A PI - fuzzy controller with flow control and energy optimization using flow sensors

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Pumps are an integral part in industrial systems involving fluid transfer and hydraulic processing. They occupy nearly 27% of electricity in the manufacturing sector. Energy saving now becomes a necessity to Cutting out wasted energy and save energy by efficient use of available energy. For saving the energy there is a need of optimizing energy by standard system and Innovation of new technology. The energy saving process can be possible by using the proper choice of equipment and their effective use. Hence unnecessary wastage of energy is an important problem in flow control systems. Hence Control of speed of motor in accordance to fluid input reduces energy consumption thus increasing the efficiency of the system which is the proposed work presented in this paper. This method also reduces a network of complex pipelines hence making the structure simple. The PI control and fuzzy controller proves to be an effective control scheme to improve the overall performance of the system.

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1. Introduction

Pumps are important components in any manufacturing sectors for transportation of gases, liquids, petroleum’s in offshore drilling platforms etc., Pumping is achieved by utilization of high speed motors. Pumps could be displacement type or centrifugal type where displacement type pumps push or squeeze the fluid directly while centrifugal types increase the speed of the fluid and convert the kinetic energy generated into pressure. A general pumping system in illustrated in Fig. 1.

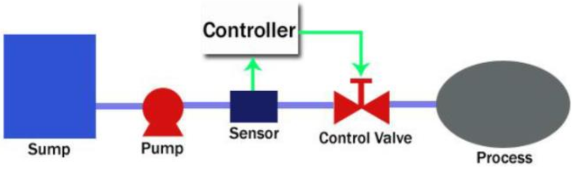

Fig. 1. A General pumping system.

Fig. 1 illustrates a storage area which may be a sump from which liquid is forced out and pumped into the network of complicated pipelines with regulation carried out by a control valve. Pumping systems utilize 20% of total energy on the globe for the motors. Hence need for energy savings becomes an important problem in pumping systems. The most efficient mean of flow manipulation is pump-speed adjustment. Since as per the "affinity law" brake horsepower varies with the cube of centrifugal pump speed, reducing pump speed reduces pressure imparted to the fluid and in return reduces centrifugal power consumption. In addition to energy conservation, there are also a number of operational benefits, such as improved reliability, process performance, reduced life-cycle cost, and decreased fugitive emissions by eliminating the control valve and the associated piping. Energy savings could be achieved to a greater extent in pumping systems involving variable pumping characteristics which necessitate a need for flow control. Energy consumption is reduced when less liquid needs to be pumped. Hence choice of pumps plays a vital role for energy savings. Pumps may be positive displacement (PD) or roto dynamic. A comparative performance [1-3] shows a constant flow irrespective of state of head for a PD type while the flow rate gradually varies for varying state of head. A system of control of pressure or flow rate may shift the operating point to a new position based on demand thus increasing energy savings considerable. Variable speed drives (VSD) are most popular in a number of variable speed applications [4-6].

2. Variable speed drives

The most common control device for a constant-speed centrifugal pump is a control valve in the discharge line as depicted in Fig. 1. This valve controls the amount of liquid delivered to the process. The valve takes a pressure drop equal to the difference between the pressure supplied by the pump and the pressure required by the process [7-9]. Throttling with a control valve makes the apparent pump curve steeper, and it will cross the system. About 75%

pumps in industries are of centrifugal type. The liquid is accelerated in the impeller and discharged into the pump at high velocity. The working of a centrifugal pump is illustrated in Fig. 2 where the impeller increases the speed of the liquid and forces it through the discharge.

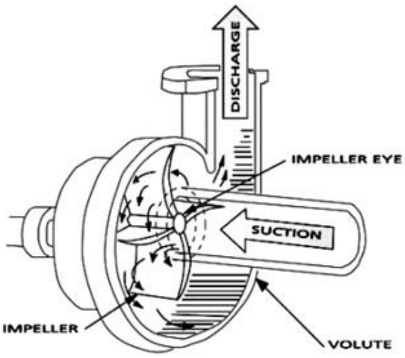

Fig. 2. Operating principle of centrifugal pump.

