Performance Evaluation Using Variable Frequency Drive in Pumping Application: A Case Study at Akim Oda Upstream Water Treatment Plant.

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ABSTRACT- This study is aimed at evaluating the optimal number of pumps required to operate a pumping plant efficiently to obtain a maximum energy savings. One of the evaluative problems being faced currently by the Ghana Water Company Ltd at Akim Oda water treatment plant is the high-energy consumption as a result of the use of single pump in the operations. Since commencing operations in 2018, the system had comprised of five pumps and VFDs integrated with a PLC and SCADA. In motor life cycle, pump cost is 10% and energy consumption 90%, thus considerable improvement in energy savings is possible by increasing the energy efficiency of the pumping system. The main problem with these induction motors is their high-power consumption. In the present study, modelling, simulation and performance evaluation of a variable frequency drive using Matlab/Simulink model was carried out. The experimental results show that the cost of electrical power consumption in kilowatt hour per month for operating the plant with closed-loop and open-loop speed control using VFD are GH¢23,049,289.72 and GH¢33,853,644.28, respectively. Simulations result also show that closed-loop control is advantageous for applications requiring high accuracy, efficiency, and responsiveness as it uses feedback to monitor and correct speed. Hence, per the experimental and simulation results, it is concluded that increasing the number of pumps with closed-loop for their operations will optimise the plant's performance by enhancing its efficiency and also save energy.

Keywords: Centrifugal pump, variable frequency drive (VFD), Motor speed control, efficiency, parallel pumps, Energy saving, Optimising, Pulse Width Modulation (PWM), Water Treatment Plant (WTP).

I. INTRODUCTION

AC motors are commonly started using methods such as direct online, star-delta, and autotransformer. However, these traditional methods do not offer speed control; that capability is provided by newer technologies like Variable Speed Drives (VFDs), which implement a soft start technique. The maintenance requirements for motors and their starters, along with the need for strict energy management, make VFDs indispensable. When considering safety and cost-effectiveness, VFDs are often preferred over traditional starting methods. An examination of motor start methods and their operational effectiveness reveals that VFDs, through their soft start function, lead to significant benefits. Their increased adoption can enhance product quality, boost productivity, and reduce operational costs.

An induction motor is a type of AC motor that resembles a synchronous machine in its stator design. When supplied with three-phase currents, it generates a rotating magnetic field; the rotor, which has no electrical connections, produces torque through electromagnetic induction from this magnetic field. Induction motors typically feature either a wound rotor or a squirrel-cage rotor.

In practice, approximately 90% of three-phase induction motors are of the squirrel-cage variety, making them popular industrial drives due to their self-starting capabilities, reliability, and cost efficiency. While they have traditionally been used for constant-speed applications, there is a growing trend towards using VFDs for speed modulation, which ensures dependable service. VFDs present significant energy-saving opportunities, especially in variable-torque applications like centrifugal pumps that commonly utilize squirrel-cage induction motors.

A VFD is an AC drive that regulates the speed of induction motors by adjusting the system's input frequency. It can control various machine tasks in automated robotics within industrial and manufacturing environments, including material handling, machining, and fan or pump applications. VFDs are a cost-effective solution to enhance the performance and efficiency of machinery. They come in several voltage models, such as 230 V for single-phase and 480 V or 600 V for three-phase motors. Selecting the appropriate drive depends on the motor's size, voltage and current ratings, and specific operating requirements. In their fundamental operation, VFDs align motor speed with load demands by modifying the frequency and voltage supplied to the motor. This capability allows motors to operate at optimal efficiency for distinct applications, thus reducing energy consumption. Given that electric motors account for over 65% of industrial power usage, the role of VFDs is crucial. They are primarily used with three-phase induction motors, which are generally preferred for their cost-effectiveness, although single-phase and synchronous motors may be suitable in certain cases.

A practical example of VFD use is at the Akim Oda Treatment Plant of the Ghana Water Company (GWC), where five 125 hp (90 kW) and five 600 hp (400 kW) three-phase induction motors are controlled by VFDs. At the plant, the five 90 kW motors are arranged vertically, connected in parallel at the low-lift intake to operate five high-pressure centrifugal pumps that draw water from a 9-meter-deep dam into a cascade aerator. Gravity then circulates the water through the treatment process before it is directed into the reservoir at the high-lift section. Concurrently, five 400 kW motors, positioned horizontally and connected in parallel, drive high-pressure centrifugal pumps that transport treated water from the reservoir to the network reservoir, located 11.17 km away in Akim Asene.

At the Ghana Water Company's Akim Oda Treatment Plant, since commencing operations in 2018, the plant has relied on just one pump, despite having five pumps and VFDs integrated with a PLC and SCADA system. Proper utilization of VFDs and associated systems would enable the plant to operate multiple pumps in a closed-loop system, optimizing efficiency and reducing power consumption. Challenges have surfaced due to a lack of expertise in managing a dual-pump operation with VFDs, leading to incidents, such as pipe bursts, attributed to excessive discharge pressures resulting from flows exceeding the pipes' maximum capacity of 2150 m³/hr. Moreover, during high water demand scenarios where low discharge heads exist, the motor's speed is adjusted according to the maximum allowable flow rate (2150 m³/hr). Utilizing VFDs facilitates this speed variation by altering the motor's voltage and frequency for optimal flow control. When flow must be regulated without VFDs—by starting the motor with a star-delta configuration and relying on a single pump with a throttling valve—controlling the flow becomes problematic. This approach risks pipe bursts due to high internal pressures when the motor operates at constant speed while attempting to reach maximum discharge rates. This study is to determine the optimal number of pumps needed to operate the plant efficiently to obtain the maximum energy savings.

II. Summary of Related Literature

There are quite a number of papers on analysis of variable frequency drive with Three-Phase Induction motors. Priyanka et al., (2017) did an experiment to study induction motor operation with VFD and without VFD for pump by simulation to analyse its performance to determine payback period, the annual energy saving and actual profit through calculation.

