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Energy savings configuration for a water-pumping system

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Abstract

Pump theory is an interdisciplinary branch in water catchment/purification systems. The main determinant of the selling price of potable water to consumers is the amount of energy utilized when pumping the water from one area to another. These studies propose a water-pump configuration that decreases the energy consumption. The configuration involved an air-compressor that generates air-pressure; the air-pressure is used to supply a pneumatic actuator that converts chemical energy to mechanical energy. The mechanical force that exists at the pneumatic actuator piston is coupled to the piston of a hydraulic actuator to produce the mechanical stroke in the cylinder of the hydraulic actuator. Applying mechanical force at the hydraulic cylinder, the pumping of water from the water-catchment to a water-tank/reservoir is achieved. Using their compress-air properties, high force realized at the actuator will allows for an optimal output of the system components. This paper highlights the benefits of fluid dynamics in water-pumping system configuration that range from better energy savings and a robust pumping arrangement.

Keywords: energy-savings, water-pump, configuration, air-compressor, actuators, modelling.

1. Introduction

One way of conveying water, gas, oil, or other fluid substances from one place to another is by using a piping system. Pipe are long, round, hollow object, usually made of metal or plastic, through which a liquid or gas can flow [1]. In most industrial applications, pumps are included to achieve this phenomenon. Pumps uses mechanical energy to do work, its basic function is to increase the flow rate and pressure of the moving fluid inside the pipe. Pumps may identified in various ways: the liquid that it pumps, a specific function in the process (work or transfer) and by its specific location in which it is applied [2].

Transfer pumps may vary in many ways but they all have three common characteristics, that of, inlet, which permit the inflow of fluid and must often, has a low pressure. Outlet (or discharge) that permit the fluid to flow outside the pump with high pressure and the casing which contain the specific mechanism used by the pump [3]. Pumps may be grouped into two categories: The Positive displacement pump that uses a piston to push or positively displaced the fluid in the pump and the dynamic pump that create a rotational force to move the liquid through the pump [4].

Observing the different pump categories, rotary and positive displacement pump are driven by some forms of drivers that are idea frame mounted or closed coupled. The four common types of drivers are: electric motor, coupler, tear wile and a lubricating system (or Bearings) [5]. These drivers are used to transfer motion without a change of direction. This study proposes a configuration that comprise of a compress-air generator together with a setup of a pneumatic-air actuator coupling with hydraulic actuator for the pumping of water from a damp to a reservoir/tank. The aim is to minimize the electrical energy needed for pumping in a bulk water system. A detailed literature survey is conducted in section 2. The proposed study area and modelling presented in section 3. Results and discussion presented in section 4

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and conclusion in section 5.

2. Literature Review

The general characteristic of a pump system is its ability to effect change of movement in fluid, gas and solid, it does so by applying the *Boyle's law* [6]. Historically, Pumps have experienced a great deal of modernisation coming from manual actuated to other forms of energy controllers [7]. Researches, has work on various method to improve the efficiency of pumps and resulted in a number of designs:

2.1. Studies carried out at the level of centrifugal pumps

Kaewnai et al, propose a computational fluid dynamics (CFD) technique in analysing and predicting the performance of a radial flow-type impeller of a centrifugal pump. The study applied in three phases, that is: mesh generation and refinement on the domain of the designed impeller, identification of initial and boundary conditions of the mesh-equipped module, calculating various results and analysed for factors affecting impeller performance. The results indicate a significant head rise. A conclusion drawn on the possibility of using this method to simulate the performance of a radial-flow type impeller of a centrifugal pump [8].

Yadav et al, study the performance analysis of a centrifugal radial flow pump designed, the idea is to vary the number of blades, by using an optimum eight (8) blades and analyse the pump’s performance. The results show that for the optimized value, pump efficiency, increased by 2.23% [9].

