Fluids vertical transfer utilizing VFD based centrifugal pumps

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Abstract. Efficiency of centrifugal pumps has been consistently improving with technology enhancements. Pump manufacturers have increased the variety of pump dimension. Pump selection is based on application selection primarily on energy conversion. In a conventional pumping system, the pump will be driven at the same speed even though the output usage is below the actual demand. As a result, energy is wasted and the pump could have been driven at a lower speed for the same operational function. One of the ideal solutions is to vary the pump speed based on real-time demand. The paper illustrates the system simulation for a high rise building water transfer and the relevant design calculations such as the volumetric flow rate and net positive suction head. Supporting this operational function, the variable frequency device (VFD) has also been designed and simulated by using the Proteus software.

1. Introduction

Pump is an electro-mechanical system which was invented with the purpose of transferring fluids based on variety, velocity and volumetric figures. Water pumps allows for transfer of water to a higher height or a determined length. In dry climatic countries, the water pump has played a vital role water supply across borders from other countries. The most popular application is via centrifugal pumps which have lower maintenance cost and has high flexibility in terms of implementation. This philosophy is centrifugal application is relevant to changes in the pump speed or diameter of the impeller and this is known as the Affinity Law.

2. Research Problem

Pump for a conventional pumping system is selected based on the demand of the application and the maximum output usage will be the data to be referred. This ensures that the pump will be able to provide sufficient water in any kind of circumstances or physical arrangement. Wasted energy will be consumed when the output flow rate is lower compared to the maximum usage. On the other hand, relevant calculations such as minor losses and Net Positive Suction Head (NPSH) have been normally neglected during the design stage. This will affect pump performance and lead to the risk of cavitation. The flow rate of the application is normally controlled by the mechanical valve. This current developed solution will effectively control the flow rate of the system. However, the drawback is the heat dissipation of the
pump that will increase since the flow will be restricted. This will shorten the life span of the pump as the pressure on the pump will significantly increase as well.

3. System Design
For the project a scaled down prototype has been designed and built to analyse the performance of the pump selected. The Proteus software has been used to design the VFD circuit. Arduino Uno has been chosen as the micro-controller to vary the frequency range of the VFD. To increase the precision of the system, all mechanical hardware has been designed using the SolidWorks software ensuring zero dimension errors. Fixed dimensions were the base to carrying out the design calculations to determine the pump capacity. Engineering calculations were based on meeting criteria are listed as below. Studies were done on all five criteria meeting the objective of ascertaining energy efficient pumping conditions.

- Volumetric Flow Rate
- Required Net Head
- Net Positive Suction Head
- Affinity Law
- Minor Loss

3.1 Volumetric Flow Rate
Understanding the characteristic of a system is important when selecting the size of a pump. According to the H – Q curve which is provided by the manufacturer, the information required when selecting the pump are the volumetric flow rates and the required net head. For this research project, the energy is conserved by changing the speed of the pump based on the output flow rate. The pump speed reduced according to the real time demand. Therefore, the volumetric flow rate of the output pipe was determined. To calculate the volumetric flow rate of the system, the Bernoulli principle was applied as shown in Equation 1;

\[ \frac{p}{\rho} + \frac{v_1^2}{2} + gz_1 = \frac{p}{\rho} + \frac{v_2^2}{2} + gz_2 \]  

Where,
- \( P \) = pressure
- \( V \) = velocity of the water
- \( g \) = gravitational force
- \( z \) = height
- \( \rho \) = density

3.2 Required Net Head
The required Net Head is essential information when selecting the pump capacity. To determine the net head required from the pump, the equation in Equation 2 was used.

\[ H_{\text{required}} = \frac{p_2 - p_1}{\rho g} + \frac{a_2 v_2^2 - a_1 v_1^2}{2g} + (Z_2 - Z_1) + h_{k,\text{total}} \]  

In the equation, \( P_1 \) and \( P_2 \) are the pressures at point 1 and 2 while \( V_1 \) and \( V_2 \) are the velocities at point 1 and 2 respectively. For the \( a1 \) and \( a2 \), these are the kinetic energy correction factors. In most cases, these two terms are often ignored since the flow of the system is turbulent. \( Z1 \) represents the height of the inlet water level while the \( Z2 \) represents the highest point of the outlet pipe and both are measured from the ground level.

