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ENERGY SAVING OF WASTEWATER PUMPING USING PROPOSED INTEGRATED DRIVE SYSTEMS

Israa Amer Dahham,

College of Engineering, University of Al-Qadisiyah, Ad Diwaniyah, Iraq.

E- mail: israa_amer2013@yahoo.com

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Abstract: *An integrated drive arrangement for a wastewater pumping system was designed and modeled to evaluate the energy saving gained from matching motors with Variable Frequency Drive (VFD) and Programmable Logic Controller (PLC). The proposed arrangement utilizes the affinity laws of centrifugal pumps to predict the performance of a pump under different rotational speed conditions. The specific energy (Es) is used as a measure of the cost effectiveness of the proposed pumping system.*

Results have shown that a reduction of 10% in pump speed can save 30% in energy of maximum speed. The energy saving potential is carried out for a real-life case study, and a conclusion to replace on-off controllers currently used for most wastewater pumping systems is necessary. The total energy saving account for more than 50% when integrated drive system was applied for a combined sewer pump station.

Keywords: Variable Frequency Drive (VFD), wastewater pumping systems, integrated drive systems, energy saving, Programmable Logic Control (PLC).

INTRODUCTION

Energy consumption of pumping systems dominates the life cycle cost of wastewater pumps. It may be as high as (35-40%) of the life cycle cost. Pumping systems are considered a major consumer of electricity. Pump motors receive electrical power (pump power input) and transform it into mechanical work (rotational energy). The rotational energy delivers liquids to higher head (pump power output). Many flow control solutions of pumping systems have been reported in the literature. The purpose of the reported solutions is to ensure pump's operational reliability and to save energy and operational expenses.

Conventional wastewater pump's motors operate at constant speed to deliver fixed and predefined flow rate. Their running speed cannot be adjusted to save power[1]. Recently, many technologies have been developed to adjust the running speed of induction motors and a noticeable reduction in energy consumption has been proven[2]. Therefore, variable frequency drives are increasingly used for speed control to reduce pump power input[3]. High efficient motors not only save energy, but also, enhance the operation, reduce the maintenance, and improve the life cycle of the motors[4]. High efficient motor drives are engineered to adapt the flow rate and thereby save power at higher percentage[5].

In European Union, pumps consume 160 billion KWh per annum of electricity[6]. Pumps are available in various sizes (1 KW to hundreds KWs) to satisfy different applications of industry. The most efficient

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control system to save energy is speed control. However, using variable speed control in wastewater pumping systems may cause significant fluctuations in the rotational speed of the pumping system, due to the large variations of the influent flow rate. The fluctuations become very complicated when combined sewer pumping system is considered, as the storm water (wet weather conditions) causes high flow rates (2-3 times of sewage peak flow rate) and consequently the nominal rotational speed of the drive becomes very high. It is not recommended to reduce the rotational speed more than 50% of the nominal speed. If the reduction of speed exceeds the recommended limit (50%), drive losses become very considerable. The following equation estimates the drive losses[7].

Pdriveloss = 0.35 Pdrivelossnom + 0.1 ( ) Pdrivelossnom + 0.55 ( ) Pdrivelossnom …….(1)

Where Pdriveloss is the drive losses under reduced frequency and Pdrivelossnom is the drive losses under normal operational frequency. T and Tnom are working and normal temperatures respectively and f, fnom are reduced and normal frequencies respectively. The factors; 0.35, 0.1, and 0.55 are empirically determined. The losses associated with the use of variable speed control in wastewater pumping systems and the wide range of fluctuations in rotational speed are considered to be the major drawbacks of the VFD system. Therefore, the focus of this study is to integrate a PLC controller to the VFD to ensure smooth frequency variations when fed to the induction motor, and to avoid the effect of the wide fluctuations in rotational speed of the motor.

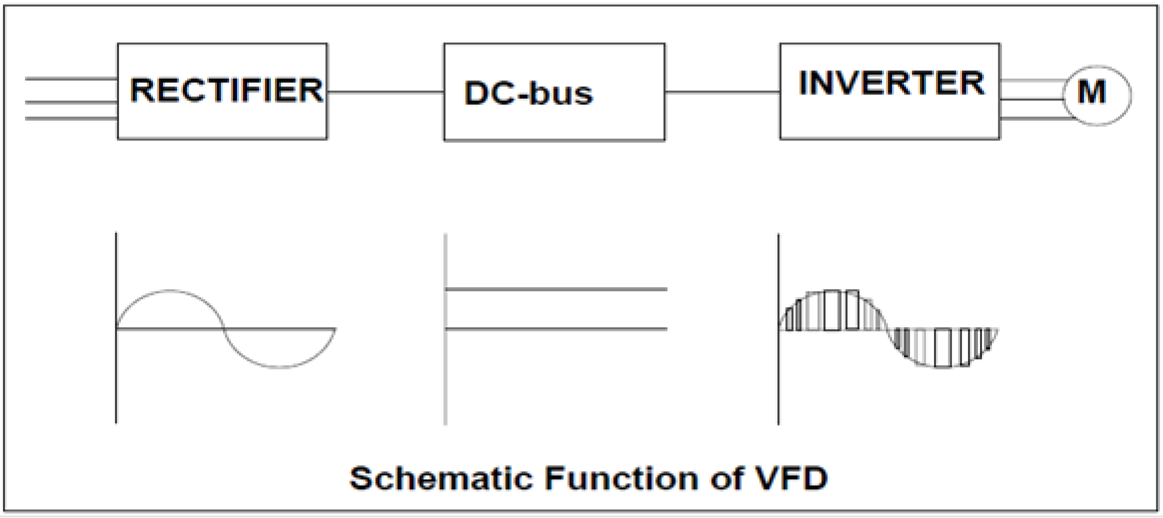
1. VARIABLE SPEED DRIVE

Basically VFD systems transform line frequency into variable frequency in two steps.