2.2. Studies carried out at the positive displacement pumps

Casoli et al. work on a model based on fluid properties in hydraulic positive displacement machines. A diaphragm pump motor is driven by a pulse width modulator circuit and activated by a pressure switch, the purpose of the pressure switch is to control the operation of the pump by regulating the frequency to a predetermined current limit, thereby, changing the pulse energy that varies the speed of the motor [10].

In another application, Stiles et al. applied a system that involve two-way communication to improve the efficiency and reduce the energy consumption. In this system, the arrangement is capable of receiving a parameter from the auxiliary device through the arrangement for providing two-way communication. This configuration will optimize power consumption of the variable speed motor over time based [11].

2.3. Studies carried out at the alternative energy power supply optimisation

Chandel et al. review various studies related in the supply of alternative energy to mitigate the high cost of irrigation and community drinking water supplies. In his study, a comprehensive literature review of solar (photovoltaic) pumping technology is evaluated and the economic viability. Based on the study, conclusions are drawn to the fact that, photovoltaic water pumping technology is cost effective as opposed to conventional electricity or diesel energy water pumps. However, governments are advice to support this technology in reducing the high installation costs [12].

2.4. Studies related to water pumping energy savings

Van Staden et al, uses a model predictive control (MPC) strategy for load shifting, taking into consideration the two electrical charging modules, the time-of-use (TOU) and maximum demand (MD). Using the closed-loop MPC optimization by applying integer programming, the result shows a 5.8% saving of the plan [13].

Zhuan and Xia, reformulated the scheduling problem of a pumping station into a reduced dynamic programming algorithm (RDPA). It’s resulted that, the RDPA allows a reduction of the operational cost by about 60% compared to a conventional control approach [14].

2.5. Control drive application in water pumping systems

Variable speed drives (VSD) is deem to save energy in a water pump system. VSD are devices used to control the speed of a motor and applicable in various industries. Khushiev and Ishnazarov, presented an overview of the applications of variable speed drive (VDS) in an electrical motor energy servings and the energy used. The VDS operating principle is aligned with the affinity laws, meaning controlling the speed of an AC motor by varying the frequency supplied to the motor. This findings review that, VSDs applications in electrical motor enhances the efficiency of the systems and saves in energy consumption, as a result, protecting the electrical motors from damaging [15].

After going through the various researches in the effort to improving the water-pump energy consumption. A different view may be observed, considering the principle of fluid dynamics, fluid mechanics describes the flow-rate of fluids, liquids and gases in a specify medium.

3. Water-Pump Configuration Overview

Fig. 1 below shows the general construction of a single stage piston pump, this pump is classified under positive displacement reciprocating pumps. A motor is used to drive the rotating disc (motor driving disc), the disc is mechanically attached to the connecting rod and act to transfer the mechanical energy of the motor shaft and disc to the piston of the actuator, therefore, causing the pumping of the water in a suction and discharge sequence.

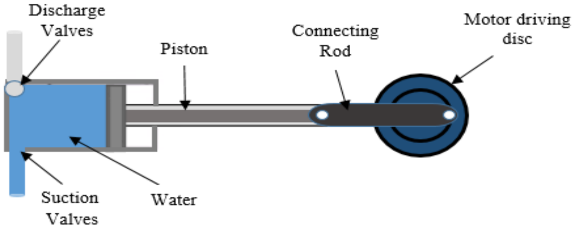

Fig. 1. Positive displacement piston pump [16].

Reflecting on the above traditionally applied pumping principle, an idea is derived in comparing the density of air and that of water; furthermore, looking at how much of the energy needed to displace gas as opposed to the displacement of liquid. Fig. 2 illustrates the configuration of a water pump system with an efficient electrical energy consumption. In this system, electricity is supplied to the drive motor that powers the compressor, the compressor and drive motor component as shown in Fig. 2. Ambient air enters the compressor and compressed air exits the outlet and it is controlled by an exchange valve that direct the air pressure through pipes to enter the pneumatic actuator. The pneumatic linear actuator converts air-energy (typically in the form of compressed air) into mechanical motion (force), this force is used in powering the hydraulic linear actuator by mechanically coupling the piston of the two actuators. Therefore, allowing the pumping of water from the water dam to the water tank.