The flow of pump control by two different methods, Matlab simulations and experimental work was analysed by Ankur et al., (2014). V.K Arun Shankar et al., (2017) also performed real time simulation of variable speed parallel pumping using affinity laws to reduce power up to 80% when there is a reduction in speed of 50%. Matlab simulations and experimental work was carried out to compare energy conservation in the operation of an induction motor, with VFD and without VFD in pumping application.

Ankush Dharkar (2017) studied the PLC and VFD, its operation which can be used along with the induction motor and can control the parameters of it for Automation in industries.

Viswanathan et al., (2020) also did an experiment with VFD and VFD for pumps to reflect a review on the stimulus and performance analysis of the induction motor with and without VFD.

PWM (Pulse Width Modulation) based speed control of three-phase asynchronous (Induction) motor was analysed by Ghulam et al., (2019). Matlab Simulink model of open loop drive system and then implemented with experimental hardware design.

Enemuoh et al., (2013). Carried out modelling, simulation and performance analysis of variable frequency drive using Matlab/Simulink model. It successfully achieved the control of the speed of the induction motor from zero to the nominal speed by varying the frequency of applied ac voltage using pulse width modulation method.

Most of the research discussed above indicate that almost all the authors used Matlab Simulink and experimental system for their analysis. Authors namely, Priyanka et al., (2017); Ankur et al., (2014); Ghulam et al., (2019); and Enemuoh et al., (2013) used Matlab simulation and experimental system for their design and analysis, while Ankush Dharkar (2017) and Priyanka et al., (2017) did experimental based analysis. It was also realised that almost all these authors based their analysis on variable frequency drive and energy saving in pumping application, also induction motor speed control.

VARIABLE FREQUENCY DRIVE

Variable frequency Drive is a power electronic device which converts a constant frequency and voltage to a variable frequency, and variable output voltage which is used to control an induction motors speed. It can electronically vary the voltage and frequency of an induction motor using a

Pulse Width Modulation (PWM) technique. In this method, harmonics may not be eliminated, but minimised according to a specific criterion. The quarter wave output in this method is considered to have a number of switching angles. These angles are selected so as, for instance, to eliminate certain harmonics, minimise the RMS of the ripple current, or any other desired performance index. The resultant non-linear equations are solved using numerical methods on a main-frame computer. A set of angles must be computed and stored for each desired level of the voltage fundamental and output frequency. The optimal (PWM) approach is particularly useful for high power, high volta inverters which tend to be limited in switching losses. As a result of their relatively inexpensiveness and reliability, they have become the preferred method of speed control for variable speed operation.

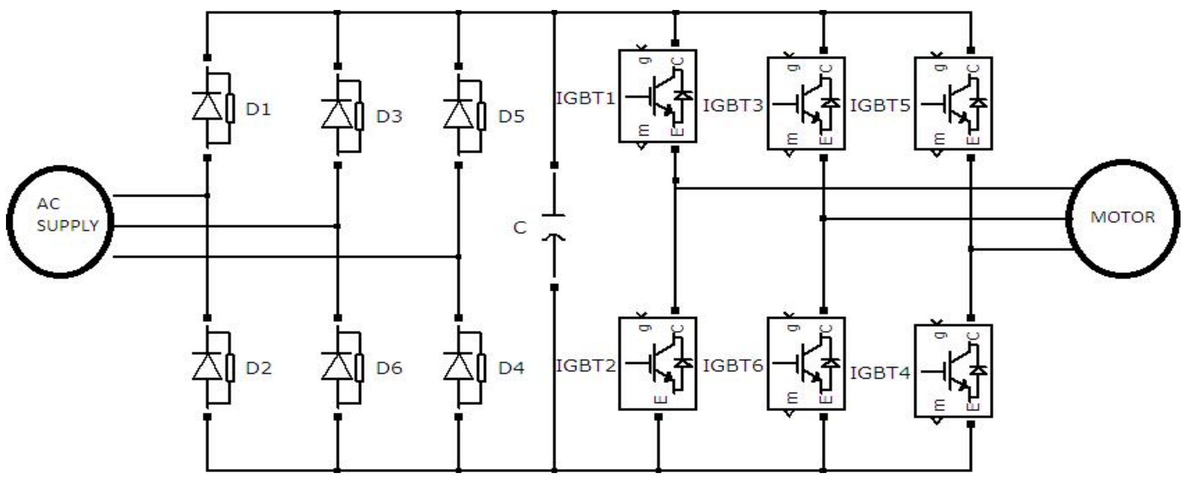


Fig. 2.1 VFD Block Diagram

A. Concept of VFD

This method is the most popular method for controlling the speed of an induction motor. In this method, if the supply frequency is reduced keeping the rated supply voltage, the air gap flux will tend to saturate. This will cause excessive stator current and distortion of the stator flux wave. Therefore, the voltage should also be reduced in proportional to the frequency so as to maintain the air-gap flux constant. The magnitude of the stator flux is proportional to the ratio of the stator voltage and frequency hence, if the ratio of voltage to frequency is kept constant, the flux remains constant. Also, increasing frequency alone increases the frequency, but causes the maximum induced torque to reduce. Increasing voltage causes the maximum induced torque to increase, but causes current to increase. Therefore, varying both stator voltage and frequency will give better speed control without compromising torque.

Insulated-gate bipolar transistor (IGBT) power semiconductor devices are used in the (PWM) system, which can adjust the speed and torque characteristics of the motor to match the load requirements. In the (PWM) system, the first step of the process is to convert the AC supply voltage into DC by the use of a rectifier as shown in Fig. 2.1. Due to the voltage ripples contained in the DC power, capacitors are used to filter the output voltage after rectification to eliminate the ripples, a process in which smoothed DC power is achieved, a section which is often referred to as the dc link. The DC voltage is then converted back into ac, the conversion which is also achieved through the use of IGBT power transistors with the PWM technique. To approximate a sinusoidal waveform, the output voltage is regulated by turning it on and off at a high frequency with the duration of on-time, or width of the pulse controlled. A process which is entirely controlled by a microprocessor which monitors, the incoming voltage, speed set-point and the DC link voltage together with the output voltage and current to ensure operation of motor within established parameters. and current to ensure operation of the motor within established parameters.

