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SCIENTIFIC PAPER

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EVALUATION OF VARIABLE SPEED DRIVES TO IMPROVE ENERGY EFFICIENCY AND REDUCE GAS EMISSIONS: CASE STUDY

Article Highlights

- Installing variable frequency drivers improve energy efficiency
- Variable frequency drivers reduce energy consumption and greenhouse gas emissions by 67%
- Variable frequency drivers are economical, with a payback period of less than one year for fan equipment
- Variable frequency driver is not economically attractive for reciprocating compressors

Abstract

Variable speed drives are the most promising technique for reducing electric motors' energy consumption. This paper discusses energy savings by installing variable speed drives to control rotating equipment motors such as pumps, compressors, blowers, and fans in oil processing facilities. In addition to energy savings, variable speed drives will improve overall equipment efficiency, increase reliability, and reduce greenhouse gas (GHG) emissions. An energy audit was performed on a case study to investigate energy consumption for all electric motors. Technical and operational constraints for installing and operating variable speed drives were discussed. Installation requires adjustments in operation schedules and parameters to allow reducing energy consumption. The case study has illustrated how to calculate energy savings for pipelines, air coolers, air blowers for furnaces, pumps with variable flow rates, and reciprocating compressing systems. Variable speed drives were technically and economically accepted in air blowers, fans, and pumps. Energy consumption and GHG emission were reduced by 67%. The payback period for the whole project was less than one year. Meanwhile, it was not valid for reciprocating compressors as the payback period was 6.2 years.

Keywords: energy efficiency, pump optimization, greenhouse gas emissions, variable speed drives.

Oil refining is an intensive energy-consuming industry. Therefore, great interest has been put into minimizing energy consumption and reducing greenhouse gas (GHG) emissions. Most of the efforts on energy optimization focus on optimizing heat exchanging networks and furnaces operations as it represents most of the energy consumption. Electric energy represents a smaller percentage of the overall energy consumption at a refinery. However, it has an interesting potential for energy saving and reducing GHG emissions with a short payback period in many cases. Electric motors are the main driver for most rotating equipment like pumps, fans, blowers, and compressors at oil refineries. They consume about 80% of the electric energy consumption at an oil refinery (60% of the electric motors are driving pumps, 15% for air compressors, 9% for fans, and 16% for various applications) [1].

Fan laws or affinity laws define the relationship between fan or pump rotational speed (N), flow rate (Q), and brake horsepower required (P). Fan laws assume that the fan's efficiency remains constant at various rotational speeds [2].

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$$\frac{Q_1}{Q_2}=\frac{N_1}{N_2} \tag{1}$$

$$\frac{H_1}{H_2}=\left(\frac{N_1}{N_2}\right)^2 \tag{2}$$

$$\frac{P_1}{P_2}=\left(\frac{N_1}{N_2}\right)^3 \tag{3}$$

where, Q is the flow rate, H is the head, P is the shaft power, and N is the pump's rotational speed. As the cubic relation between pump speed and horsepower requirement, a minor decrease in the speed will result in great energy savings. Fig 1 illustrates the change of the pump characteristic curve with changing speed. As the speed decreases, the Q-H curve moves toward a lower flow rate (Q) and head (H); there is a unique Q-H curve for every rotating speed. So, adjusting the rotating speed will give the exact required flow rate and significantly reduces energy consumption. Furthermore, as the speed decreases, the pump's best efficiency point (BEF) will also change [3]. So, adjusting the speed keeps the operating point as near as possible to the BEF point, resulting in energy savings. There are multiple ways to control the speed of the pump. Combustion engine or steam turbine drivers are equipped with speed control techniques that adjust speed as needed. Meanwhile, electric motor drivers have a constant speed and need gearboxes or belt drives to control speed. Fortunately, VSD could be integrated with electric motors to control their rotating speed.

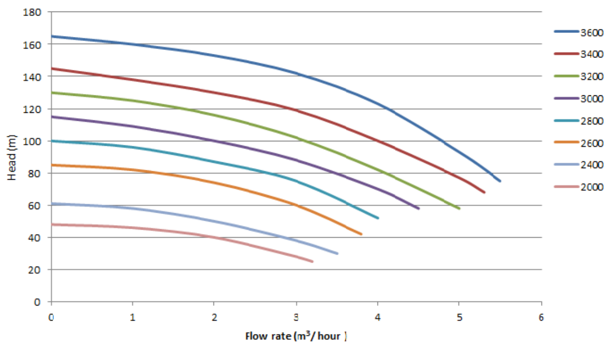

Figure 1. Pump performance curves at various speeds.