1. Rectify the sine voltage (Vac) to DC voltage (Vdc).

2. Chopping the DC voltage into small pulses (recreate AC voltage with desired frequency).

A VFD consists of three main parts; Rectifier, DC-bus, and Inverter as shown in **Figure (1)**. The first part (rectifier) is responsible for converting the supplied (Vac) into DC voltage (Vdc). The DC-bus part will function as a power reservoir where capacitors store energy and to eliminate ripples generated. Then, inverter draws



power from DC-bus and recreates (Vac) with new (desired) frequency.

Figure 1: VFD schematic diagram [Typical]

The output from the VDF system is fed to a motor that drives a pump. The motor will rotate

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proportionally to the supplied frequency according to the following formula:

N=120f/p ……………………………………… (2)

Where N is the motor rotation speed (rpm), f is the supplied frequency, and p is the number of poles of motor's winding. A typical frequency converter circuit diagram is shown in **Figure (2)** .

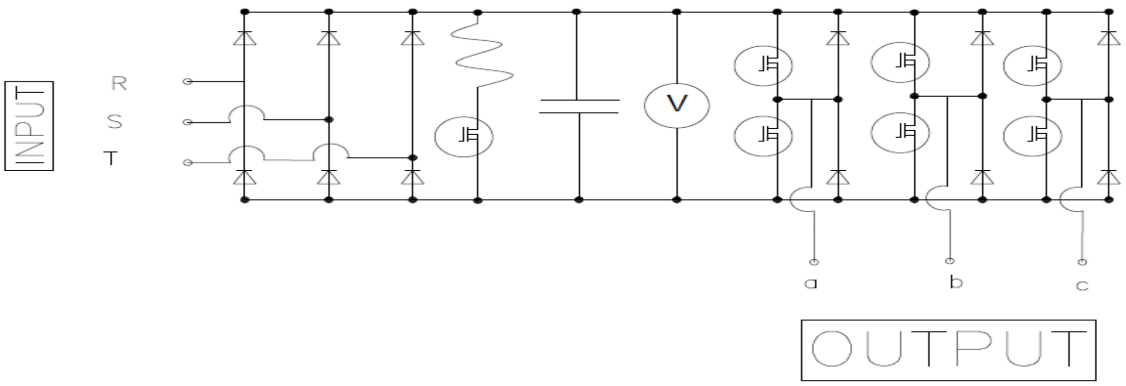

Figure 2: wiring diagram of a typical VFD [Ref: Roba A. Y., Technical and financial analysis of using variable frequency drive for water pumps compared with fixed frequency, MSc thesis, 2014]

The inverter part of the VFD system creates voltages of controllable frequency and magnitude. The output voltage of the inverter can be modeled as[8]:

Vsa=3/π Van-1/3(Vbn+Vcn) …………………………………………… (3)

Vsb=3/πVbn-1/3(Vbn+Vcn) …………………………………………… (4)

Vsc=3/π Vcn-1/3(Vbn+Vcn) ………………………………………… (5)

Where;

V_{aN}, V_{bN}, V_{cN} : amplitudes of inverter output voltages.

V_{sa}, V_{sb}, V_{sc} : Instantaneous inverter output voltages

When a motor is connected to a VFD, a chopped square voltage will be supplied, and harmonics are expected to be experienced. As these harmonics induce additional heat losses, induction motor needs to be de-rated, a margin between maximum output power and nominal-rated output power is required[9]. However, an excited range of frequencies will be experienced and a probability of exciting one of the system's natural frequencies will be raised leading to vibrations and noise. Therefore, if one of the natural frequencies of a motor is within the duty range of the VFD, this frequency needs to be blocked to avoid probable vibration and noise. A PLC was connected to monitor and control a VFD controlled pumping system. This PLC-VFD integrated system is aimed to overcome overheating and noise problems associated with using VFDs to control induction motors. However, PLC-VFD integrated systems have been approached by many researchers to enhance the performance of controlled induction motors. A hybrid method was proposed by Takiyar[10] to control induction motors. Khan[11] demonstrated energy and cost saving in pulp and paper industry. Verma[12] used voltage to frequency ratio (V/Hz) supervised by a PLC controller to control single phase induction motors. Ahir[13] used Supervisory Control and Data Acquisition (SCADA-VFD) system to control 3-phase induction motor. Most accomplished research focuses on induction motor's protection considerations. This work aims to functionally integrate operating system (pumping system), VFD-IM (IM: induction motor) start and speed control mechanism, and PLC controller to enhance both the pumping and the VFD performances.

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2. PUMPING SYSTEM DESCRIPTION AND ANALYSIS

Wastewater pumping system usually consists of pumps, piping, and valves components. Pumps are the main component of the system and the most energy consuming parts in wastewater conveyance and treatment systems. Pumps generates pressure that is necessary to lift liquids from a low to high levels and to overcome friction resistances of piping and valves. The most used pumps in wastewater sector are centrifugal pumps. The selection of a pump depends on both process requirements (system characteristics) and pump specifications (pump characteristics). Both system and pump characteristics are shown in **Figure (3)**. The best operating conditions of the system is the intersection point between the pump and system curves. It is called the Best Efficiency Point (BEP). Working below the BEP may cause cavitations (air bubbles) and working above it may cause high temperature rise (overheating).

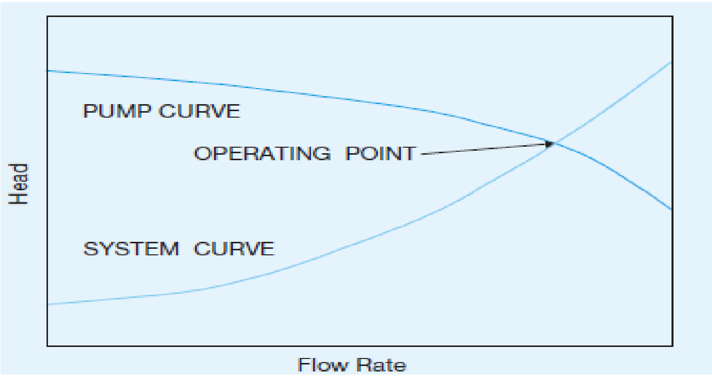

Figure 3: system and centrifugal pump curves [Ref. Variable speed pumping, A guide to successful applications, US DOE, Industrial technologies program]

However, the BEP imposes constant flow rate and speed of pump. Wastewater pumping system is a supply-controlled system that is designed to pump influent wastewater continuously. Influent wastewaters are time-dependent flows (duration profile) as shown in **Figure (4)** .