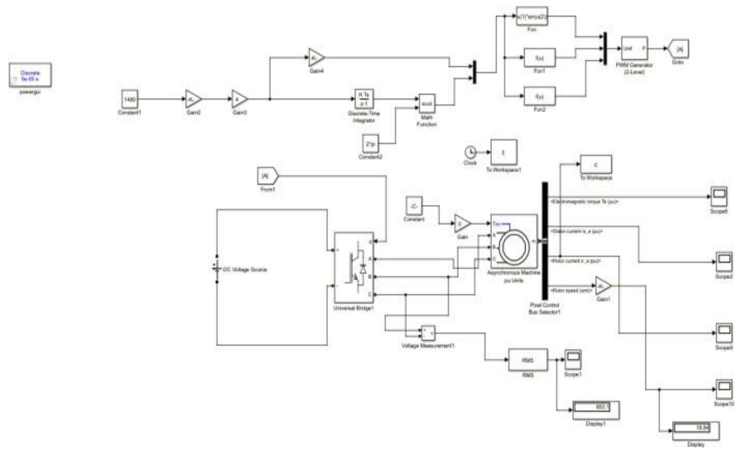


Fig. 2.2 Simulation Model Block for Open - Loop Control of IM

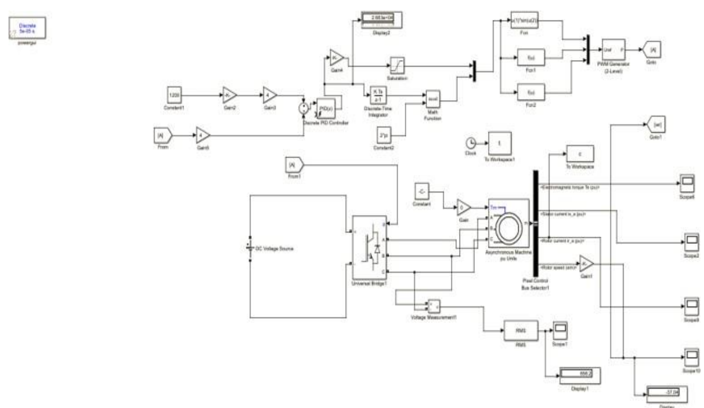


Fig. 2.3 Simulation Model Block for Closed - Loop Control of IM

B. Working Principle of VFD

There are different methods for the speed control of induction motor such as controlling supply voltage, changing number of stator pole, adding external resistance on rotor side and variable frequency control. Among the above-mentioned methods variable frequency control is more efficient and effective. This method varies frequency and voltage; hence the speed is also change accordingly.

A VFD uses a three-stage process to control the motor:

Rectifier: The incoming three phase AC power is converted into a DC supply.

DC-Link: A capacitor or filter is used to smooth out the DC voltage.

Inverter: This is the crucial stage that converts the DC power back into a three-phase AC supply with variable voltage and frequency.