Variable speed drives (VSD) are electronic devices that change the motor rotation speed by changing the frequency of the electric current supplied to the motor. As the frequency of the supplied electric energy decreases, the rotational speed of the motor, energy consumption, and head decrease and vice versa [2]. That allows the motor speed to match the required flow rate. At lower demanded process flow rates reducing motor speed will reduce energy loss in friction and throttling by control valves or recycling. Modern VSD can adjust the rotation speed with an accuracy of ±0.1% independent of the motor load [4]. Such great speed control capability in VSD will achieve a greater flow rate control. Therefore, a small reduction in motor speed produces great savings. For example, reducing pump speed by 20% will reduce energy consumption by 50%. Fig 2. illustrates the expected savings when reducing motor speed.

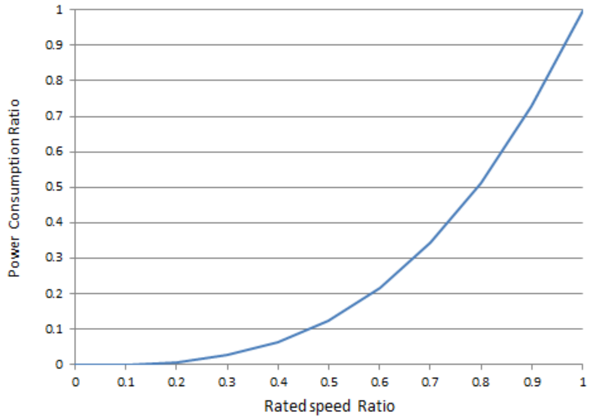

Figure 2. The relationship between motor power and rotation speed.

VSD consists of a Rectifier, regulator, and inverter. The supplied alternative current (AC) is converted to direct current DC in the rectifier, then the inverter converts the DC to AC adjusted at the required new frequency. The regulator controls the VSD components [4]. After great advancements in VSD technology, it became the most efficient controller and energy-saving technology for electric motors with variable load in operations. VSD installation reduces energy consumption, improves process control, provides soft starting for motors, and eliminates valve throttling to control the flow. Another advantage of using VSD is reducing GHG emissions [4].

VSD limitations

Despite the great benefits of VSD, there are multiple limitations to its widespread use. Harmonics, overheating, old motors compatibility, and limited space for installation are the major technical obstacles to installing VSD. Harmonics in electrical systems refers to the deviation of current and voltage waveforms from ideal sinusoidal waveforms. They are created via non-linear loads (like VSD) connected to power grids. Harmonics distort all equipment connected to the grid, causing overheating for cables, motors, and transformers [5]. There are multiple solutions to eliminate harmonics effects from VSD driving systems like Line reactors, passive or active filters, and Harmonic filters. Harmonic filters are the best technique to demolish harmonics effects; they are easy to apply, decrease system losses and increase the system's protection [4]. Most motors cooling systems depend on a fan connected to the motor shaft. As the speed decreases, the flow rate of cooling air decreases.

Overheating issues become clear at much-reduced motor speeds, so an external air-cooling source will help under such conditions [6]. Old motors may not have good compatibility with VSD drives, they have poor efficiency at low motor loads, and motor coil insulations may not withstand higher operating temperatures or electrical stresses. Finally, VSD drives need space for installation. A significant improvement has been achieved in reducing the size of units, including a built-in filter. In addition, manufacturers could provide customized space solutions that fit customers needed dimensions [7].

Effect of rotational speed change on efficiency

Affinity laws assume that the pump or fan efficiency stays constant at all rotation speeds. Therefore, the efficiency of the fan or pump decreases when reducing the speed lower than rated. For example, the efficiency drops when the rotation speed falls under 30% of the rated full speed. However, affinity laws could not predict decreased efficiency with rotation speed [8].

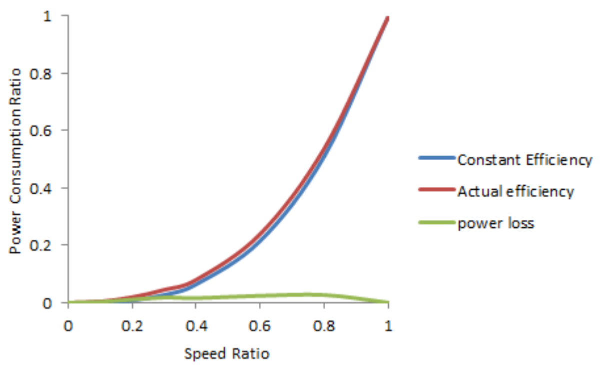

Figure 3. Case study shows the power loss due to a decrease in pump efficiency with speed reduction.