In many flow applications, a mechanical throttling device is used to limit flow. Although this is an effective means of control, it wastes mechanical and electrical energy. Because a VFD alters the frequency of an AC motor, speed, flow, and energy consumption are reduced in the system thus increasing the energy save. Applying a VFD to the pump allows control of the pump's speed electrically while using only the energy needed to produce a given flow. The use of VFDs can bring further total system cost reductions, due to the elimination of components required for valve control only. In a valve flow control system [10-13], there are losses in the valve and additional piping required to bring the valve to a height where it can be adjusted. A VSD changes equipment speed to provide the torque-energy input needed to supply the hydraulic-energy output to the process. In this type of control system, the curve is not changed to match the required operating point, as previously discussed for control valves. Operation of VSD is attributed to three laws given by

$$\frac{Q_1}{Q_2} = \left(\frac{N_1}{N_2}\right); \qquad \frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2; \qquad \frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

where 'Q' denotes the volume flow rate of pump output, 'N' the speed of rotation and 'P' the pump shaft input horse power. For pumping systems where the flow demand often drops, control valves will frequently be operating at lower throttle positions, wasting more energy by a greater pressure drop across the valve. Additionally, to achieve the required turndown, the percentage of system-pressure drop allocated to a control valve must be increased from the 5-20 percent normally stated to minimize energy costs. The energy savings are proportional to the cube of the speed; therefore, in these applications, the energy savings from using a VSD are considerable. Variable-speed drives can increase process efficiency by reducing energy use and process variability. The savings are greatest for large flow systems, high turndowns, difficult process fluids, and extremely sensitive processes. However, engineers with mechanical, electrical, and control skills are needed to ensure the total system design and implementation will not result in bearing, cable, or noise problems and process oscillations or overheating at low flow.

3. Proposed work

In the proposed system the control signal is directly used to control the speed of the motor as shown in Fig. 2.2. This effectively replaces the need for a by-pass line and the control valve, hence resulting in a simpler system and improved efficiency.

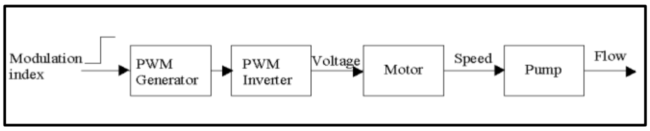

Fig. 2.2 Schematic of proposed work.

The output from the flow sensor i.e in the range of 0-20mA is converted to a voltage level of 0-3V which is then fed to the LabVIEW/DSP, which is then compared with the set point to generate the error. The error output is processed in the Controller Block to provide the control output. An experimental set up is shown in Fig. 3.

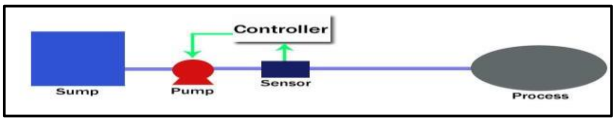

Fig. 3. Experimental setup Model.

The control output determines the voltage level to be generated in the power circuit for providing appropriate speed at the pump. The control output which received by the PWM generator in turn controls the amplitude of its sine wave signal to obtain the necessary speed at the output. The PWM signals which are in the form of pulses are suitably interfaced with the Power. The 3Φ inverter of the Power Module, which is capable of driving 1HP motor, is configured as H-bridge for providing 1Φ AC. The power is supplied from a fixed voltage 1Φ AC source, which rectified and inverted to obtain a variable voltage 1Φ AC supply at the Power Module, which is fed to the drive of the pump. The torque (T) developed by a universal motor operating on ac depends on the value of field flux(φ), current(I) and power factor (cosØ), as given by,

$$T = k\, I \cos\emptyset$$

Hence a variable voltage method of speed control is used. A lab view implementation of the proposed work is illustrated in Fig. 4.

