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Modeling and Simulation of Energy Efficiency Improvement for Water Level Control

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Abstract: *In this paper, energy efficiency improvement process for water level control with variable frequency induction motor drive will be presented. The primary benefit of a variable frequency drive (VFD) is that it allows motors to operate at reduced speeds, and thus at a lower power, without a loss of torque. The VFDs also allow for efficient operation over the entire life of the motor. The technical considerations of using a VFD are presented in this paper, along with a method for choosing and modeling a variable speed to achieve maximum energy efficiency improvements. For variable frequency induction motor drive, the proportional-integral-derivative (PID) controller will be applied. For sense of water level, the proximity sensor will be employed. This system is mainly utilized in water treatment system and purified drinking water production process. The modeling and simulation will be carried out using Matlab/Simulink software.*

Key Words: *Variable frequency drive, energy efficiency improvement, water level control, flow rate, PID controller.*

1. INTRODUCTION:

There are various methods to improve the energy efficiency of electric drives. One obvious option is to select the best available variable speed motor drive motor technology. An ultimate solution for a VSD motor is to use copper rotor windings, an optimized rotor slot form and high-quality lamination stacks instead of standard motor materials. However, the best improvements in the drive performance can be achieved by replacing constant-speed mechanically controlled processes with variable-speed-controlled processes or by replacing DC motor drives with induction motor VSDs. New very efficient motor types such as permanent magnet synchronous motors may also be used instead of the induction motor, but as the induction motor still remains the workhorse of the industry, this thesis concentrates on its energy efficiency improvement performance in a variable speed drive.

Electrical drives play an important role in the field of energy efficiency. Modern power electronic drives provide good opportunities to efficiently control the energy flows. Electric motors are the most important type of electric load. Electric motors are used in a wide range of applications, such as fans, compressors, pumps, mills, elevators, transports and cars. Electric motors use over half of all electricity consumed in developed countries, and hence, it is important to utilize electric energy in electric motor drives as efficiently as possible. In electricity utilization, electric-motor-driven systems are by far the most important type of load in industry, using about 70 % of the consumed electricity. Therefore, as electric motor drives are Improving the efficiency of the induction motor can be done by used widely in various sectors, they are an attractive target for energy efficiency improvements. The wide use of drive systems provides a large potential for significant energy efficiency improvements. Even small efficiency improvements would produce extensive efficiency improvements globally.

2. INDUCTION MOTOR LOSSES AND EFFICIENCY:

Losses in induction motor occur in windings, magnetic cores, besides mechanical friction and windage losses. These losses can be classified as follows:

1. Stator Resistance
2. Rotor Resistance
3. Iron Core Losses
4. Stray Losses
5. Windage and Friction Losses

Losses in the induction motor also can be classified based on their electrical frequency such as fundamental and harmonic losses. Frequency harmonics are to be considered only when the induction motor is static converter fed and thus the voltage time harmonics content depends on the type of the converter and the pulse width modulation used with it. Due to their low price and reliability induction motors are widely used in the industry. The electricity bill for a motor for some months may be more than its cost, therefore, even small efficiency improvement will produce notable cost efficiency improvement. Using the variable frequency drives (VFDs) in speed control save the energy and maintain the motor efficiency at high level compared with the mechanical solution of using adjustable nozzle in application such as pumps and fans. The speed control use with belts and pulleys, throttle valves, fan dampers and magnetic clutches are reduced the system efficiency. By using variable speed drives (VFDs) the following benefits are obtained as follow:

1. Gentle startups and gradual slowdowns reduce motor stress.
2. Small size makes them ideal for usage.
3. Energy efficiency improvements are up to 20 percent.

VFDs provide precise and efficient speed control in conveyor systems used in the food, paper, automotive and consumer goods industries. They are also used in crushers, grinding mills, rotary kilns, presses, rolling mills and textile machinery. Improving the efficiency of the induction motor can be done by two ways: (i) By improving the motor design (efficient motors): The efficiency of the motor can be improved from three to eight percent. Heavier copper wire, higher core-steel grade, thinner core laminations, better bearings and reduced windage design add up to better efficiency. Even though initial cost is higher, payback can be very short, especially for motors that are in permanent use. (ii) By introducing control strategies based on optimal air gap flux, which reduce the motor losses for the already working motors.