III. MATLAB SIMULINK MODEL

a) Waveform Analysis for IM Open-Loop Speed Control With VFD

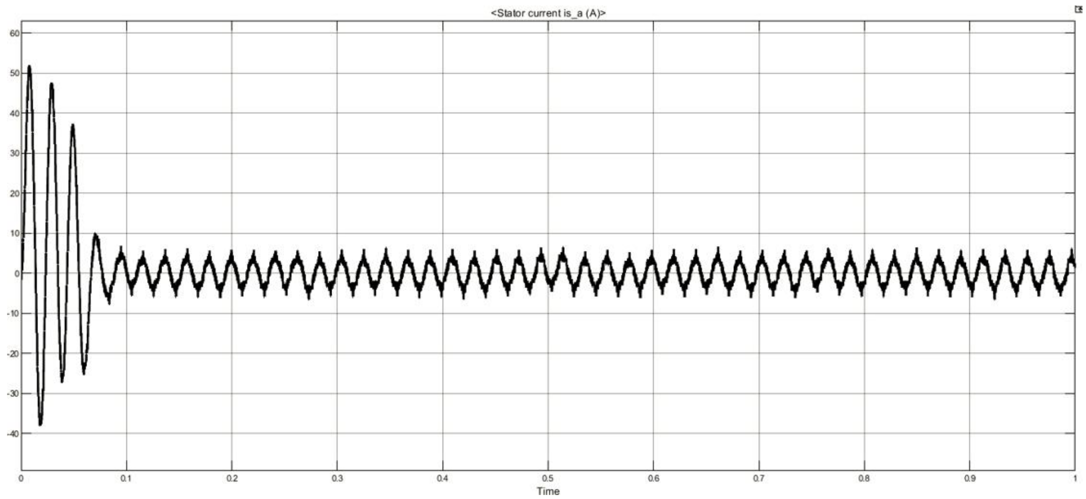


Fig. 3.1 Stator Current Waveform for IM with VVVF Open-loop System

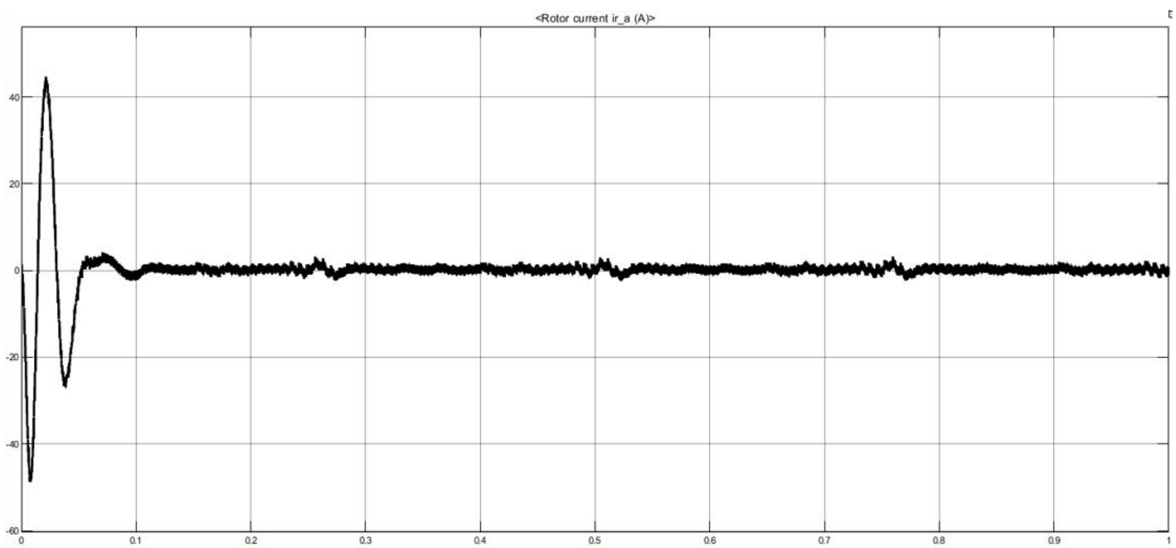
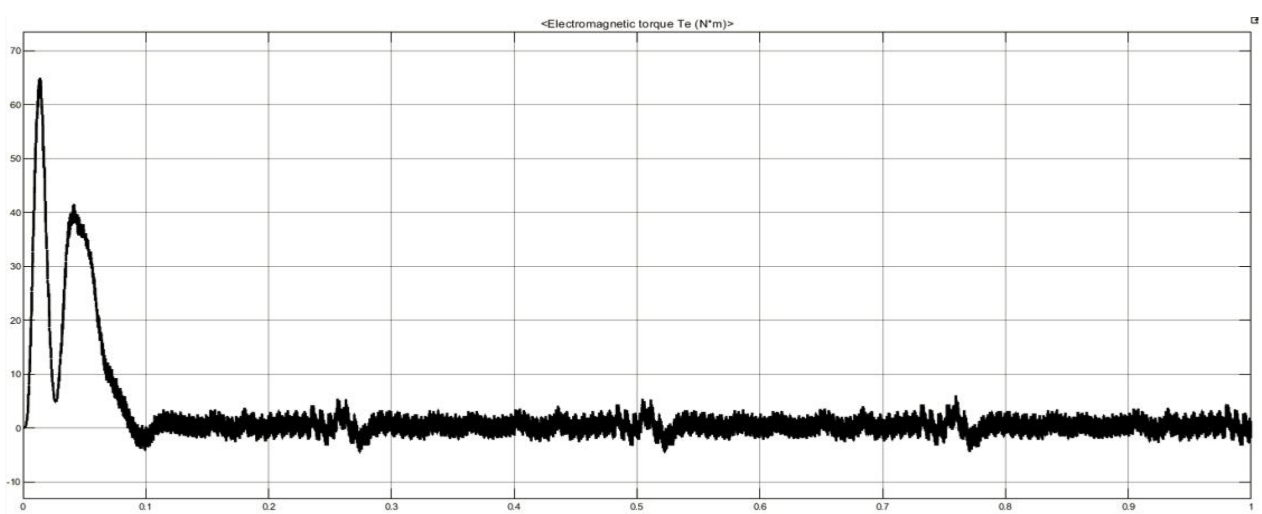