Pumps are normally selected and sized to accommodate the highest flow rate. It is seen from figure (4) that only small percentage of time of the day, wastewater influent runs at maximum flow rate. Therefore, pump drive motor is needed to operate at its maximum speed for only small percentage of the time of the day. However, conventional wastewater pump's motors operate at constant speed to deliver fixed and predefined flow rate, and usually on-off control system based on predefined low and high levels is applied in most wastewater pumping systems. **Figure (5)** shows a pump station of a 46000 population city to be considered as a case study for energy saving scenario using integrated PLC-VFD control system instead of the on-off control system. The on-off control system is recognized to consume energy much more than needed and operate at a frequent start-stop operation. The start-stop operation system normally causes additional loads on the power components and increases the temperature rise of the motor (overheating).

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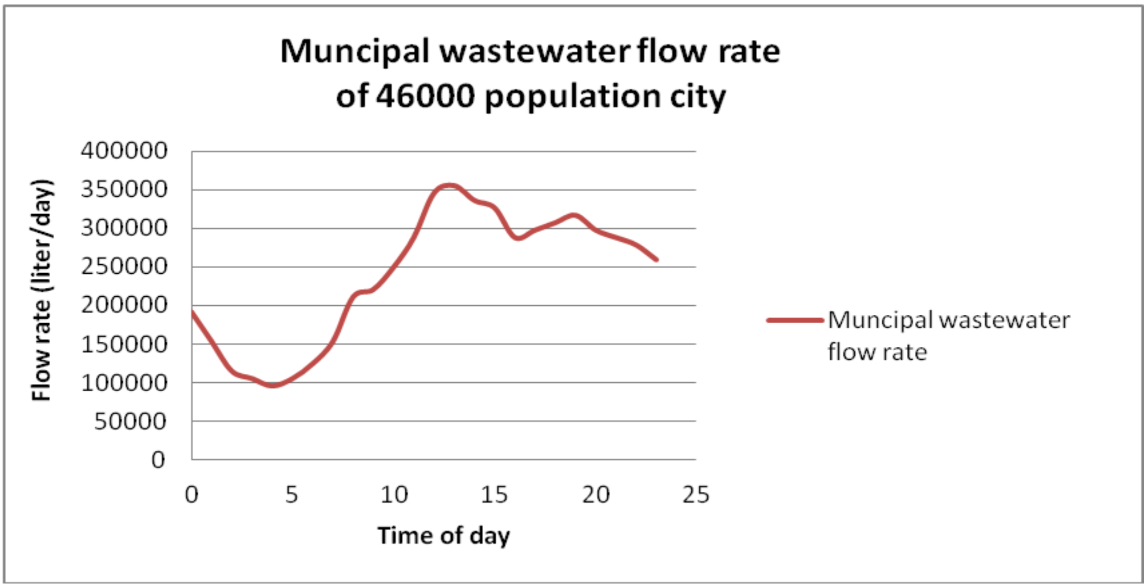

Figure 4: typical muncipal wastewater flow rate of 46000 population city during 24 hrs [Author's estimation based on GDS guidelines].

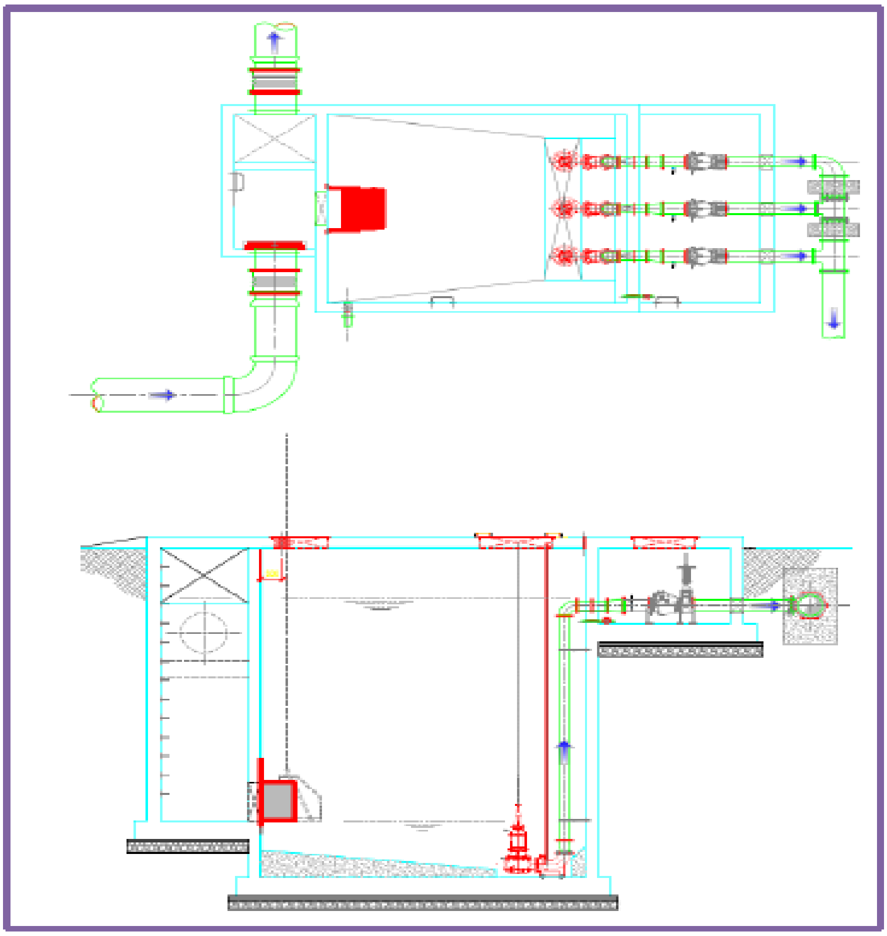

Figure 5: a wastewater lifting pump station for 46000 population city [Typical]