3. VARIABLE FREQUENCY INDUCTION MOTOR DRIVE:

Variable frequency electrical motor drive technology has advanced dramatically in the last two decades with the advent of new power semiconductor devices and magnetic materials. This technique provides continuous wide ranges speed compared to the mechanical Variable Frequency Drive. Therefore, compared to the mechanical Variable Frequency Drive, the electrical Variable Frequency Drives have potential for energy efficiency improvements.

Basically, the variable speed induction motor drive is composed of some distinguish elements such as a controllable power converter, an electric motor which drives a mechanical load at an adjustable speed and also driver controller. The main elements of the Variable Frequency Drive (VFD) system are as shown in Figure 1.

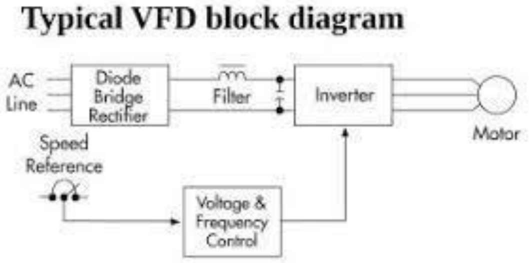


Figure.1 Block Diagram of a Variable Frequency Induction Motor Drive

The power converter receives AC or DC supply voltages from the main power supply and feeds the motor with appropriately condition voltage, current and frequency. In close loop the controller receives command from reference signal and actual speed information from the load. The actual speed should follow the reference signal command value as accurately as possible in a short time without ripple and overshoot. The mechanical load has a torque-speed characteristic representing the counter torque which must be overcome by the VFD. Currently the most promising VFD technology use Insulated Gate Bipolar Transistors (IGBT) to generate the variable voltage and frequency required to control the speed of an AC motor via Pulse Width Modulation (PWM) microprocessor-based algorithms.

4. ENERGY EFFICIENCY IMPROVEMENT WITH VARIABLE FREQUENCY DRIVE:

Approximately 50% of the motors goes into the operation of fans, blowers and pumps. These particular loads such as fans, blowers and pumps are attractive to look at from the energy efficiency improvements point of view. The speed control is the most effective method of using energy exactly according to the needs of the process. Centrifugal fans and pumps follow a variable torque load profile, which has horsepower proportional to the cube of speed and torque varying proportional to the square of speed. Using a fixed speed motor would require some type of mechanical throttling device, such as a vane or damper; but the fact remains that the motor would still be running full load and full speed i.e. full power.

Energy efficiency improvements can be sufficient to pay back the capitalized cost in a matter of a couple of years (or less), depending on the size of the motor. In conventional control system, by adding with outlet dampers to fans or throttling valves to pumps to get the effective and simple control. But severely affect the efficiency of the system. Newer methods include direct variable speed control of the fan or pump. This method produces a more efficient means of flow control than the existing methods. In addition, adjustable frequency drives offer a distinct advantage over other forms of variable speed control. In replacing constant-speed motors with VFDs, solely on the basis of reducing energy expenditure.

Even today most of the developments of the concern provide energy efficiency improvements from 30 % up to 80% in compare to general (traditional) pumps which are used today. Energy efficiency improvements is one of the main sources of competitive advantage of the enterprise in the market. The share of expenses for energy in the cost price of the national produce comprises about 50%, a similar parameter for the advanced countries is only 5%. Due to optimization of engineering systems it is possible (up to 30 – 40%) to lower energy consumption. Systems of ventilation are being one of such energy consumption reserves. They consume energy for air treatment. (heating, cooling, humidifying, drying). Besides, energy is spent for fan drives moving air inside the airway system. However, the most energetically expenditures are the heating of the incoming air, about 75% of energy consumption is spending on it.

5. APPLICATION OF VFD IN WATER LEVEL CONTROL FOR ENERGY EFFICIENCY IMPROVEMENT :

In process control, the basic objective is regulating the value of some quantity. To regulate means to maintain that quantity at some desire value regardless of external influences. The desired value is called the reference value or set point. The typical actuators used in liquid level control systems include pumps, motorized valves, on-off valves, etc. In addition, level sensors such as displacement float, capacitance probe, pressure sensor, etc. provide liquid level measurement for feedback control purpose.