Fig. 3.2 Rotor Current Waveform for IM with VVVF Open-loop System



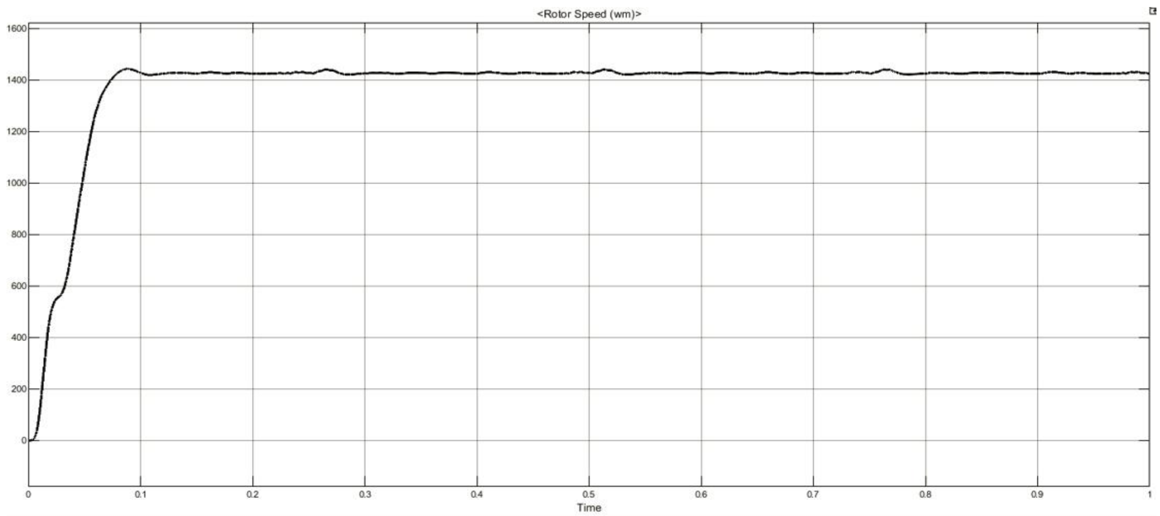


Fig. 3.3 Electromagnetic Torque Waveform for IM with VVVF Open-loop System

Fig. 3.4 Rotor Speed Waveform for IM with VVVF Open-loop System

b) Waveform Analysis for IM Closed-Loop Speed Control With VFD

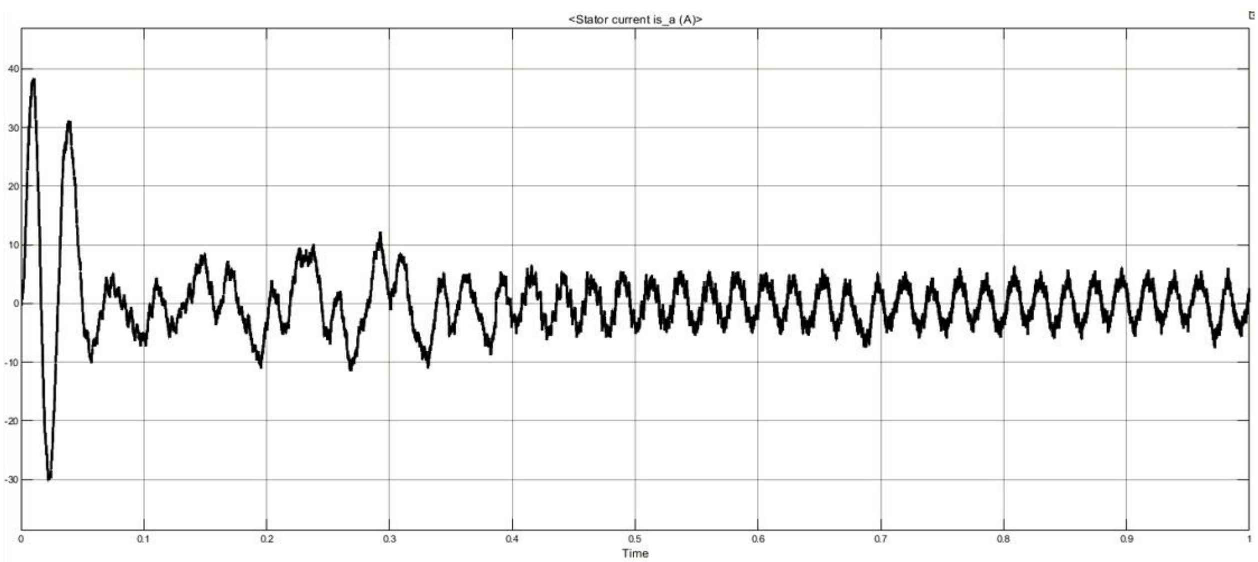


Fig. 3.5 Stator Current Waveform for IM with VVVF Closed-loop System

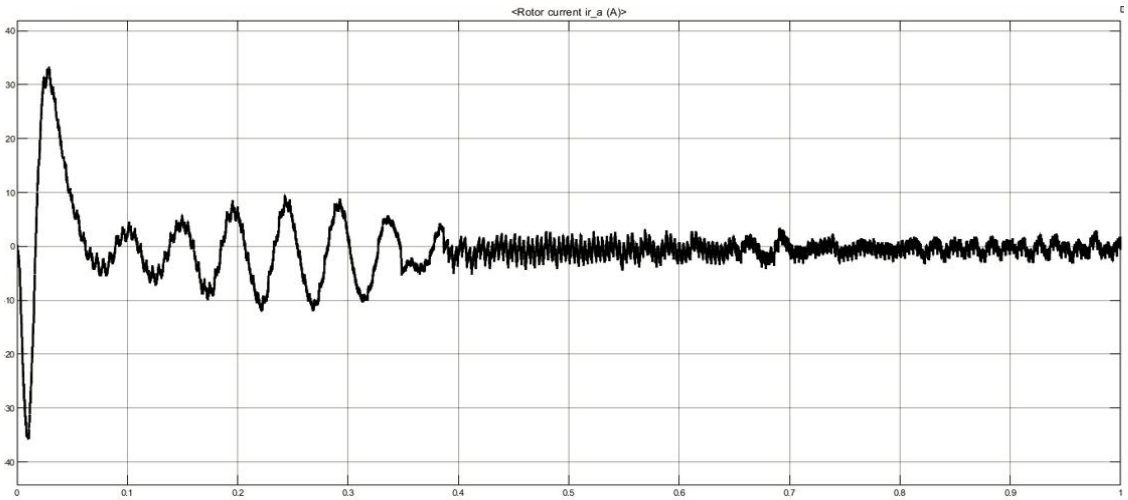


Fig. 3.6 Rotor Current Waveform for IM with VVVF Closed-loop System

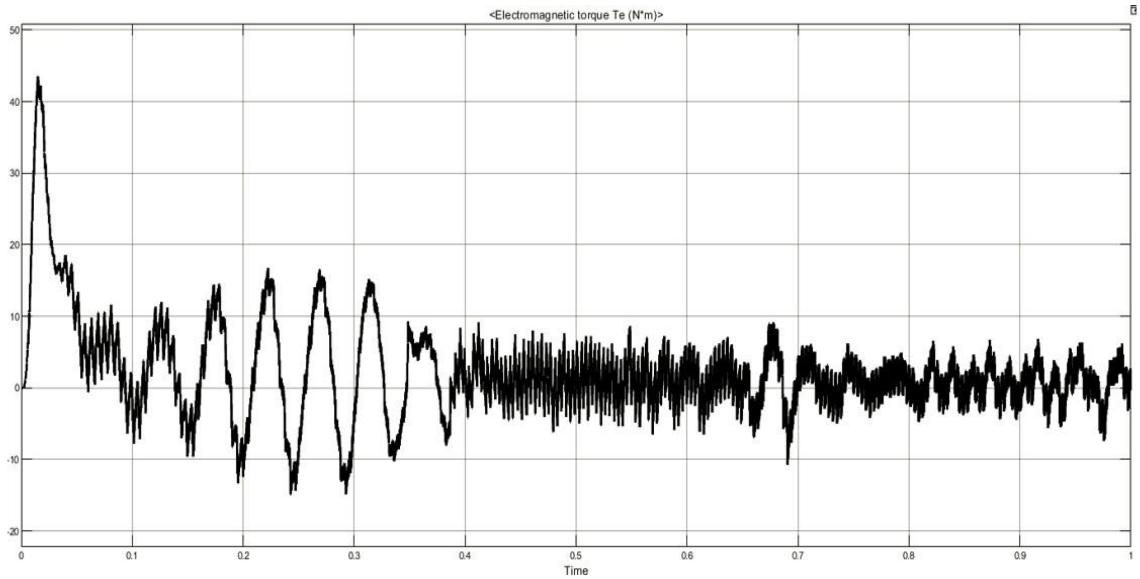


Fig. 3.7 Electromagnetic Torque Waveform for IM with VVVF Closed-loop System

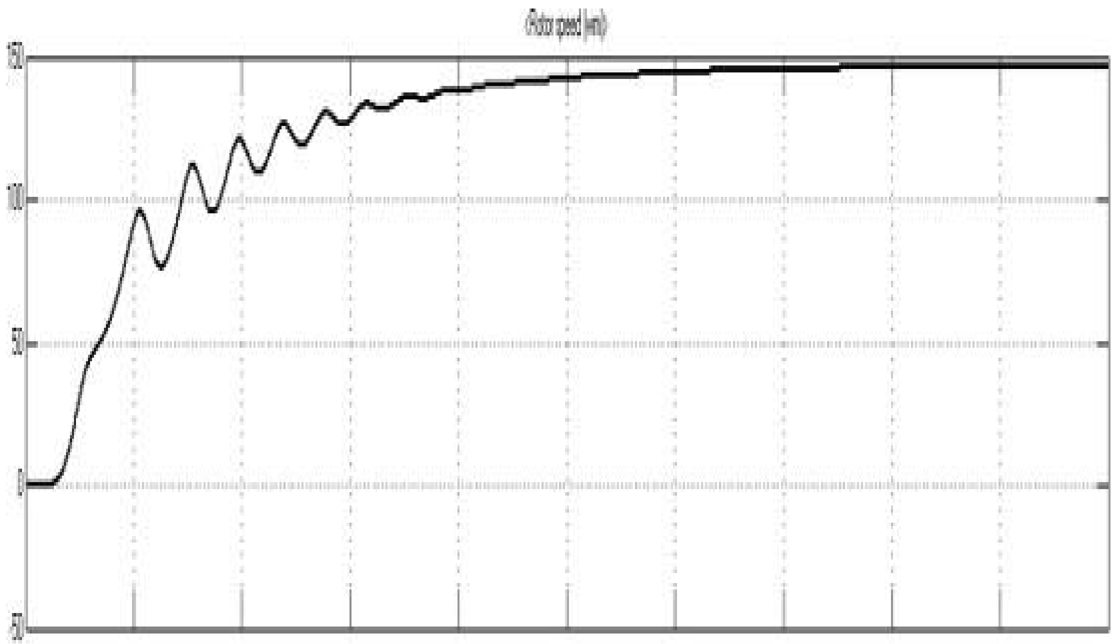


Fig. 3.8 Rotor Speed Waveform for IM with VVVF Closed-loop System

IV. Plant Flow Pattern

The flow pattern diagram outlines the water intake system and the stages which raw water after being pumped from the dam (off-river reservoir) goes through during the treatment process before finally deposited into the clear water reservoir, ready to be pump at the pumping station for distribution.

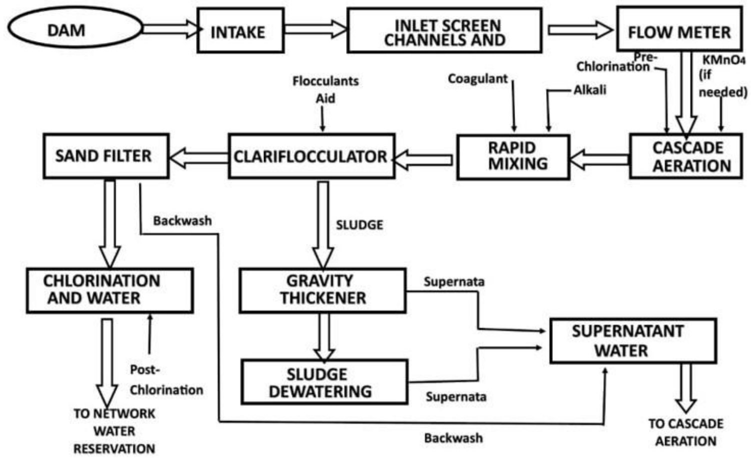


Fig. 4.1 Schematic Diagram of Akim Oda Water Treatment Plant (WTP) Hydraulic Flow