3.3 Net Positive Suction Head
Net Positive Suction Head (NPSH), is important term when it comes to the pump selection. Based on the Equation 3, it is found that the NPSH is the value of the suction head based on the consideration of external factors such as location above sea levels. In a pump application, there are two types of NPSH which are known as NPSH required and NPSH available. NPSH required is the value of suction head required by the pump and it is provided by the manufacturer \([4]\). On the other hand, NPSH available is the suction head which is available from the pipeline system. These are values in which the user should apply design calculations according to the layout and operating conditions of the system. As a rule of thumb, the NPSH available from the system should be always greater than the NPSH required by the pump. The consideration of the NPSH value during the design stage will enhance the reduction for cavitation to occur \([6]\).

\[
NPSH_a = \pm h_s - h_L + h_A - h_v
\]

Where,
NPSH\(_a\) = net positive suction head available, ft
\(h_s\) = static suction head (if positive value) or static suction
\(h_v\) = vapour pressure of liquid at the operating temperature
\(h_A\) = absolute pressure at liquid surface
\(h_L\) = head loss due to the friction in the suction line of the pump

3.4 Affinity Law

Affinity Law is a principle which is specifically used to determine the performance of the pump when either the speed of the pump or the size of the impeller had been changed. According to this law, the torque created by the pump is proportional to the square of the speed of the pump. In other words, the torque of the pump will be increased by a factor of four when the original speed of the pump has been increased twice. As an engineering principle, the power of the device is the multiplication product of the speed and torque. Therefore, the power produced by the pump will be triple of the speed\([7]\).

\[
\left(\frac{N_1}{N_2}\right) = \frac{V_1}{V_2}
\]

\[
\left(\frac{N_1}{N_2}\right)^2 = \frac{H_1}{H_2}
\]

\[
\left(\frac{N_1}{N_2}\right)^3 = \frac{P_1}{P_2}
\]

Where,
N = speed of the pump’s motor
V = volumetric flow rate
H = dynamic head
P = power of the pump

3.5 Minor Losses

In fluid mechanics, the minor loss can be defined as the friction loss caused by the roughness of the internal surface of the pipeline. According to the calculations performed, it also showed flow restriction caused by the joint and valve. The actual flow rate will be significantly affected by friction losses\([1]\). To determine the losses, the equations utilized include the Reynolds Number, Volumetric Flow Rate, Colebrook Equation, and the Darcy Weisbach. The equations shown in at below have been used for the performance monitoring on the research project.
Reynolds number;
\[
Re = \frac{V_{avg}D}{v}
\]

Volumetric flow rate;
\[
V = \frac{\dot{V}}{A}
\]

Colebrook equation;
\[
\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{e/D}{3.7} + 2.51\frac{Re\sqrt{f}}{f}\right)
\]

Darcy Weisbach equation;
\[
h_L = f \frac{L V^2}{D 2g}
\]

To apply equations, the Engineering Equation Solver (EES) software was required since there are more than two unknowns found in the equations.

4. Prototype Implementation
The prototype for this research project was constructed based on the engineering drawing development using SolidWorks as shown in Figure 1. As for the media of transferring water, a PVC pipe with the diameter of 1 inch was been chosen and used throughout whole system. Meanwhile, the VFD has been built based on the required electronics and component rating.
5. Variable Frequency Drive

In a Variable Frequency Drive (VFD), there are three main sections which operate in different types of functions to optimize the system and generate the pulse width modulation (PWM). These sections included the rectifier, DC Bus, and inverter. The main function of the rectifier is to rectify the AC input so that the output does not have negative voltage. It was constructed by diodes with a full wave bridge layout. The DC bus operates as the stabilizer and smoothen the rectified voltage. To stabilize the voltage from its source, the capacitor with a large capacitance is connected to the rectifier. To design and simulate the circuit, the VFD was constructed using Proteus. The VFD circuit diagram is illustrated on Figure 2. To isolate the power switch and microcontroller, the gate driver was connected between the gate of the MOSFET and the Arduino. The system will be operated by using the frequency of 50Hz. To calculate the capacitance value, the inductance value has been assumed as 100mH.