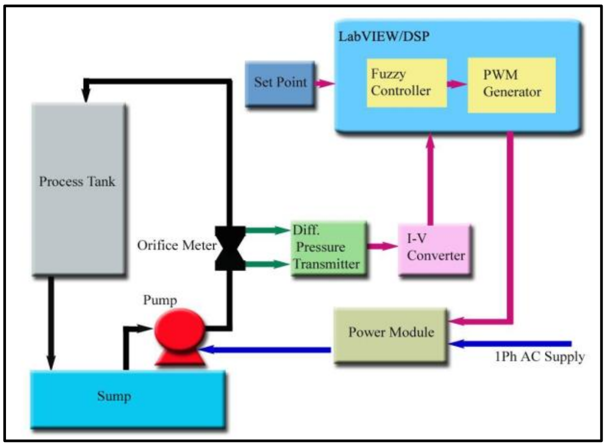

Fig. 4. Lab view implementation of proposed work.

A centrifugal pump with a suction head of 6m, drive power of 0.125kW, input power of 270W and at total head of 24m and 230V AC/DC has been used.The flow transmitter of the system is a combination of an Orifice Meter coupled with a Differential Pressure Transmitter, whose output is a 4-20 mA current signal which corresponds to (0-1000) Litre per Hour (LPH) flow rate of the pump. Other sub-systems are sub-circuits performing supporting functions in providing temperature compensation, zero and span control, voltage regulation etc. The PWM outputs Va and Vb are taken through the 6014 DAQ ports ao0 and ao1 respectively at a voltage level of 5V DC. The CMOS buffers provide the isolation between the DAQ and Power Module. 4050 is non-inverting and 4049 is an inverting CMOS buffer. The channels ao0 and a01 are each connected to buffers of 4050 and 4049 through a pull- down resistor of 10K. The signal Van is connected to PWM1 and ~Va is connected to PWM2 terminals of the Power Module. Similarly the signal Vb is connected to PWM3 and ~Vb is connected to PWM4 terminals of the Power Module. PWM1 and PWM3 form the positive side and PWM2 and PWM4 form the negative side of the H-bridge.

The Flow Transmitter used for measuring flow is a Electronic Transmitter which measures the difference in pressure at two points, which are fed from two sides of the Orifice Plate and converts it to proportional Electronics Signal. The signal here is a 4-20mA current signal which corresponds to the Flow rate of 0-1000LPH (litre per hour).This current signal is converted in to 0-3V voltage signal using an I-V converter so that it can be effectively interfaced with the LabVIEW through DAQ card or to the ADC channel of the DSP.

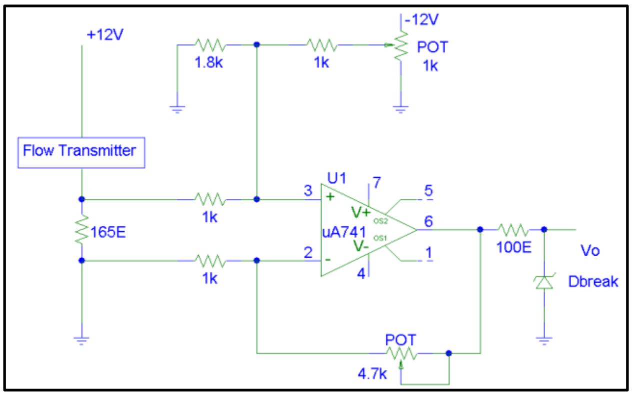

Fig. 5. I - V converter.

In inverter circuits in order the output to be sinusoidal with magnitude and frequency controllable, the legs A and B of the full-bridge inverter are controlled separately by comparing *Vtriangle* with sinusoidal control signals *Vcontrol* and *–Vcontrol*. The frequency of the triangular wave form establishes the inverter switching frequency and is kept constant along with its amplitude *Vtriangle* as shown in Fig. 6. The triangular wave form is at frequency *fs*, also called as carrier frequency establishes the frequency with which the inverter switches are switched as shown in Fig. 7.

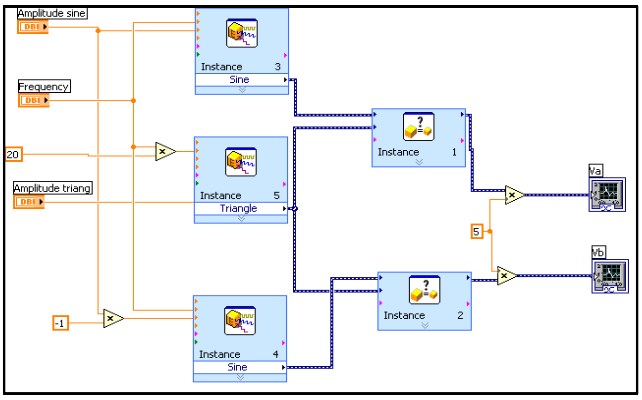

Fig. 6. PWM generation module in labview.