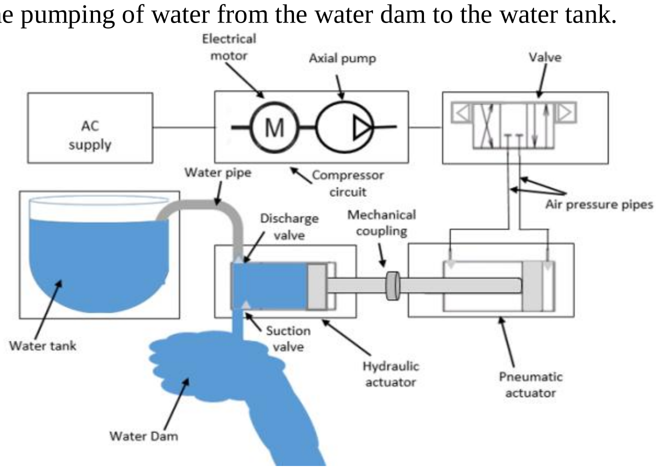

Fig. 2. Proposed water system schematic

The following methodology will sued for this research; starting from modelling the supply energy to the drive motor, second by the compressor and finally modelling the pneumatic actuator in order to obtain the force that need to power the hydraulic actuator.

3.1. Modelling of water-pump system

The electrical power supply by the grid expressed as:

$$P_e = VIcos\theta \quad (1)$$

Where V is the supply voltage (Volts), I is the supply current (ampere) and θ the phase angle (degree).

Power transfer from the shaft to the pump is the product of the shaft torque (T) and angular speed of the shaft (w_m), this power is converted to rotational torque that is experienced at the shaft of the motor, it's the power that is used by the compressor to generate a compressed air and maybe call mechanical power (P_m).

$$P_m = (P_e)(\eta_c)(\eta_d) \quad (2)$$

Where: η_c is the efficiency due to the motor and η_d is the efficiency of the compressor
Consider the mechanical power (P_m) directly proportional to the indicated output power of the compressor (IP) [17].

$$P_m \approx IP = \left(\frac{n}{n-1}\right)(P_1.V_1)\left(\frac{P_2}{P_1}^{\left(\frac{(n-1)}{n}\right)} - 1\right) \quad (3)$$

To determine the outlet pressure (P_2) of the compressor,

$$P_2 = P_1.\sqrt[\left(\frac{n}{n-1}\right)]{\frac{P_m}{\left(\left(\left(\frac{n}{n-1}\right)P_1V_1\right)+1\right)}} \quad (4)$$

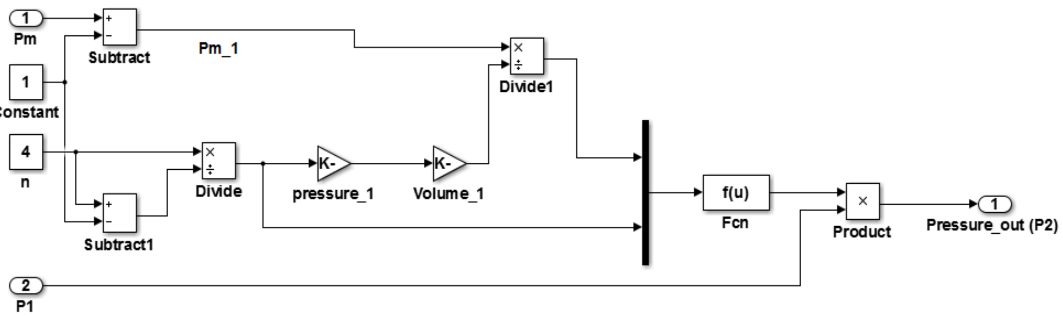

Fig. 3. Simulink block diagram of the outlet pressure (P2) of the compressor.

Where P_1 is the inlet pressure of the compressor, V_1 the inlet volume in (meter/seconds), and (n) the index factor.

