumps needs smaller flow, Add-Sub pumps control technology is a better choice. Then it is a viable technology to change the number of running pumps, but this approach applied inappropriately would lead to water pumps and inverters overload. How can we avoid this? Let us take Figure 4 as an example to analyze.

Now we can assume that the flow rate of the system requirement is changed to 50% of the rated flow, how can we achieve this goal? The easiest method is to use the synchronous frequency conversion technology, that all pumps running at the same frequency. As shown in Figure 2, the operation frequency of all pumps is reduced to $25\,Hz$ and parallel pumps characteristics changes from curve 2 to curve 5, at the same time the union operating point of the parallel pumps changes from point A to point B. All the pumps in parallel by simultaneously changing the operation frequency, just like one pump [6].
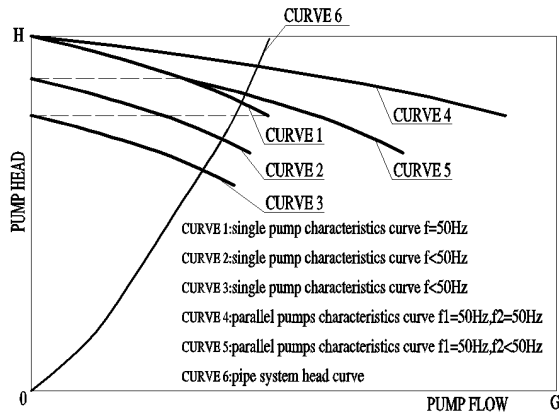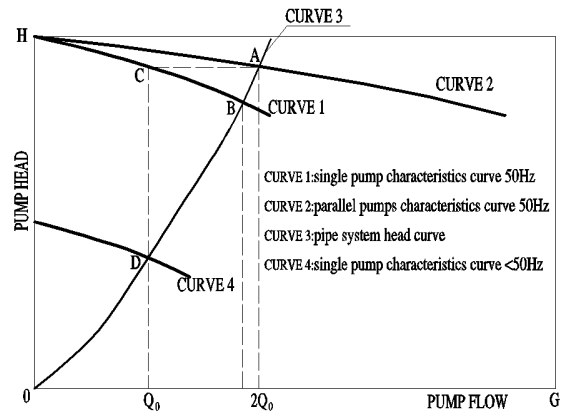
Figure 3. Inverter Configuration   Figure 4. Pump Overload Analysis

In Figure 4, the single pump characteristics curve is illustrated with curve 1 and the pump running at the power frequency. The curve 2 illustrates two parallel pumps characteristics curve and all the two parallel pumps running at the power frequency also. The curve 3 illustrates the pipe system head curve. We still assume that the flow rate of the water system requirement is changed to 50% of the rated flow. First of all, what would happen when only one pump is put into operation? A pump operating point is point B and the water pump actual flow is much greater than its rated flow, the pump and inverter overload or even stop working. We can change single pump characteristics curve from curve 1 to curve 4 by changing the operating frequency, and then pump operating point changes from point B to point D. The pump actual flow rate is just equal to its rated flow, which can be clearly seen from Figure 4. Now the remaining question is how to solve the frequency value corresponds to the curve 4. The following example illustrates the calculation method [1].

Table 1 below shows the pump parameters, the left data is percent of rated flow (%) and the right data is pump head (KPa).

Table 1. Performance Parameters of Pump

List	Percent of rated flow(%)	Pump head(KPa)
1	0	380
2	70	350
3	100	330
4	120	310

Pump performance can be expressed with the formula (1) above, all the coefficient A, B, C can be calculated by curve fitting of the data in the table. The calculated result is $A = 380$ $B = -0.2619$ and $C = -0.00238$. Then the complete formula to express the pump characteristics list as below:

$$H = 380 - 0.2619 \times Q - 0.00238 \times Q^2 \tag{5}$$

For this water system, when system flow is rated flow the pipeline system resistance is 330Kpa, so pipe system head characteristics list as formula (6) below.

$$\Delta P = S \times Q^2 = \frac{330}{200^2} \times Q^2 = 0.00825Q^2 \tag{6}$$

In fact formula (5) is the expression of the curve 1 and formula (6) is the expression of the curve 3. Point D is intersection point of curve 1 and curve 3. We can get the value of point D by solving formula (5) and formula (6).

$$380 - 0.2619Q - 0.00238Q^2 = 0.00825Q^2 \tag{7}$$

The answer is $Q_B = 177.15$.

Variable f_1 is operating frequency corresponds to the curve 1 and Variable f_4 is operating frequency corresponds to the curve 4. So according to the pump law of hydraulic similarity, we can get:

$$\frac{f_1}{f_4} = \frac{Q_B}{Q_D} \tag{8}$$

$$\frac{50}{f_4} = \frac{177.15}{100} \tag{9}$$

By solving the Equation (9), we can get $f_4 = 28.2$. We can draw the conclusion that when the pump operates at 28.2 Hz, the pump flow had reached its rated flow. If pump operating frequency exceeds this value, it is bound to cause the water pump and inverter overload.