Liquid is flowing into a tank some rate, Qin, and out of the tank at some rate, Q_{out}. The liquid in the tank has some height or level, h. It is knowing that the output flow rate varies as the square root of the height as,

$$Q_{out} = K\sqrt{h} \qquad (1)$$

where Q_{out} = flow rate output
K = proportional constant
h = water head

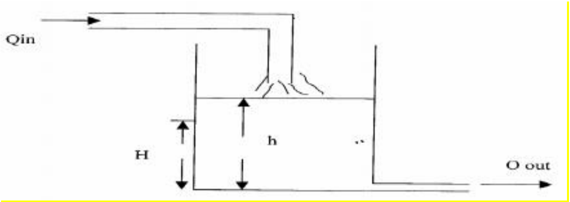
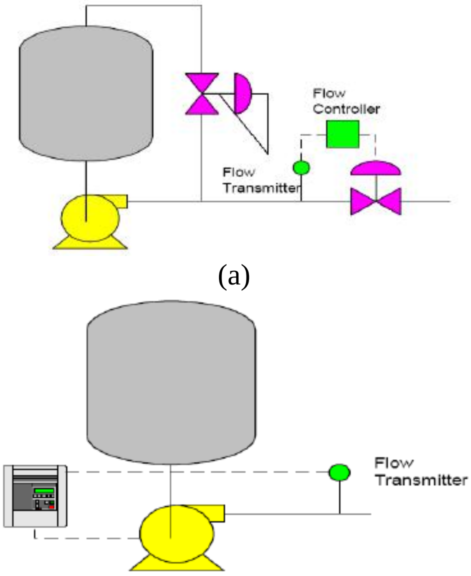


Figure .2 Basic Water Level Control Scheme



(a)

(b)

Figure.3 Water Level Control Methods: (a) Conventional Flow Control and (b) VFD Flow Control

So the higher the level, the faster the liquid flows out. If the output flow rate is not exactly equal to the input flow rate, the level will drop, (Qout > Q_{in}) or rise, if (Qout < Q_{in}).

This process has a property called self-regulation. This means that for some input flow rate, the liquid height will rise until it reaches a height for which the output flow rate matches the input flow rate. A self-regulating system does not provide regulation of a variable to any particular reference value. In this case, the liquid level will adopt some value for which input and output flow rate are the same, and there it will stay. But if the input flow rate changed, then the level would change also, so it is not regulated to its references value. If it is wanted to maintain the level at some particular value, H, in Figure.2 regardless of the input flow rate. Then something more than self - regulation is needed. In Figure 3 (a), a human can regulate the level using a sight tube S to compare the level h to the objective H and adjust a valve to change the level.

In automatic water level control system, the level of the water in the tank will be detected by the sensor, and it will consider as an input. Then it will be sent to the controller of variable frequency drive (VFD). Than the output will be sent to the controlled motor so that the motor can adjust its speed so that the water level in the tank maintains its reference value. In conventional water level control system, the output from the controller will be sent to the servomotor to adjust its valve position to open or closed while the motor is applied by rated voltage and running rated speed. In comparison of the two schemes, the water level control by VFD system can provide energy efficiency improvement compared to servo motor valve control. The block diagram for energy efficiency improvement process for water level control with variable frequency induction motor drive is shown in Figure 4. Figure 5 shows the motor speed and current relationship of VFD and without VFD during staring.