The control signal *Vcontrol* is used to modulate the switch duty ratio and has a frequency *f1*, which is the desired fundamental frequency of the inverter voltage output. F1 the amplitude modulation ratio $M_a$is defined as,

$$M_a = {V_{control}}/{V_{triangle}}$$

where *Vcontrol* is the peak amplitude of the control signal. The frequency modulation ratio M_f is defined as

$$M_f = {f_s}/{f_1}$$

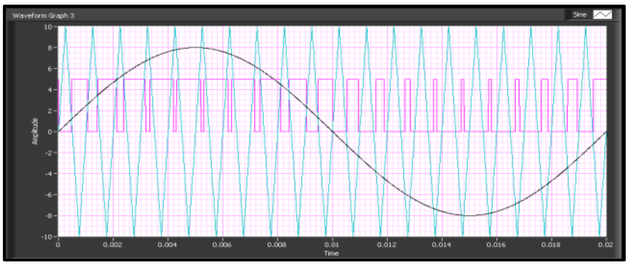

Fig. 7. Sinusoidal PWM signal.

The comparison of *Vcontrol* with the triangular wave form results in the following logic signals to control the switches in leg A:

Vcontrol>Vtriangle: T_A+ON and $V_{AN}=V_d$

Vcontrol<Vtriangle: T_A-ON and $V_{AN}=0$

For controlling the leg B switches, *-Vcontrol* is compared with the same triangular waveform, which yields the following:

(*-Vcontrol*) >*Vtriangle*: T_B+ON and $V_{BN}=V_d$

(*-Vcontrol*) <*Vtriangle*: T_B-ON and $V_{BN}=0$

There are four combinations of switch on-states and the corresponding voltage levels:

1. T_A+, T_B- ON : $V_{AN} = V_d$, $V_{BN}=0$;
3. T_A+, T_B+ON : $V_{AN} = V_d$, $V_{BN}=V_d$; $V_o=0$
4. T_A-, T_B-ON : $V_{AN} = 0$, $V_{BN}=0$; $V_o=0$

In this type of PWM scheme, when a switching occurs, the output voltage changes between zero and $+V_d$ or between zero and $-V_d$ voltage levels. Hence this type of PWM scheme is called PWM with a unipolar voltage switching. This scheme has the advantage of effectively doubling the switching frequency as far as the output harmonics are concerned. Also the voltage jumps in the output voltage at each switching are reduced to V_d.

The output voltage is given by

$$(V_{AO})_h = 2.\frac{1}{\sqrt{2}}.\frac{V_d}{2}.\frac{(\hat{V}_{AO})_h}{V_d/2}$$

Also, $V_{o1}=M_a*V_d$ $(M_a\leq 1.0)$

In unipolar switching scheme results in an odd symmetry [*f(-t)=-f(t)*] as well as a half- wave symmetry [*f(t)=-f(t+1/2T)*]. Therefore only odd harmonics are present and the even harmonics disappear from the waveform of V_o.

4. PI – Fuzzy controllers

The approximate model is used to obtain the values of the parameters $K_p, \theta\ and\ \tau$

The PI controller is designed from the following equations stated by Cohen θ and Coon.

$$K_c = \frac{1}{K_p}\frac{\tau}{\theta}(0.9 + \frac{\theta}{12\tau})$$

$$\tau_I = \theta\,\frac{30+3\theta/\tau}{9+20\theta/\tau}$$

The parameters of the PI controller, K_c and τ_i are calculated from the model parameters, using Cohen and Coon Method as,

$$K_c = 0.041$$

$$\tau_i = 0.619$$

V

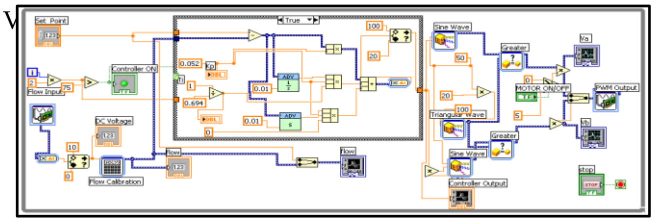

Fig. 8. Labview implementation of PI controller.