This pressure is therefore apply through the air-valve to power the pneumatic actuator. Pneumatic actuators are the devices used for converting pressure energy of compressed air into the mechanical energy to perform useful work.

The outlet pressure in equation (4) adding to the atmospheric pressure (P_{atm}), is the actual pressure that is used by the valve to activate the pneumatic actuator.

$$P_a = (P_2) + (P_{atm}) \quad (5)$$

The cross sectional area (A) of the cylinder is obtain by using the formula:

$$A = \frac{\pi(D)^2}{4} \quad (6)$$

Where D is the diameter of the pneumatic actuator cylinder.

To obtain the outstroke force experience at the piston of the pneumatic actuator, the pressure from the compressor directed by a directional control valve that passes through the air pressure pipes, as indicated in Fig. 2. This pressure is multiplied by the cross sectional area of the pneumatic actuator cylinder.

$$F_a = (P_a)(A) \quad (7)$$

Where P_a is the inlet pressure to the pneumatic actuator.

To determine the in-stroke force of the piston, equation (7) still applies. However, additional calculation needed to exclude the area of the piston rod from the total area of the cylinder to obtain the effective area.

4. Results and Discussion

Two different cases were investigated in order to reveal the quality of the proposed pump configuration solution for the water-pump system. The first case shows the simulation results of the drive motor directly driving the water-pump as seen in Fig. 1. The second case will reveal the simulation results with the inclusion of the configured system in Fig. 2. The both cases were tested in a simulation with the inclusion of a constant supply voltage from the grid and parameter characteristic shown in table 1 below.

Table 1. System parameters [17 and 18].

Categories	Values
Supply voltage	220V
Supply current	100A
Power factor	0.8
Motor efficiency	85%
Pump efficiency	90%
Pressure (P1)	200.5kpa
Atmospheric pressure (Pa)	101.325kpa
Volume	$20m^3$
Diameter	30m
Polytropic index (n)	4
Rotating speed	750rpm
Constant	1
Compressor rated pressure	200kpa
Compressor rated power	17.6kw
Frequency	50Hz

The selected compressor is capable of generating 200kpa, having a 17.6kw motor, 50 Hz rated power and running at full load speed of 750rpm, as shown in Table 1. During the simulations, it has been assumed that the display period is 10s.

4.1. Water pump system without the configuration setup

This section shows the simulation results based on the performance of an electrical motor that is directly driven by a pump, connecting with a constant grid power supply system.

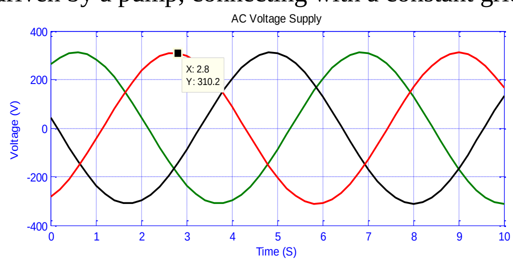

Fig. 4. Supply voltage

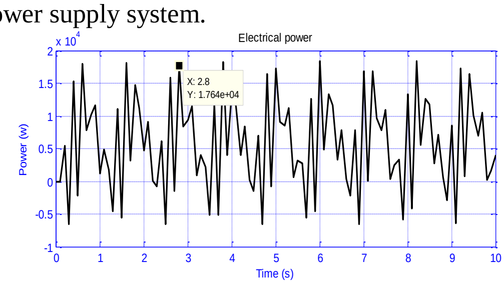

Fig. 5. Electrical power (Pe)

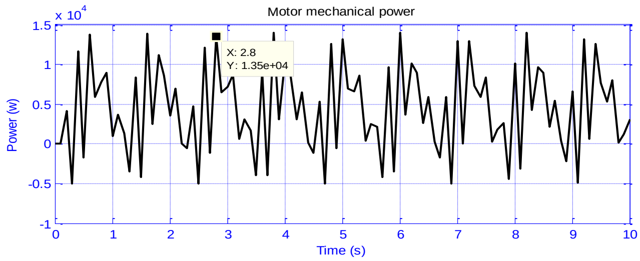

Fig. 6. Mechanical power (Pm)