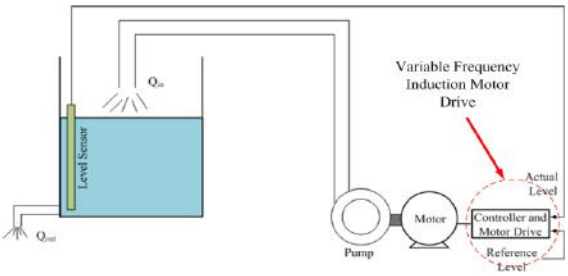


Figure.4 Block Diagram for Water Level Control with VFD

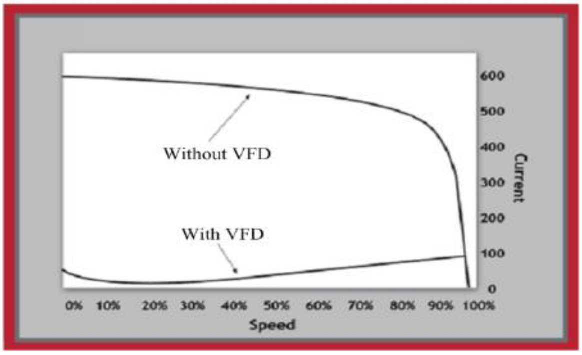


Figure.5 Motor Speed and Current Relationship

6. CALCULATED ENERGY EFFICIENCY IMPROVEMENT BY VFD:

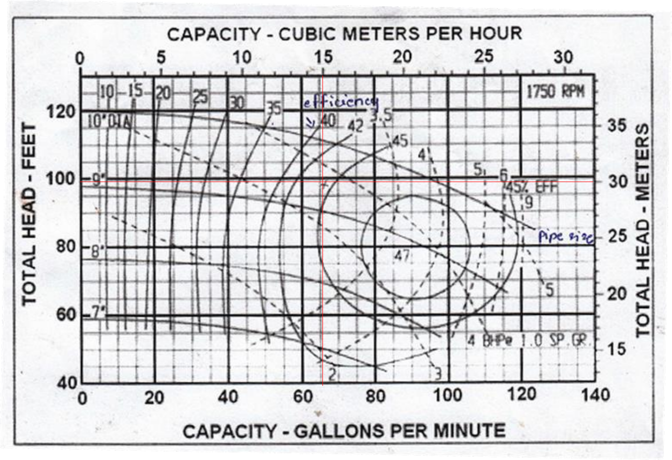


Figure.6 Head Vs Flow Rate Curve

For the loss reduction calculation for VFD, the following data are taken:

Tank capacity = 100000 Liter (100 m^3)
Tank Area = 10 m^2
Tank High = 10 m

For the pump motor, the following are assumed:

Total discharge head = 30 m
Flow rate = 15 m^3/hr

According to Figure .6 the required hydraulic power is 3.69 hp. Since the efficiency is 44 %, the motor power is taken as 8.5 kW. With VFD, the water level is controlled by the flow rate control. The control scheme is linear as shown in Figure 7.

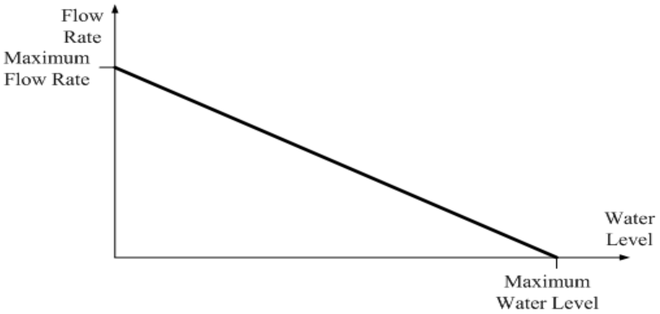


Figure.7 Flow Rate versus Water Level with VFD

The flow rate will be maximum at minimum (empty) water level and will be zero at maximum water level (for both VFD and other control). For 15,000 L/hr flow rate with 100,000 L capacity tank, the time required to fill tank is:

$$\text{Time} = \frac{2\times\text{Tank Capacity}}{\text{Flow Rate}} = \frac{2\times 100{,}000}{15{,}000} = 13.3 \text{ hour} \qquad (2)$$

Since power is proportional to cube of speed, the pump motor consumed power as function of time is obtained as follow

$$P_{consumed} = P_{rated} \times \left[1-\left(\frac{t}{13.3}\right)^3\right] \qquad (3)$$

For the 8.5 kW motor, the power consumptions are obtained as follow

For other control, $P_{consumed} = 8.5\,\text{kW}$ at all time

For VFD control, $P_{consumed} = 8.5\times\left[1-0.000425\,t^3\right]$ (4)

where, t is in hour.

With VFD, the power consumption is decreased as the flow rate (and hence speed) reduced. With other control, the power consumption is constant although flow rate (speed) is reduced. The power versus time graph is obtained as shown in Figure 8.

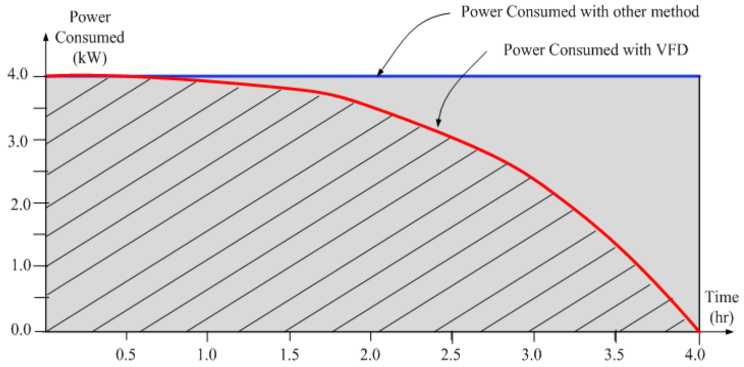


Figure.8 Power Consume versus Time Graph for VFD

Energy Consumed with other method is

$$W_{consumed} = \int_0^{13.3} P_{rated}\, dt = 8.5\times\int_0^{13.3} dt = 8.5\times[13.3-0] = 113.05\,\text{kWh} \qquad (5)$$

Energy Consumed with VFD method is

$$W_{consumed} = \int_0^{13.3} P_{rated}\left(1-0.000425t^3\right)dt = 8.5\times\left[\int_0^{13.3} dt - 0.000425\int_0^{13.3} t^3\, dt\right] = 84.79\,\text{kWh} \qquad (6)$$

Energy efficiency improvement = 113.05 – 84.79 = 28.26 kWh per filling of tank.