\[ f = \frac{1}{2\pi\sqrt{LC}} \]
\[ 50 = \frac{1}{2\pi\sqrt{(100m)C}} \]
\[ C \approx 100\mu C \]

The inverter was constructed with power switches and is controlled by an external controller. The amount of power switches connected was dependent on the number of input phases of the application. At this point, the DC source from the DC bus converted into pulse width modulated waves before it supplied current to the motor. In order to control the speed of the motor, the power switches were consistently switched on and off according to the desired frequency and duty cycle. For the filtering part of the circuit, the resonance circuit or known as the RL circuit was used. With the RL circuit, the square wave AC output will be smoother to achieve a sine wave AC output. The diode arrangement in the H Bridge configuration for the VFD is shown in Figure 3.
6. AC Motor Speed Control

To determine the speed of the induction motor used for this research, there were two common terms which were considered, synchronous speed and the rated speed. The rated speed is the actual speed of the motor while the theoretical speed is represented by the synchronous speed. The rated speed was less than the synchronous speed due to external factors. As per the synchronous speed equation determinant used, it was found that the main factors which affected the synchronous speed were the frequency and the number of poles. The frequency is directly proportional to the synchronous speed while the number of poles is reverse proportional to the speed \([2]\). Controlling an AC induction motor requires an inverter circuit which can produce a forward and reverse voltage. Therefore the inverter circuit was constructed with the H bridge layout and the pulse was sent to the gate of the MOSFET. In each of the half cycle, there were only two MOSFETs triggered by the microcontroller. This design resulted in six different operating conditions if any two of the MOSFETs are triggered. However, it was found that only two of the conditions can be used to power the load. During operation, the MOSFET T1 and T4 worked as a pair to supply forward voltage to the motor while the reverse voltage was supplied when T2 and T3 are triggered. The Figure 4 below shows the timing diagram for each of the power switches.

7. Testing & Analysis

During testing, the first test was based on the speed of the motor that was changed by feeding different frequency ranges to the VFD. The frequency range was set between 20 Hz to 50 Hz considering safety precautions. The flow rates of the pump were recorded when the speed of pump was changed. This is shown in Table 1.
Table 1. Flow Rates of the Pump at Different Speeds

| Frequency (Hz) | Speed of the motor (rpm) | Flow rate (litre/min) |
|---------------|--------------------------|----------------------|
| 20            | 1200                     | 36.34                |
| 30            | 1800                     | 55.67                |
| 40            | 2400                     | 74.83                |
| 50            | 2850                     | 90.95                |

The second test carried out was on the measurement of power consumption at different pump speeds. In this test, the wattage meter was used to measure the power consumption of the pump. Similar to the first test, the pump speed was varied between 1200 rpm to 2850 rpm and the power consumption was recorded at each speed difference as shown in Table 2.

Table 2. Pump Power Consumption at Different Speeds

| Pump Speed | Wattage of the pump (kW) |
|------------|---------------------------|
|            | Theoretical | Practical |
| 1200       | 27.62       | 28.23     |
| 1800       | 93.21       | 95.46     |
| 2400       | 220.95      | 226.24    |
| 2850       | 370.00      | 372.30    |

Based on the data recorded during the two tests conducted, it was found that the flow rate generated by the pump is directly proportional to the pump speed.

8. Testing & Analysis

In conclusion, the research has proven that the power consumption of the pump can be reduced by applying the philosophy of the Affinity Law. To achieve the objective of energy reductions, the VFD is accepted based on the test results as the most suitable solution since it will able to reduce the pump speed without sacrificing on the pump lifespan. With the combination of feedback system, energy conservation can be achieved. For instance, a flow rate sensor can be implemented at the output of the tank to examine the usage of the water consumption. By using the data of a particular sensor, the pump speed can be varied based on the current status of the water demand via the water circuit monitoring.

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