4.4. Variable Flow Controller

Author developed an intelligent controller based on single board computer as shown in Figure 5 below, which adopts variable flow technology. The controller main includes CPU module, real-time clock, analog-to-digital converter (ADC), digital-to-analog converter (DAC), digital-input module with optical isolation, digital-output with optical isolation, and RS232 & RS485 communication module. The controller completes data acquisition through the digital-input and analog-input channels and carries on the analysis to the data, then control the pumps and frequency converters to work correctly through the digital-output and analog-output channels [5].
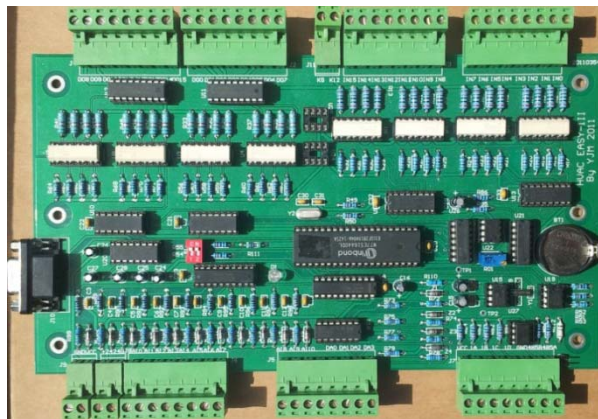

Figure 5. Controller for Variable Flow Technology

The dedicated control algorithms and control strategies for variable flow water systems are developed for the controller. The control algorithms include normal PID control algorithm and fuzzy control algorithm for different control purpose. Practice has proved that fuzzy algorithm is more reasonable than the PID algorithm for most variable flow control. The dedicated control strategies include synchronous frequency conversion technology, Add-Sub pumps control technology and anti-overload technology. Many projects have achieved obvious economic results at minimum costs [3].

5. Conclusion

Pumps are the most common engineering facilities in the field of building, but we still need to figure out how to make them work correctly. Most importantly, inverters have come into wide use nowadays with the development of variable flow technology. Combined application of inverters and water pumps brings us not only good energy-saving benefits but some new problems, such as inverters configuration and overload etc. This paper has presented a theoretical study to solve the problems.

To understand the characteristics of the pump, establishment of mathematical model of water pump is the premise. Formula (1) and formula (2) illustrate the pump performance and they are basic equations for pump without inverts. We can derive mathematical model of water pump with inverter by combining the basic formula with the pump law of hydraulic similarity.

For those multiple-pump systems, it is clear that the number of inverters should be equal to the number of pumps. This is determined by the characteristics of pumps in parallel. Synchronous frequency conversion technology may be a good choice for water system with smaller number of pumps.

The paper also discussed the issues related to overload. From the discussion, one may conclude that the most important reason which causes overload is pump head exceeds the pipeline system requirement. For those multiple-pump systems, this problem occurs often when only a fraction of pumps are put into operation. Frequency conversion technology is a valid method of overcoming overload. Method of calculating operating frequency is more complex and the article illustrates calculation method with an example. This method needs not only the mathematical formulas but also actual performance parameters of pump.

For projects application, a suitable controller is necessary. The controller with the dedicated control algorithms and control strategies for variable flow technology can solve all those issues discussed above.

References
[1] Zhang Lin, Xu Hui, Yu Yonghai. Fitting Method for Pump Characteristic Curve Based on Optimal knots Spline Approximation. *Journal of Hydroelectric Engineering*. 2008; 27(2): 141-144.
[2] Korving H, Ottenhoff EC. Analysis of the Causes of Pump Failure and Differences of Failure Characteristics. *Water Science and Technology*. 2008; 57(8): 1271-1276.
[3] Jinming Yang, Yi Lin. *Control Algorithms and Control Strategies for Variable Primary Flow Chilled Water Systems.* Proceedings of the 2012 International Conference on Computer Application and System Modeling. Shenyang. 2012; 634-637.
[4] Jinming Yang. *Fuzzy Control for Variable Cooling Water Flow System*. Proceedings of the 2012 International Conference on Building Materials and Structural Engineering. Wuhan. 2012; 105-108.
[5] Jinming Yang, Yi Lin. *Development of Dedicated Controller for HVAC.* Proceedings of the 2012 International Conference Frontiers of Advanced Materials and Engineering Technology. Xiamen. 2012; 1472-1479.
[6] Jinming Yang. *Variable Flow Technique for Heating Circulating Pump*. Proceedings of the 2010 International Conference on Computer Application and System Modeling. Taiyuan. 2010; 1307-1310.
[7] Yang Junhu, Guo Bin, Wang Yue, Zhang Yunzhou. Relationship of Performances and Design Parameters for Non-overload Centrifugal Pumps. *Transactions of the Chinese Society of Agricultural Machinery*. 2012; 43(11): 119-122.
[8] Edson, Roberto Alves, Viana, Augusto Nelson Carvalho. Optimization of Parallel Variable-speed-driven Centrifugal Pumps Operation. *Energy Efficiency*. 2008; 1(3): 167-173.
[9] Burt Charles M, Piao Xianshu, Gaudi Franklin, Busch Bryan, Taufik N N. Electric Motor Efficiency under Variable Frequencies and Loads. *Journal of Irrigation and Drainage Engineering*. 2008; 134(2): 129-136.
[10] Miller A Keith, Bode John R, Sachs Robert, Jensen Kirt. *Innovative Devices That Enable Variable Flow Systems for Energy Savings*. Proceedings of International Mechanical Engineering Congress and Exposition. Denver. 2011; 453-460.