If the tank is filling daily, the annual efficiency improvement can be obtained as follow:

Efficiency improvement unit = 28.26 kWh × 365
= 10314.9 kWh, (361021.5 kyats/year)

7. ENERGY EFFICIENCY IMPROVEMENT STUDY USING SIMPOWER BLOCKSETS :

The Simulink model for energy efficiency improvement by VFD is shown in Figure 9. The two identical motors 8.5 kW, 400 V, 50 Hz are supplied from the same source, one motor is operated with VFD and the next motor is operated without VFD. The power consumed by each motor and the energy taken by each motor is measured and the resulting data are shown in Figure 10 through Figure 13.

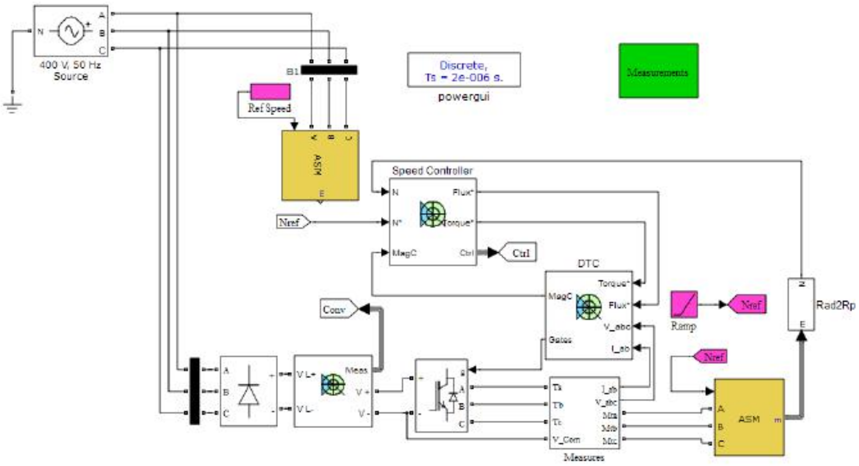


Figure.9 Simulink Model for Energy Efficiency improvement with and without Variable Frequency Drive

TABLE1

BLOCK PARAMETERS FOR VFD CONTROLLED INDUCTION MOTOR DRIVE

SN	Name	Parameters
1.	AC Supply	3- phase, 400 V, 50 Hz
2.	Induction Motor	3- phase, cage rotor, 400 V, 50 Hz, 8.5 kW, 4pole
3.	Variable Frequency Drive	Three phase uncontrolled rectifier and inverter with DTC control

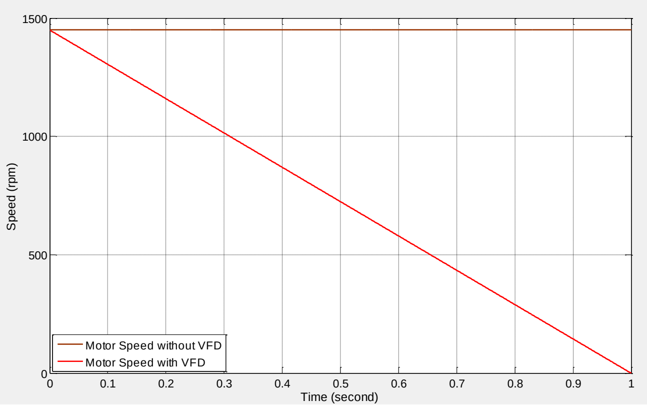
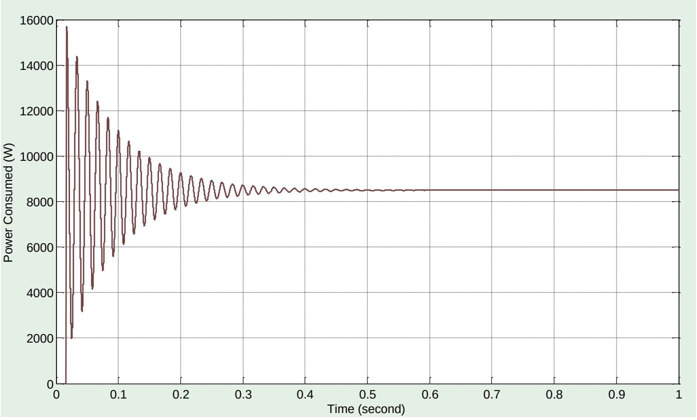
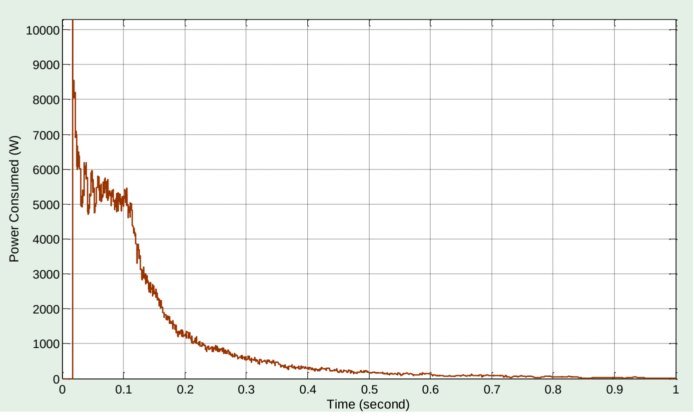