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The pumping station was originally designed to receive combined sewer (sewage and storm water influents). The duration profile of the combined sewer influents is shown in **Figure (6).** The storm water influent (wet weather conditions) is three times the maximum sewage influent flow rate (dry weather conditions). Therefore, the designed flow rate of pumps is based on the maximum wet weather conditions flow rate. During the dry weather conditions pumping, pumps become oversized and the frequency of the start-stop operation will be very high, resulting in an excessive loads and overheating.

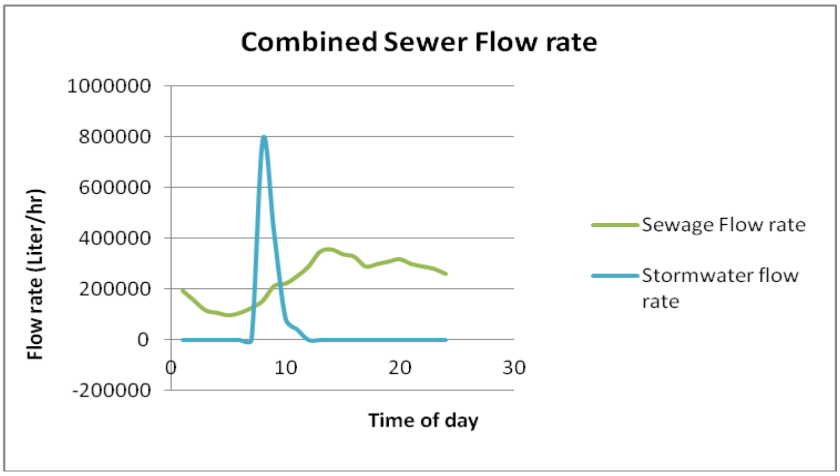

Figure 6: combined sewer flow rate of a 46000 population city [Author's estimation based on GDS guidelines].

The on-off control system becomes unfavorable in wastewater pumping systems and a trend towards using motor's speed control system is expanding. The speed control system not only save energy, but also enhance performance and life cycle of the motor[4]. Energy saving was economically evaluated using the specific energy concept. The specific energy (Es) is a measure of how much energy consumed per a unit of volumetric flow rate. It is expressed as;

$$Es = Pi/Q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Where, Pi is the input power and Q is the volumetric flow rate.

Therefore, Es is constant when on-off control system is used and variable when speed control is used. The difference between the Es of the two control solutions represents the energy saving per volumetric flow rate. The total saving per day is simply the product of Es difference (Es,VFD -Es,on-off) and the daily volumetric flow rate.

$$Es,T = (Es,VFD - Es,on\text{-}off) \times Q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

3. PLC-VFD SYSTEM MODELING

The integrated PLC-VFD control system for a combined sewer pumping station is shown in **Figures (7,8,9) .** The VFD start-control system of the three pumps is shown in **Figure (7)** .

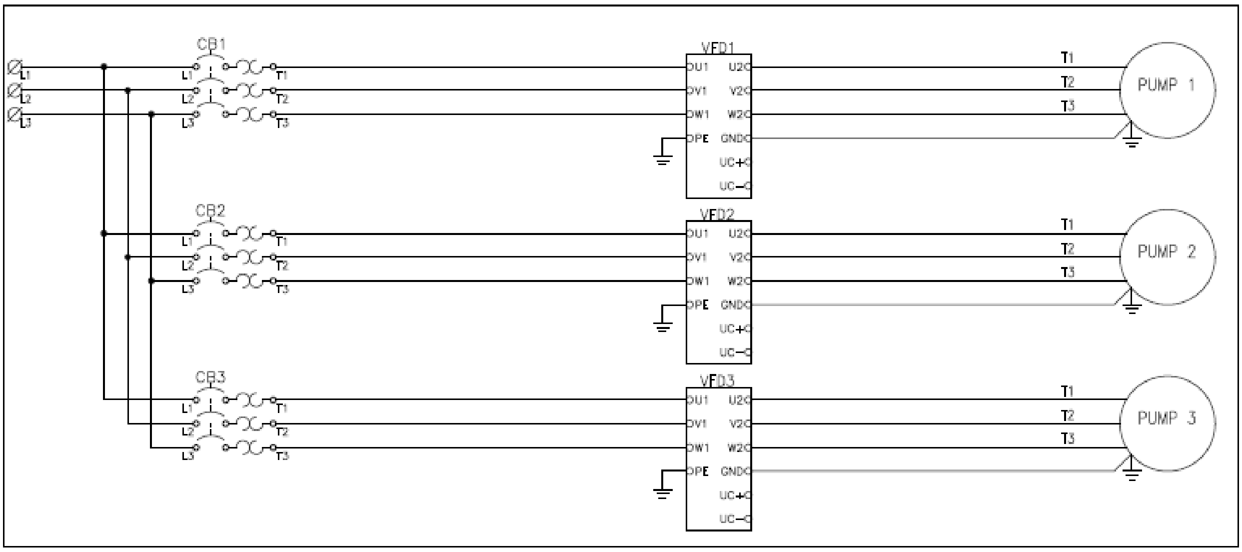

Figure 7: VFD start-control of 3 wastewater pumps arrangement

The VFD start-control arrangement eliminates the Direct-on-Line (DOL) connection disadvantages (high starting current) and ensures smooth start of the pumps. It is also used as speed controller for the drives of the three pumps. The VFDs connection to pumps is shown in **Figure (8)**.