Fig 4.2 Flowmeter Chamber (low-lift section)

The flowmeter chamber is located between the off-river reservoir and the cascade aerator. This section also known as low-lift section provides a means for untreated water to be pumped from the dam into the cascade aerator after it has gone through the screening process. The process is carried out with the help of five induction motors which are being aligned vertically with their pumps and their speed being controlled by variable frequency drives.

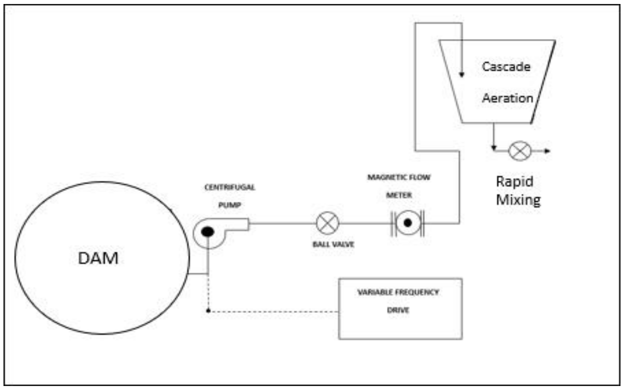


Fig. 4.3 Schematic Diagram of the Low-lift Section of Plant

Fig 4.4 Picture of the Five VFD at the Low-lift Section of the Plant

V. Pump

The pump used here is a centrifugal pump connected to an induction Motor as a driver. Centrifugal pumps are commonly used to transport fluids by converting rotational kinetic energy into hydrodynamic energy with the fluid flow. The rotational kinetic energy is provided by an induction motor.

The fluid enters the pump impeller near or along the rotating axis and its speed is increased by the impeller in the axial direction, parallel to the rotating shaft. The liquid flows in the outward radial direction into a volute chamber from where it comes out.