Fig 3. Illustrates results from a case study from Coelho and Andrade-Campos [9] or pump at various rotation speeds, at speed 30% of rated speed, the pump efficiency will be 60% of rated efficiency, and the energy loss due to efficiency decrease will be 1.8% of the rated power. The consumption will be only 13% of the rated power. The efficiency of the motor and VSD is also affected by reduced loads. As the speed decreases, the load and energy consumption decreases, so the efficiency of both motor and VSD will decrease. Fortunately, the motor has constant efficiency up to approximately 20% of rated power, and their decrease begins to be sharply lower than 20% of rated load as was indicated in Fig 1. [10]. On the other hand, VSD efficiency is still preserved at reduced loading, even at loads as low as 25% of the rated load [11]. As a result, VSD and motor efficiency will begin to have a clear effect at loads lower than 20% of the total load. However, the efficiency of the motor, pump, and VSD decreases sharply at extremely low loads, the energy saving achieved will outweigh the losses due to efficiency loss.

Economic considerations for VSD

Evaluating the economic factors for installing VSD is the most important step in VSD feasibility studies. As mentioned in [12], the companies are evaluating the financial benefits of projects based on indicators such as return on investment (ROI) and payback period (PBP). The payback period is the most important indicator calculated by Eq. (4). Payback period of fewer than two years is the most common for VSD replacement projects. However, an acceptable payback period depends on the availability of Funds and expected reliability improvements. Therefore, improving the equipment reliability favors the VSD installation even at a payback period longer than two years. In addition, VSD is the best energy-efficient solution for variable torque applications [13].

$$PBP = \frac{Total\ \ VSD\ \ Costs}{Total\ \ Energy\ \ Savings\ \ with\ \ VSD\ \ per\ \ year} \tag{4}$$

The total cost of VSD installation includes the cost of VSD Purchasing, cables, and installation Labor. The cost of VSD purchasing is most of the cost. Cable cost is variable according to required cable lengths and sizes. There are two types of VSD according to the operating voltage. First, low-voltage VSD is a good fit for lower-power equipment, and its cost is low. The second is medium voltage VSD, which deals with medium voltage VSD like 3300 V or 6600 V; it is very convenient with large power motors like 500 kW or above [14]. The prices for medium voltage VSD are higher than low voltage VSD. However, the prices for medium voltage VSD have decreased, comparing prices mentioned in [12] and [15]. The prices dropped by 45% from 2013 to 2019. Table 1 indicates the average cost per kW for VSD applicable for equipment in the oil and gas industry from local distributors in Egypt.

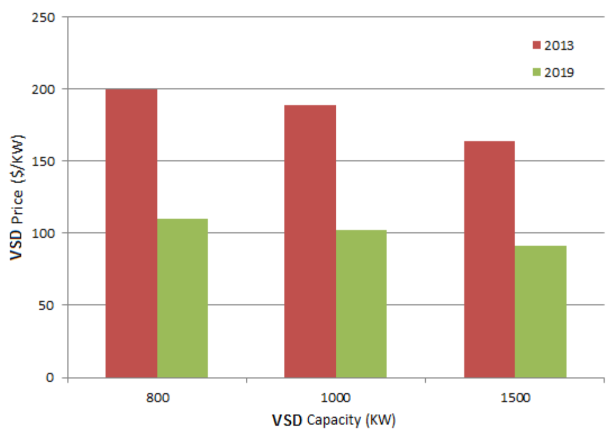

Figure 4. VSD prices 2013 vs. 2019.

Table 1. Average cost per kW for VSD in Egypt from the local market, prices in USD/kW.

Voltage Type	Low		Medium
Motor capacity, kW	0–10	10–100	500–1000
Average VSD Cost USD/kw	150	90	110

MATERIAL AND METHODS

Estimating Energy savings must be performed carefully. Errors usually overestimate energy savings and favor the installation of variable speed drives due to neglecting efficiency change with speed or neglecting the constraints of the system curve, including head and power requirements at reduced flow rates [16]. Energy savings by the VSD system depends on two factors: the ratio of reduction in rotational speed; the second is characteristic system curves.