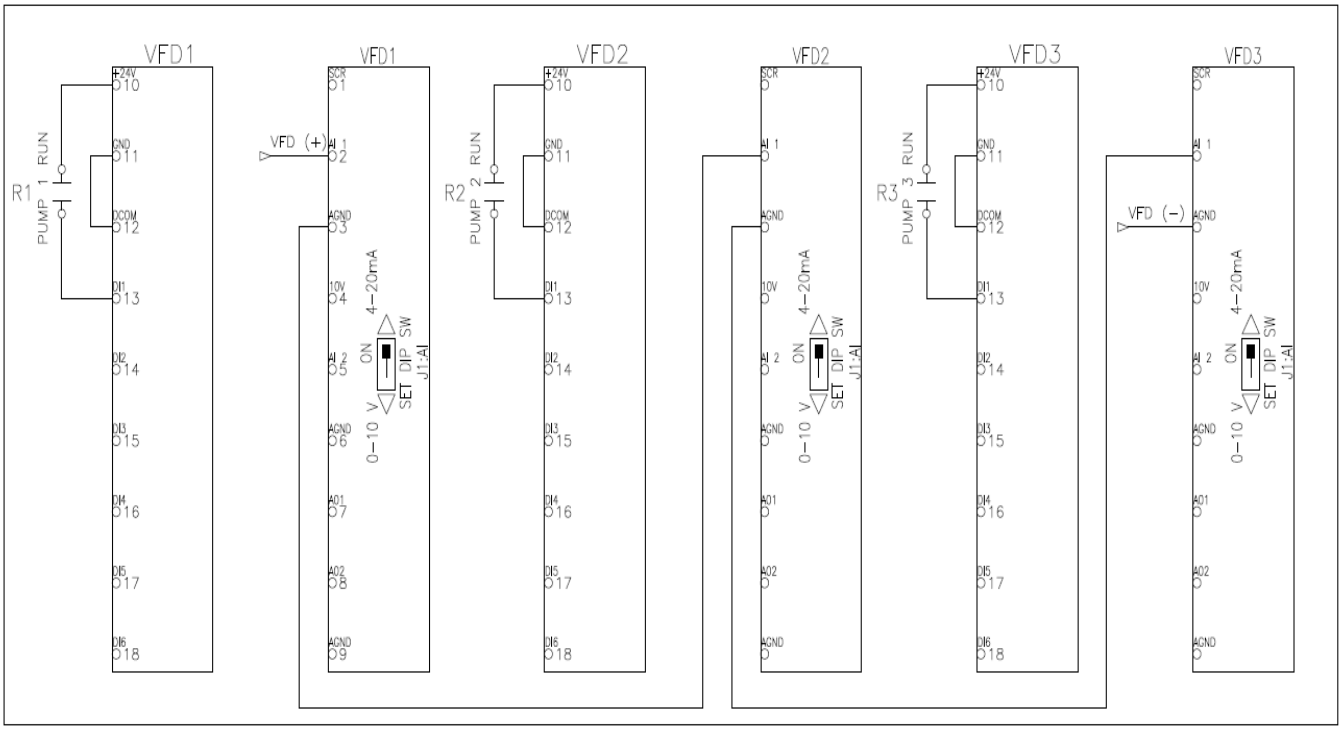

Figure 8: VFD – pumps connection diagram

The PLC control system is used to monitor both pumping and VFDs performance and send control signals to motor drives through an (I/O) module, as shown in **Figure (9)** .

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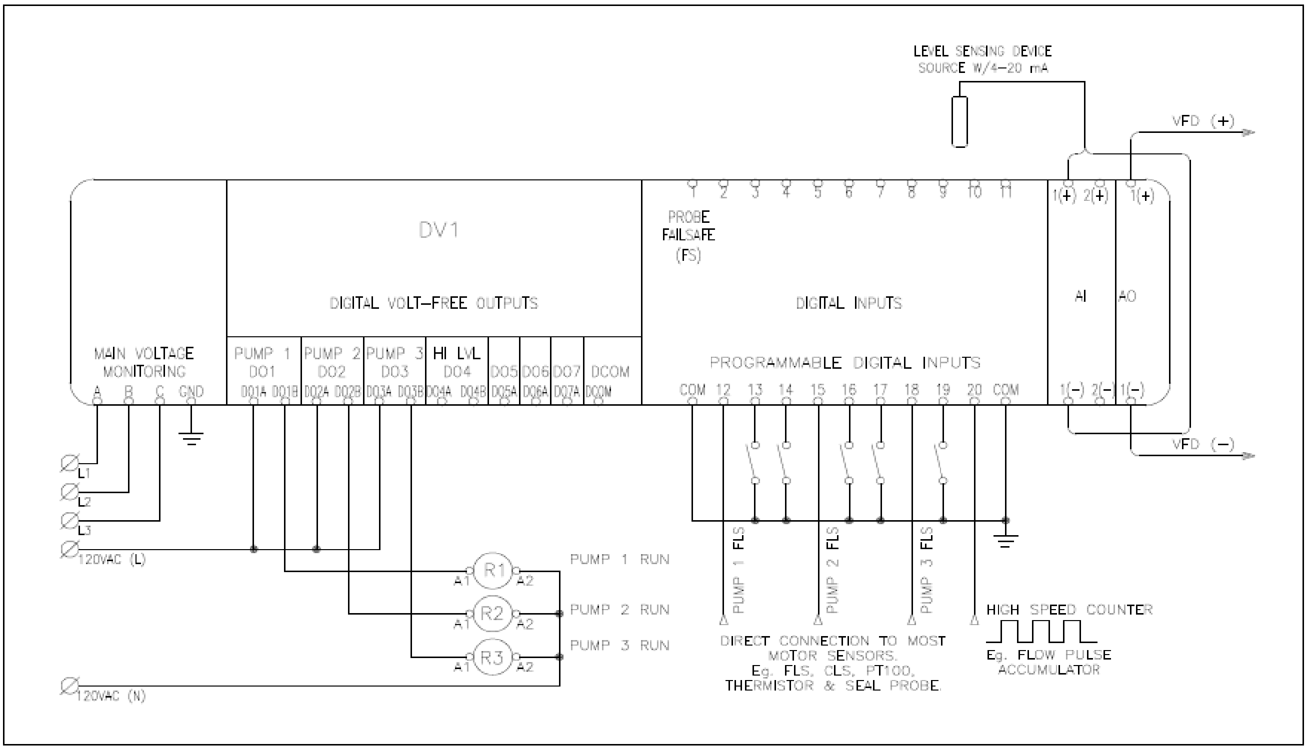