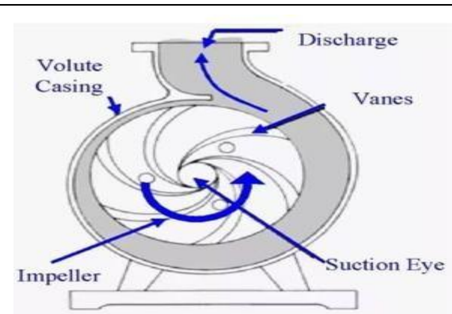


Fig. 5.1 Liquid Flow Inside a Centrifugal Pump

Working of Pump

In pumping applications, several pumps are most often connected in parallel to produce the required flow which is the case at the Akim Oda treatment plant, where at both the low-lift and high-lift five pumps are connected in parallel for their upstream water pumping operations. This is done so that two or more pumps could be operated in parallel at a reduced speed rather than cycling the pumps on/off by using one pump at a time according to the demand, research by Anibal (2005) has shown that this system can save significant amount of energy and also optimise pumps operation, diagram is as shown in fig. 5.2 below.

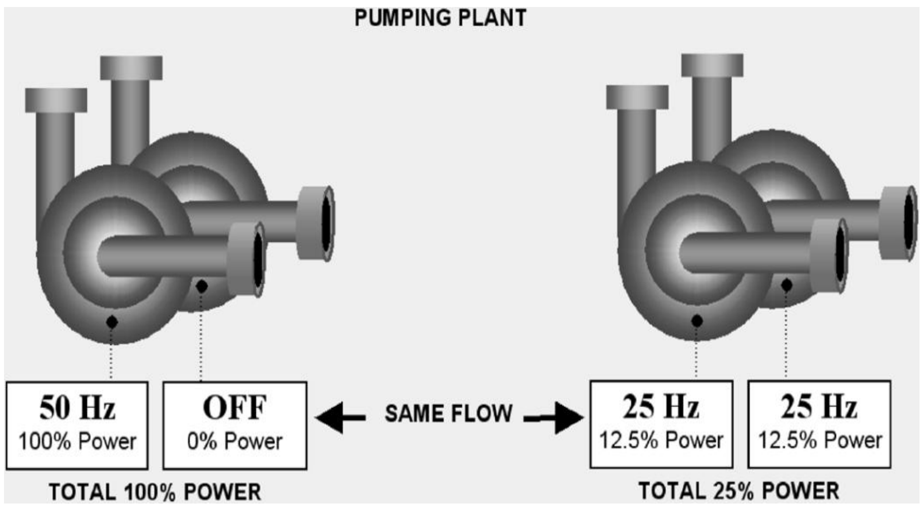


Fig. 5.2 Pumping Plant Using Relationship to Consider with Close loop Circuiting Independent System Where Head is not a Major Factor

Fig. 5.2. shows two low static head pump system, with independent piping circuits, operating both pumps at 50% of the rated flow requires approximately 25% of the power required for a single pump operating at 100%. This allows pumps to stay warm with no condensation in the winding, with seals staying wet and alive, it also eliminates high-shock starts on the system. This system can also possibly control the water-hammer effect, which can degrade the pipes by controlling acceleration using VFD. Speed control of an induction motor is achieved from various tests performed with its protection done by implementing its software and hardware. Programmable logic controller (PLC) provides good accuracy when used with inverter for tests on induction motor for speed regulation compared to the conventional V/F control method. It provides better efficiency and allows two or more pumps to be connected in parallel in practical pumping application as shown in fig. 5.3 below, especially when a large quantity of water is required to be pumped against a relatively small head. In such cases two or more pumps are used which are so arranged that each of these pumps working separately lifts the water from a common sump and delivers it to a common collecting pipe through which it is carried to the required height Fig. 5.3. If $Q_1, Q_2, Q_3 \ldots Qn$ are the discharging capacities of n pumps arranged in parallel the total discharged delivered by these pumps will be $Q_t = (Q_1 + Q_2 + Q_3 \ldots Qn)$. With the discharge capacity of each of the n pumps being same, equal to Q then the total discharge delivered will be $Q_t = nQ$.

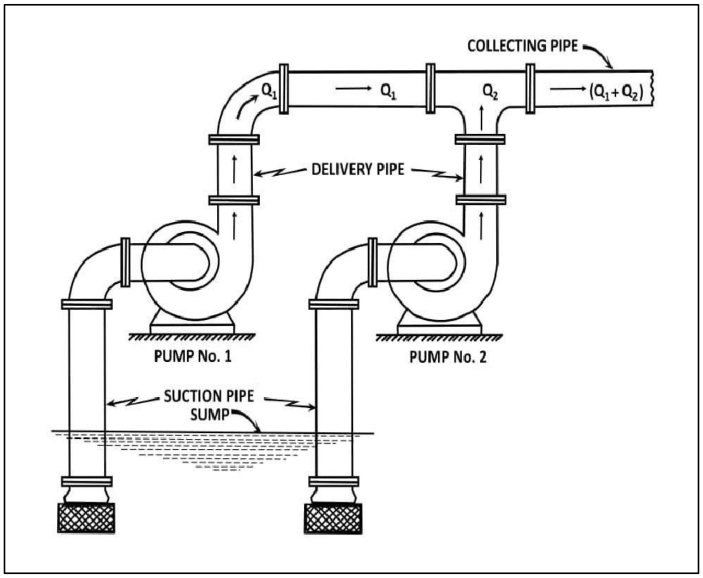


Fig. 5.3 Two centrifugal pumps arranged in parallel

VI. Case Study for Induction Motor Performance Evaluation with Open-loop and Closed-loop Speed Control Using VFD

A) Speed variation by changing the supply frequency

Supply Frequency Control or v/f Control
The synchronous speed is given by,

$N_s = 120f/p$

N_s = synchronous speed
F = supply frequency
P = no. of pole

Table 6.1. Observation of V/f Control

VOLTAGE(V)	FREQUENCY(Hz)	SPEED (rpm)
375	42	1260
339	40	1200
320	38	1140
299	36	1080
280	34	1020
260	32	960
245	30	900

Thus, by controlling the supply frequency smoothly, the synchronous speed can be controlled over a wide range. This gives smooth speed control of an induction motor.