The system characteristics curve illustrates the frictional and static head of the system against the flow rate. Systems with a dominated frictional head than a static head (the frictional head includes both head loss from throttling valves and pipeline friction) will have greater energy savings than systems with a dominated static head [6] since the speed reduction ratio must keep the head after reducing speed higher than the system curve to allow the flow.

There are several methods for estimating the expected energy savings by installing VSD on the pump and fan motors. A simplified method [4] to calculate the energy saving is based directly on applying affinity laws, assuming a constant efficiency for different fan speeds:

$$E_{motor} = T_o \times W_{rated} \times LF_{motor} \tag{5}$$

where. E_{motor} is the electric energy consumption without VSD (kWh), T_o is the number of operating hours, W_{rated} is the rated motor capacity (kW), and LF_{motor} is the loading factor for the motor:

$$SP_F = \left(\frac{N_1}{N_2}\right)^3 \tag{6}$$

where SP_F is the energy-saving factor, and N is the rotation speed:

$$E_{VSD} = \frac{T_{o,VSD} \times SP_F \times E_{motor}}{T_o} \tag{7}$$

where E_{VSD} is the electrical energy consumption (kWh) with VSD installed, and $T_{o,VSD}$ is the operating hours after installing VSD (h).

$$ES_{VSD} = E_{motor} - E_{VSD} \tag{8}$$

where ES_{VSD} is the energy savings in kWh.

The air compressing system could benefit from installing VSD by lowering the system's pressure and keeping start and stop cycles as low as possible. The energy-savings factor could be calculated using equation (9) to estimate the horsepower reduction factor (FR) based on current and proposed operating pressures [17].

$$FR = \frac{[(P_{dp} + P_i)/P_i]^{(K-1)/(K*N)} - 1}{[(P_{dc} + P_i)/P_i]^{(K-1)/(K*N)} - 1} \tag{9}$$

where P_{dp} is the reduced discharge pressure, P_{dc} is the discharge pressure at current operating conditions, P_i is the inlet pressure, k the ratio of specific heat for air (k = 1.4; dimensionless), and N is the number of stages; all pressures are in kPa.

Another advantage of reducing energy consumption is a similar reduction in the emission of GHG. The reduction in GHG due to applying VSD could be calculated similarly using equation (10) [18].

$$ER_{GHG} = ES_{VSD} \times \sum E_f \tag{10}$$

where ER_{GHG} is the GHG emission reduction per annum for CO_2, SO_2, and NO_x (kg), ES_{VSD} is the electrical energy saving (kWh), and E_f is the emission factor. Emission factors for natural gas electricity generation are 448.6 kg/MWh, 0.36 kg/MWh, and 0.36 kg/MWh for CO_2, NO_x, and SO_2, respectively [19].

Equations (5–10) assume that the energy loss due to motor and VSD efficiency decrease is negligible compared to the saving ratio of energy consumption.

Case study

A Qarun oil processing facility case study was selected to evaluate the savings by applying VSD to electric motors. This facility works at a variable feed flow rate. It receives crude oils from remote areas to perform preliminary oil processing. As a result, there are variations in inlet feed flow rates; multiple reasons, including variable production schedules, variable water content, and non-uniform tank settling and drainage durations, cause such variation.

The energy audit in Table 2. indicated the energy consumption profile for various rotating equipment at the facility. It includes the power load factor measured on-site and annual energy consumption in MWh for each piece of equipment at current operating conditions. Some equipment has duty and standby, and energy consumption was calculated based on the number of units in service. In addition, some equipment works on variable flow rates, and the flow rate variation is controlled through a control valve on pump discharge. Operating hours were indicated to calculate the total energy consumption per year in MWh.

Table 2. Energy audit at Qarun oil processing plant.

Equipment	Operating location	Rated power KW	Load Factor %	Installed units	Operating h/day	Running units	Total energy consumption MWh/year	Flow rate status
Pump shipping	Pipeline	450	0.86	3	12	2	3,401	Fixed
Pump-disposal	Pipeline	750	0.86	3	16	1	3,769	Fixed
Open drain	Pipeline	10	0.80	2	2	1	6	Fixed
DSD	Pipeline	21	0.85	2	12	1	78	Fixed
Heater pump A	VFP	56	1.00	2	24	1	490	Variable
Heater pump B	VFP	56	1.00	2	24	1	490	Variable
Heater pump C	VFP	56	1.00	2	24	1	490	Variable
Utility pumps	VFP	45	0.56	2	24	1	222	Variable
Potable pumps	VFP	15	0.94	2	24	1	124	Variable
Air blower	Fired Heater	3	0.49	11	24	11	142	Fixed
Air cooler fans	Air cooler	25	0.82	6	24	6	1,077	Fixed
Compressor	Compressor	100	0.44	2	24	1	385	Fixed
Total							10,674	