Figure 9: PLC connection diagram

The PLC consists of five main parts; digital input module, digital output module, voltage monitoring input, VFDs connection and process monitoring (flow meter). The VFDs connection and process monitoring part is responsible for acquiring real-time data of motor drives speed and wastewater flow rates. A stored program within the PLC relates wastewater flow rate to motor drive speed based on affinity laws and calculates the corresponding speed of the drive. An output signal will be generated and sent to the drives to match the running speed of the motors with the incoming flow rates.

4. RESULTS AND DISCUSSIONS

Figure (10) shows the wet and dry weather flow rates of a 46000 population city pumping station. The designed flow rates of wet and dry weather conditions are also demonstrated. As the pumping station was designed for a combined sewer practice, the designed pumping flow rate was based on the combined flow rate. The short period of the rainy season in Iraq makes the pumps operate at an oversized conditions for the whole of the year. It is clearly seen that the designed flow rate is twice of the maximum dry weather conditions flow rate and approximately three times the average dry weather conditions flow rates. Therefore, separate sewer system was proposed and power consumption calculations were carried out for a sewage sewer pumping system.

The power consumed was simulated using affinity laws and shown in **Figure (11)** . It is seen that actual power required for pumping is variable and the designed power available for pumping is constant. As the power available for driving the motors is constant and in excess, the pumping becomes intermittent and start-stop profile will be obtained as shown in **Figure (12)** .

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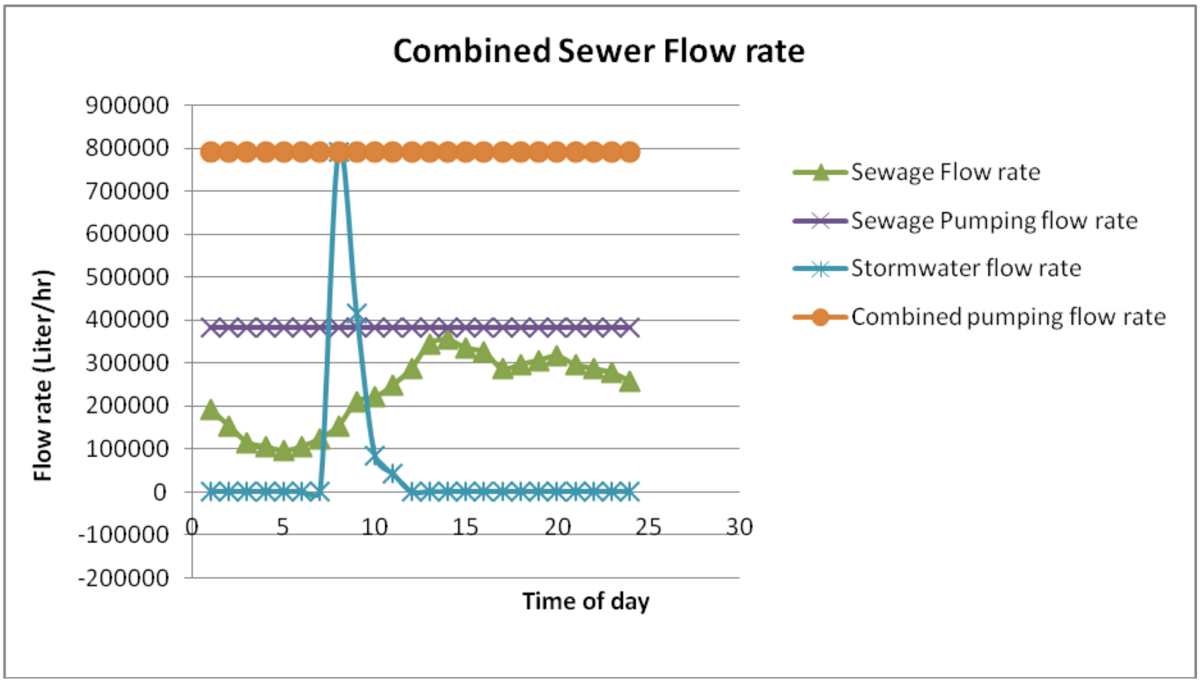