Fig. 8 depicts a lab view implementation of PI controller. Fuzzy logic is widely used in machine control. Fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans. The input variables in a fuzzy control system are in general mapped into by sets of membership functions similar to this, known as "fuzzy sets". The process of converting a crisp input value to a fuzzy value is called "fuzzification".

The two input variables are "Error" and "Error Rate" that have values defined as fuzzy sets as shown in Table 1 respectively. The output variable, "Modulation Index", is also defined by a fuzzy set with the decision is based on a set of rules:

- All the rules that apply are invoked, using the membership functions and truth values obtained from the inputs, to determine the result of the rule.
- This result in turn will be mapped into a membership function and truth value controlling the output variable.
- These results are combined to give a crisp answer, a procedure known as "defuzzification".

This combination of fuzzy operations and rule-based "inference" describes a "fuzzy expert system".

Table 1. Fuzzy Rule Base.

Output	**Error Rate**					
		NH	NM	AZ	PM	PH
Error	NH	NE	NE	NE	NE	NE
	NM	NH	NH	NH	NH	NH
	AZ	PM	PL	Z	NL	NM
	PM	PH	PH	PH	PH	PH
	PH	PE	PE	PE	PE	PE

The "centroid" method is very popular, in which the "center of mass" of the result provides the crisp value. Another approach is the "height" method, which takes the value of the biggest contributor. The centroid method favors the rule with the output of greatest area, while the height method obviously favors the rule with the greatest output value. The crisp

Output value is given by,

$$Crisp\_out = \frac{\sum_{i=0}^{N} Output_{mf[i]} * Output[i]}{Output_{mf}[i]}$$

Table 2. Comparison of Settling Times.

Controllers	**Settling Time**
PI Controller	67s
Fuzzy Controller	13s

Table 3. Comparison of Power Consumption.

Flow(LPH)	**Power(W)**	
	Variable Speed Method	**Valve Control Method**
200	20	228
300	30	228
400	40	228
500	60	228
600	80	228
700	100	228
800	180	228
900	200	228
950	220	228

The results were tabulated from the experimental set up shown in Fig. 9.

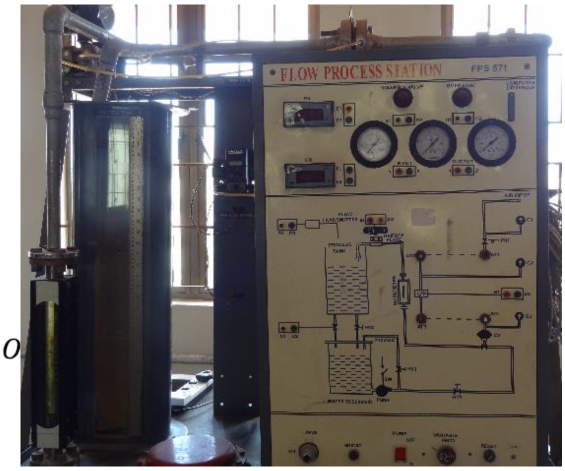

Fig. 9. Experimental station in laboratory.

5. Conclusion

The variable speed method of flow control in addition to energy savings provides other benefits of lower speed, such as reduced hydraulic forces on the impeller created by the pressure profile inside the pump casing as shown in Tables 2 and 3. These forces are carried by the pump bearings and so reducing speed increases bearing life. In addition, vibration and noise are reduced and seal life is increased. Also the control valve and by-pass lines are effectively replaced, hence making the system simple and efficient. The PI controller meets the objective of the system at the cost of high settling time. But the fuzzy controller proves to be an effective control scheme as the settling time and oscillations are highly reduced, hence improving the overall performance of the system. The TMS320LF2407DSP controller proves to be the best motor controller as its PWM and ADC circuits reduces the software overhead; the processor's computational ability is fully utilized for controller processing.

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