Figure.10 Operating Speed of the two Motors without and with Variable Frequency Drive

The operating speed of the two motors with and without VFD control is shown in Figure 10. Without VFD control, the motor is operated at constant speed of 1450 rpm. With VFD control, the motor speed is varying with time. In water level control, as the water level increased the motor speed will decrease and the less power will be consumed by the motor.



(a)



(b)

Figure.11Power Consumed by Motor: (a) without VFD and (b) without VFD

The power consumed by the motors and energy consumed by the motors are shown in Figure 11 and Figure 12 respectively. Without VFD, the power consumed by the motor is constant and thus the energy taken by the motor is linear. With VFD, the power consumed by the motor is exponential form and thus the energy taken by the motor is parabolic.

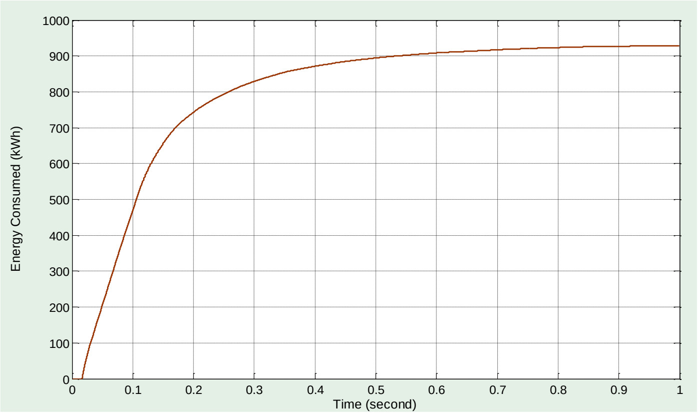


Figure.12 Energy Consumed by Motor with Variable Frequency Drive

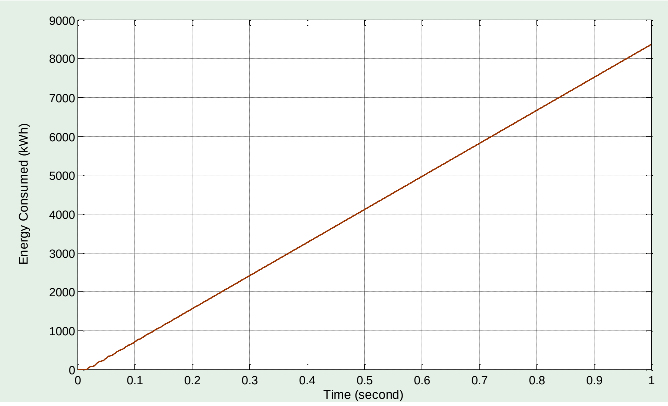


Figure.13 Energy Consumed by Motor without Variable Frequency Drive

At the end of simulation, the energy consumed by the motor (without VFD) is 8.35 kWh whilst the energy consumed by the motor (with VFD) is 0.9 kWh. Thus in water level control, energy consumed by the motor can be saved by using variable frequency drives.