Figure 10: combined sewer flow profiles

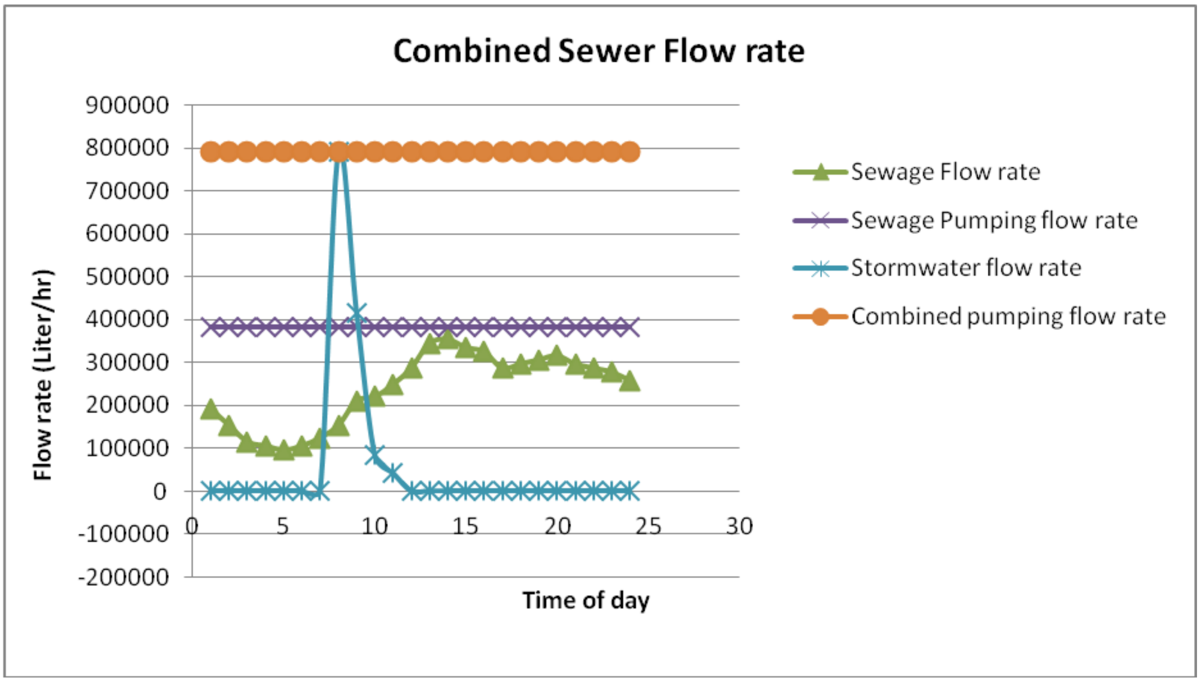

Figure 11: power consumption profiles

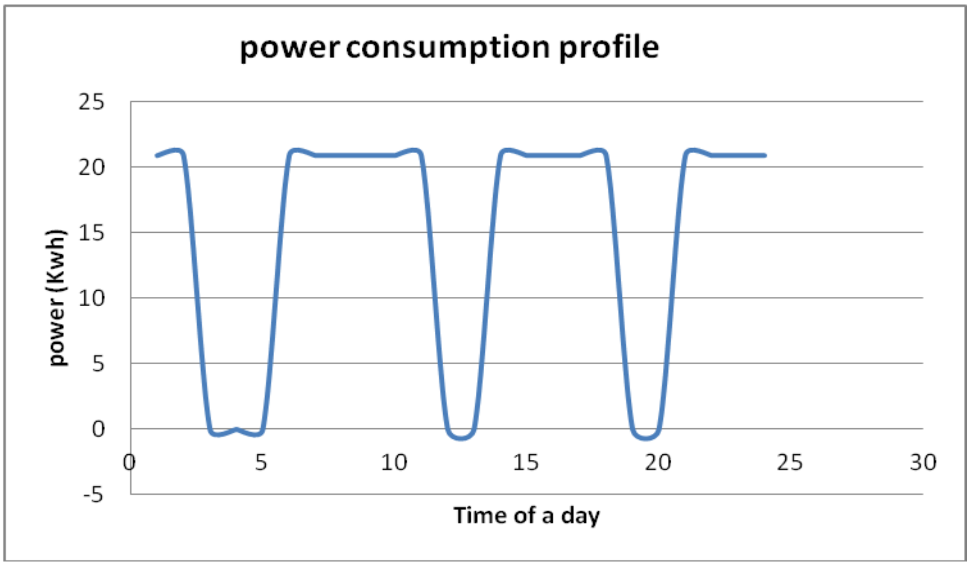

Figure 12: power consumption under intermittent conditions

A comparison between designed power and actual required power is shown in **Figure (13)**.

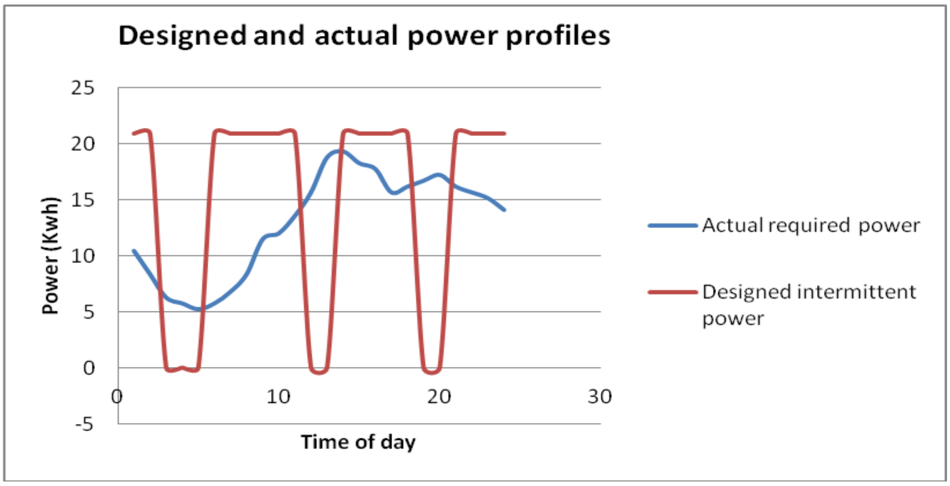

Figure 13: designed and actual power profiles

The total power consumed per a day was calculated from the area under the curves. The area under the actual power required to run the motor drive is (298.4673 KWd) and the area under the designed power profile is (501.3624 KWd). If intermittent operation scenario is considered, the area under the designed power curve becomes (355.1317 KWd). However, start-stop operation imposes an additional consumed power due to high starting currents. The additional power was estimated from the motor specifications and it was found (60 KWd), resulting in a total power consumption of (415.1317 KWd). Therefore the difference between the designed and actual powers is (116.6644 KWd). It contributes to 39% additional power to be saved using VFD control. **Figure (14)** demonstrates the required frequency to run the motor drive of pumps at a speed proportional to actual flow rates.