The expression for the air gap flux is given by,

$\Phi_g = \quad 1 \quad ( )$

$$\overline{4.44k_1T_{ph1}} \quad \overline{f}$$

This is according to the e.m.f equation of a transformer where,

K_1 = Stator winding constant
T_{ph1} = Stator turns per phase
V = Supply voltage
F = Supply frequency
Φ_g = Magnetic flux

It can be seen from the above expression that if the supply frequency f is changed, the value of air gap flux also gets affected. This may result into saturation of stator and rotor cores. A phenomenal which leads to the sharp increase in the (magnetisation) no load current of the motor. It is therefore necessary to maintain air gap flux constant when supply frequency f is changed. To achieve this, it can be seen from the above expression that along with f, v also must be changed so as to keep (v/f) ratio constant.

B) Comparison of power consumption for closed and open loop speed control

Table 6.2. Reading of power consumption with closed-loop and open-loop speed control with VFD

PROCESS	3 phase IM with close-loop speed control using VFD	3 phase IM with open-loop speed control using VFD
VOLTAGE	200	375
CURRENT(A)	120	190
SPEED(RPM)	1084	1260
POWER FACTOR	0.95	0.94
POWER CONSUMED(Kw)	78,979.2	116,000.7

VII. Evaluating Power Consumption and Cost of Operating with Closed-Loop and Open-loop Speed Control Using VFD

This section deals with the analysis by comparison between energy consumption, and their cost of operation within a period of time, with closed and open loop speed control using VFD. The water pumping is done for 20 days within the month, energy consumed and cost of operation for one month with closed and open loop speed control using VFD is shown in Table 7.1 below.

Table 7.1 Observation and calculation of energy consumption

SN. NO	PARAMETER	SPEED CONTROL WITH CLOSED-LOOP	SPEED CONTROL WITH OPEN-LOOP
1	Number of pumps	2	1
2	Energy consumption per day(kWh)	631833.6	928005.6
3	Energy consumption per month (kWh)	12636672	18560112
4	Amount per month (Gh cedis)	23049289.72	33853644.28

Fig. 7.1 represent the percentage of energy consumed in their operations per month for closed-loop and open-loop speed control with VFD.

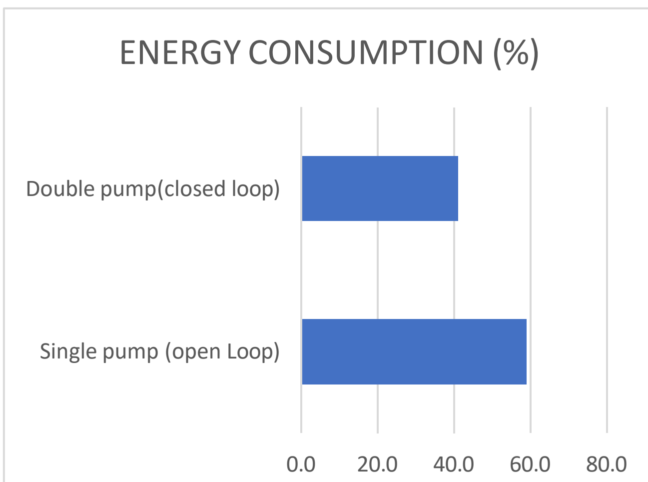


Fig. 7.1 Percentage of Energy Consumption per Month for Closed-loop and Open-loop Speed Control with VFD

Fig. 7.2 represent the cost of power consumption for their operation per month for closed-loop and open-loop speed control with VFD.

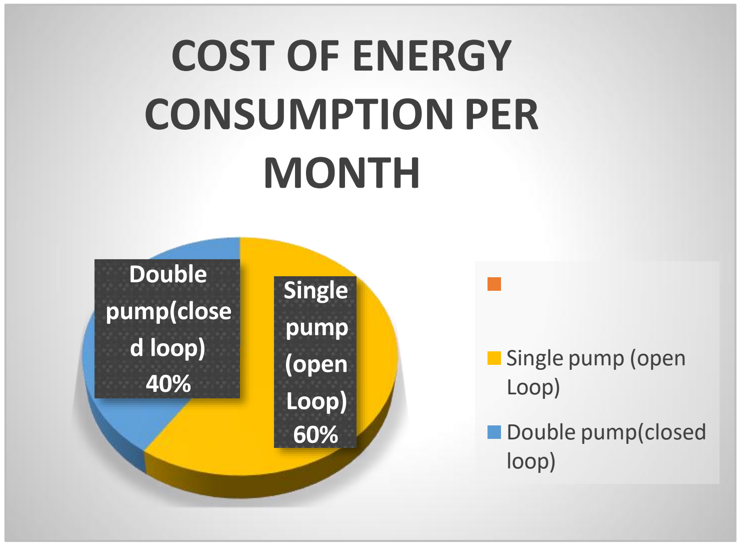


Fig. 7.2 Cost of Energy Consumption per Month

III. Conclusion

This study has given the opportunity to assess and evaluate how VFDs can optimise the efficiency, save energy and reduce costs of operation at the Akim Oda water treatment plant. In motor life cycle, pump cost is 10% and energy consumption 90%, also according to green energy savings the amount of work or load on a motor is equal to amount of energy to power the work. VFD is a very cost-effective technology that can lead to better process control, so motor consume less power. The experimental results show that energy consumption per month for operating the plant with closed-loop and open-loop speed control with VFD are 41% and 59%, respectively. To evaluate the plant operation, MATLAB/Simulink was also used to simulate the system to observe the motor speed considering using closed-loop and open-loop speed control. The result shows that for high-precision with significant load variations, closed-loop control offers superior performance. Hence per the experimental and simulation results observation, it can be concluded that increasing the number of pumps for their operations optimise the plants performance by enhancing its efficiency and also save energy.

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