8. ENERGY EFFICIENCY IMPROVEMENT STUDY USING SIMULINK CALCULATION BLOCKSETS:

In practice, the motor operating time is about 6.5 hour to fill full capacity of the tank. In Simpower simulation, this time is very large and cannot be simulated. Thus the calculation blocks are implemented in Simulink and the resulting Simulink model is shown in Figure 14.

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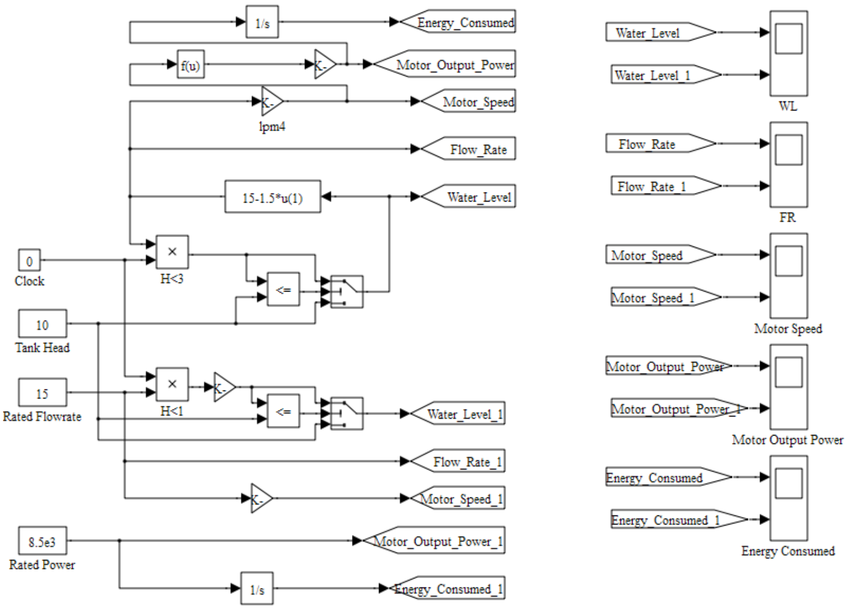

Figure.14 Simulink Model for Loss Reduction Calculation

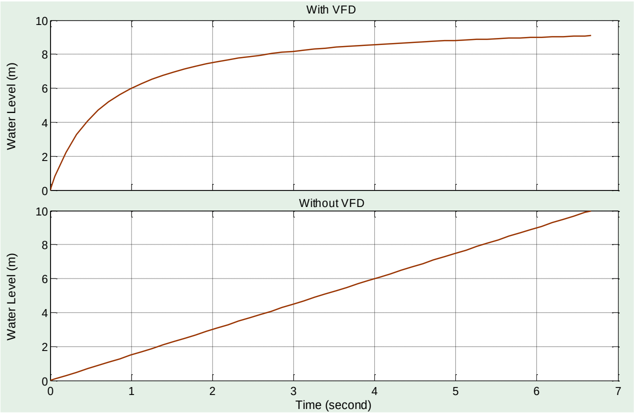

Figure.15 Water Level Variation

Figure 15. shows water level variation with and without VFD. Without VFD the water level increasement is linear and with VFD, water level increasement is exponential. At the end of 6.667 hour, the water level is 10 m without VFD and 9.2 m with VFD.

The following figure shows flow rate variation with and without VFD. Without VFD the flow rate is constant and with VFD flow rate is exponential. With VFD, flow rate is 15 m^3/h at starting and 1.5 m^3/h at the end of 6.667 hour.

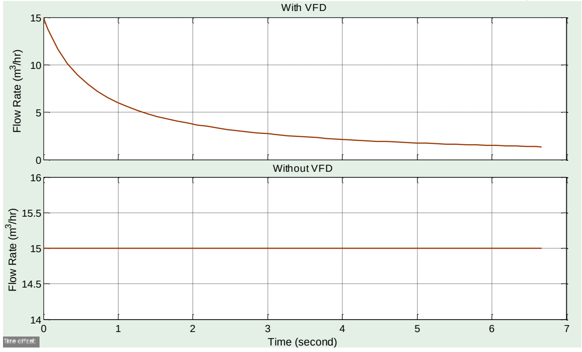

Figure .16 Flow Rate Variation

Figure 17 shows motor speed variation with and without VFD. The speed variation is similar to flow rate variation. Without VFD the motor speed is constant at 157 rad/sec (1500 rpm) and with VFD motor speed is exponential. With VFD, motor speed is 157 rad/sec (1500 rpm) at starting and 3.5 rad/sec (33.4 rpm) at the end of 6.667 hour.