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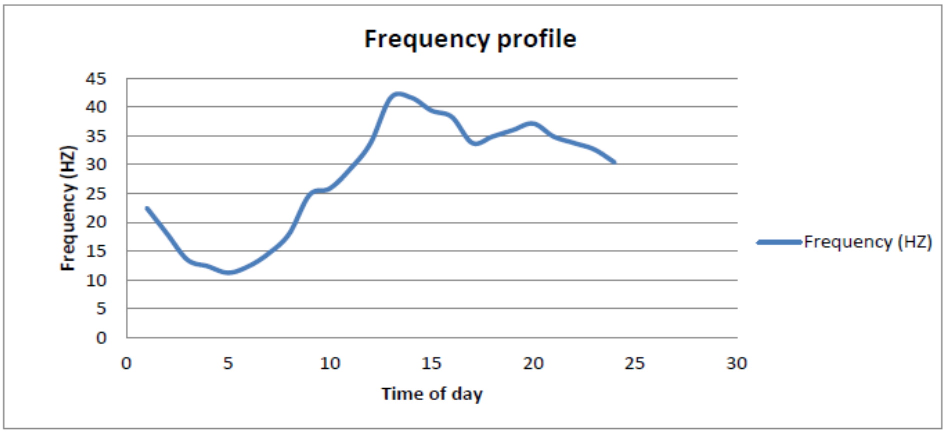

Figure 14: estimated frequency profile

The frequency profile was translated into RPM of motor drive and shown in **Figure (15)** .

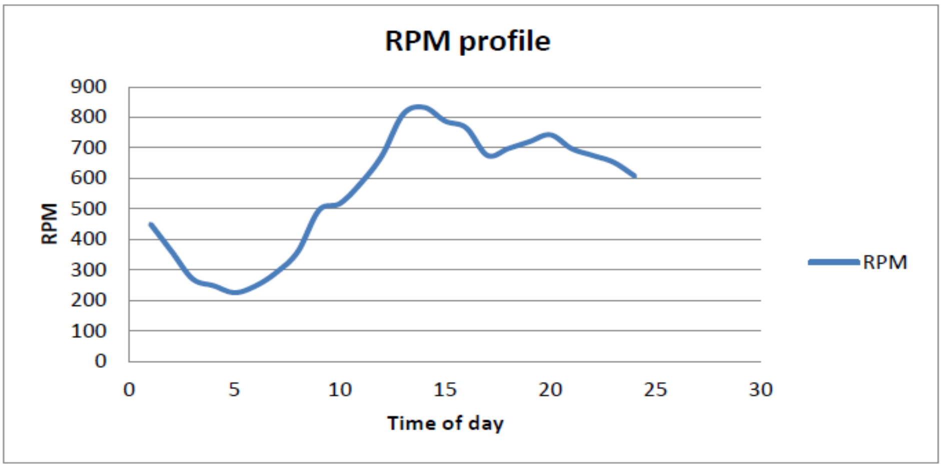

Figure 15: RPM profile of motor drive proportional to actual flow rate.

As shown if **Figures (14,15)** , frequency and RPM profiles suffer frequent fluctuations and practically very difficult to obtain. Therefore, a discretization of the frequency was applied using the PLC control system to operate the motor drive at stepped profile as shown in **Figure (16)**. A minimum frequency of (25 HZ) was assumed to avoid overheating and noise of drivers.

It is clearly seen from **Figure (16)** that the frequency was controlled using a PLC controller and applied in four ranges during a day. This ensures that the motor drives will operate at four constant RPMs during a day, and avoid sudden and frequent fluctuations. This results in 30% energy saving and consequently the cost of operation.

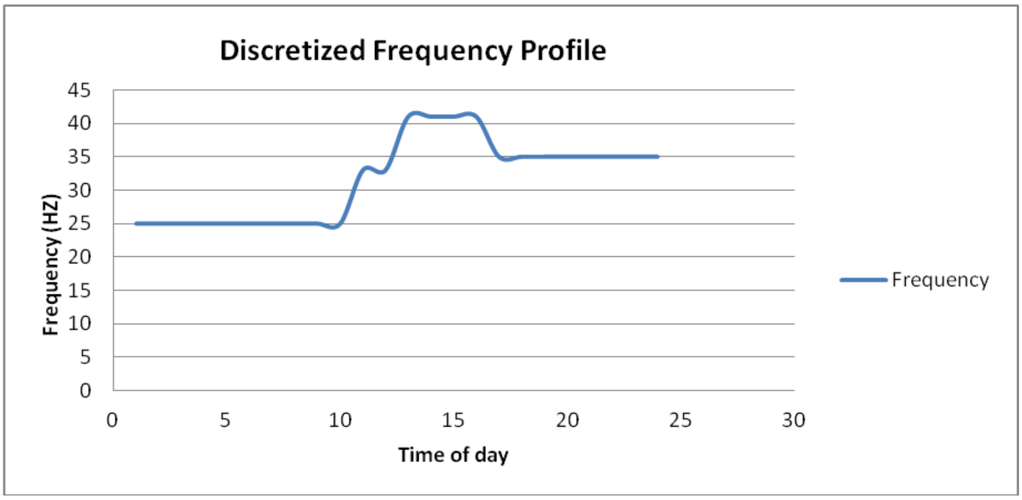

Figure 16: discretized frequency profile

CONCLUSIONS

A VFD-PLC integrated system was successfully implemented to control wastewater pumping system. The applied control system has demonstrated a considerable energy saving due to balanced rotor drive rotation speed. The VFD part is effectively control the drive rotation and the PLC part monitors both process and voltage. Drive's rotation speed was successfully related to actual flow rate of influent wastewater using affinity laws. The frequency profile was controlled using a PLC controller and discretized into four distinctive and smooth ranges to avoid frequent fluctuations of the frequency and consequently keep the vibration of the motor drive to minimum.

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