Based on the operation principle of the pump system, the motor speed of the compressor together with the compressor output air pressure, determines the force experience at the hydraulic actuator to pump the fluid. Fig. 4 shows the waveform of a three phase voltage supply to the compressor unit, and indicated the peak voltage rating to be 310.2V. Fig. 5 represents the electrical power that is used to supply the compressor, it could be noticed that, at any point in time, the maximum potential electrical power that the compressor may receive from the supply power is 17.64kw. Hence, the mechanical maximum power that actually dose the movement is 13.5kw, as seen in Fig. 6. This power is used as shown in Fig. 1 to drive the motor. Hence, performing the actual pumping of water.

4.2. Water pump system with configuration setup

This section shows the simulation results based on the configuration setup of a pump system under a constant voltage supply and with the inclusion of the compressed-air system.

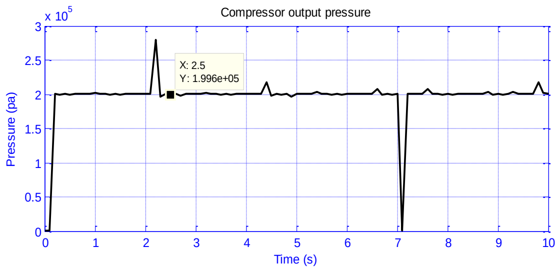

Fig. 7. Compressor air-pressure

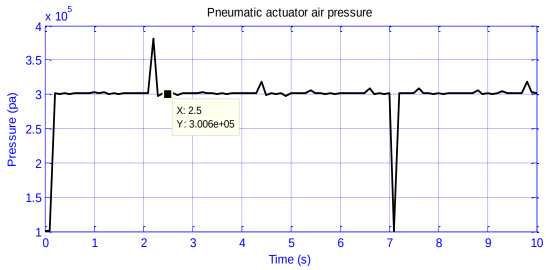

Fig. 8. Pneumatic actuator pressure

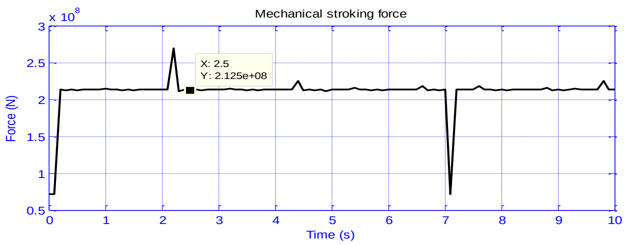

Fig. 9. Mechanical stroking force

The fluid dynamics technique is added to minimize energy usage in pump system. The mechanical power seen in Fig. 6, is now used to power the compressor that generates compressed air as indicated in Fig. 7. Fig. 8 shows the compressed air pressure of 300.6kpa that is used by the pneumatic actuator to produce an average force of 212.5MN as shown in Fig. 9. This force is use by the hydraulic actuator to pump water as shown in Fig. 2

5. Conclusion

A water pump configuration is modelled, developed and simulated using the MATLAB/Simulink program that can save the amount of energy used in the pumping of water from a catchment/Dam to the water tank/treatment reservoir. The above system has laid it concept on fluid dynamic principle. Liquid with different viscosity and specific gravity maybe pumped since the operating pressure to the pneumatic cylinder will remain constant. As well as, an improved operational speed. The result shows that, using the fluid dynamic principle, a small electrical motor of rated power 17.6kW will deliver a stroking force of 212.5Mpa that is apply for the pumping of water, compare to a larger motor in an electric pump system. Hence, saving the cost of electrical energy consumption.

Conflict of Interest

The authors declare no conflict of interest. However, shall appreciate a sense of recognition.

Author Contributions

This research is a section of an academic finding toward achieving a PhD degree. Therefore, the main author contributes as a student, while the co-authors are the study leaders and have input valuable ideas to the realisation to the article. All authors had approved the final version.

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