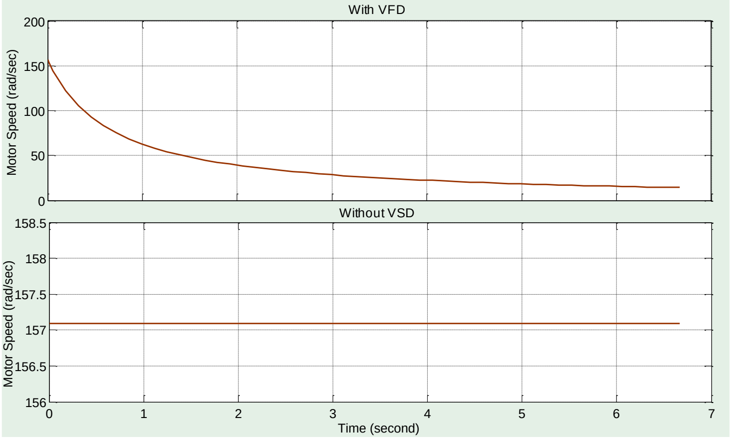

Figure .17 Motor Speed Variations

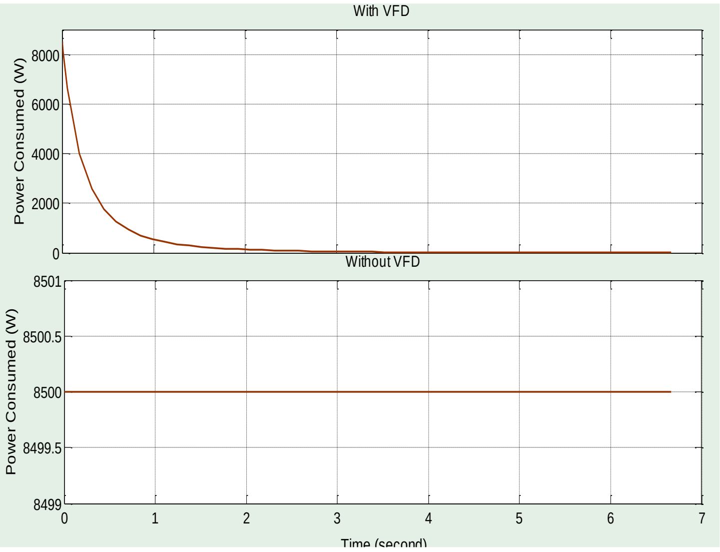

Figure .18 Power Consumed Variation

Figure 18 shows power consumed variation with and without VFD. The power consumed by the motor without VFD is constant at 8.5 kW. The power consumed by the motor with VFD is 8.5 kW at starting and gradually decreased and nearly zero at the end of 6.667 hour.

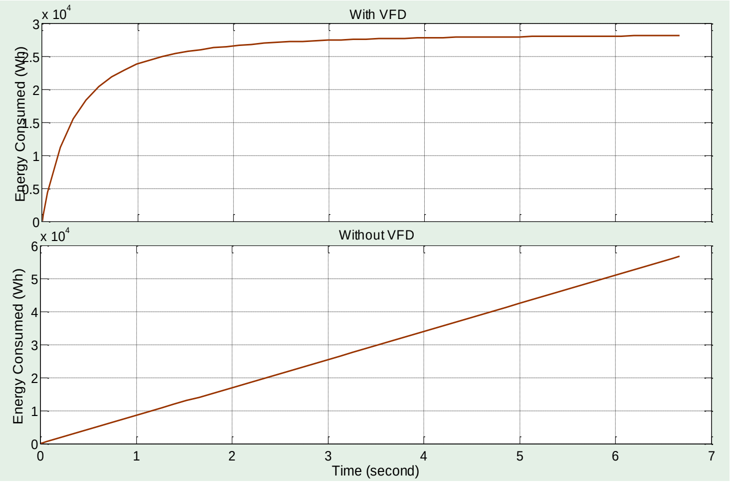

Figure.19 Energy Consumed Variation

Figure 19 shows energy consumed variation with and without VFD. The energy consumed by the motor without VFD is 55.5 kWh after 6.667 hour. The energy consumed by the motor with VFD is 28 kWh at the end of 6.667 hour. Thus energy efficiency improvement with VFD is about 50 %.

10. CONCLUSION:

The energy efficiency improvement by VFD for water level control is presented in this paper. For energy efficiency improvement study, a sample water filling system is considered. The energy efficiency improvement performance is study with calculation as well as simulation model. According to the results, the use of VFD can save energy for water level control system.

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