RESULTS AND DISCUSSION

The potential energy savings, GHG emission reduction, and cost savings by using VSD drives at Qarun oil processing facilities are evaluated in this section. Eqs (1–10) are used in the evaluation process at various flow rates. The financial indicators have been evaluated at current operating conditions and compared between operations with VSD installed against those without it. VSD losses were not included as it depends on the manufacturer and VSD loading factor. Also, VSD efficiency will be above 90% for loads up to 50% of its rated power [11]. Even the efficiency of the motor and fan or pump will decrease with decreasing the speed; Losses were estimated to be a very slight percentage compared to savings achieved.

Operation conditions like pump operating schedules, flow rates, and pressures were considered, so there is no negative impact for applying VSD into the plant. The cost calculations do not include the cost of labor as laborers are already available at Qarun Company with the required experience. When installing a VSD connection, energy feed lines bypasses could connect power directly to the motor. Therefore, the equipment could be in service without being affected in case of a VSD breakdown. In cost calculation, installing VSD has been considered for operating and standby equipment. The standby VSD represents a complete backup for the working VSD, which improves the overall reliability of equipment at the plant. The calculations and results were divided into groups; every group has similar operating conditions like pipeline pumps, variable flow rate pumps, fired heater blowers, air coolers fans, and air compressor motors. This will clarify in the results which equipment best fits VSD operation.

Energy savings were calculated for installing VSD on pumps installed on major plant pipelines, including (Pump shipping, Pump-disposal, Open Drain, and DSD). The results for all pipelines are illustrated in Table 3. The four pipelines have fewer than 24 h, so we can extend the operating hours to 24 h and simultaneously decrease the pump speed and flow rate. Operational constraints were considered while extending operating hours. For example, open Drain pumps have a restriction on flow rate, we could not extend the 2 h of operation to 24 h, and it will not be practical in operation. Installing VSD on all pipeline pumps saved 4,758 MWh/year and reduced energy consumption by 65%. GHG emissions were reduced by 2,137,861 kg/year. Three pipelines could reduce the flow rate and compensate for that by extending the operating hours to 24 h/day. Pipelines that restrict flow rates are less attractive opportunities for energy savings. All pipelines have a payback period of less than one year except for an open drain line, with a payback period of 4.5 years, which is extremely high compared with other pipelines.

Variable flow rate pumps, including heater pumps A, B, and C, utility pumps, and potable pumps, could not be replaced with smaller flow rate pumps, as the flow rate continuously changes and rises to the rated flow rate frequently for short durations during daily operation. So, we have two options for its optimization; first, we could install an additional smaller pump to work on a lower flow rate and keep the main pump for peak demand. However, installing an additional smaller pump is not feasible due to limited space for equipment. The second option is installing VSD on current pumps. As shown in Table 3, Installing VSD on pumps to regulate the flow will save 1433 MWh per year and

Table 3. Operation status before VSD installation VS after VSD installation.

Equipment	Operation without VSD				Operation with VSD				Energy Savings MWh/year
	Run hours per day	Rated flow rate BPD	Operating flow rate BBL/day	Energy consumption MWh/year	Run hours per day	Flow rate BBL/day	Reduced speed ratio	Energy consumption MWh/year	
Pump shipping	12	100,000	100,000	3,401	24	50,000	0.5	850	2,551
Pump-disposal	16	30,000	30,000	3,769	24	20,000	0.66	1,625	2,144
Open drain pump	12	13,000	13,000	78	24	6,500	0.5	19	59
DSD	2	10,000	10,000	6	4	6,500	0.5	1	4
Heater Pump A	24	25000	16500	491	24	16500	0.66	141	350
Heater Pump B	24	25000	17800	491	24	17800	0.71	177	314
Heater Pump C	24	25000	12500	491	24	12500	0.5	62	429
Utility pumps	24	7500	2000	222	24	2000	0.27	4	218
Potable pumps	24	4350	1000	124	24	1000	0.23	2	122
Air blower	24	1200	720	142	24	720	0.6	30	110
Air cooler fans	24	$3.56*10^8$	$3.56*10^8$	1077	24	$2.136*10^8$	0.6	232	845
Compressor	24	8400	8400	385	24	7560	0.9	328	58
Total				10677				3471	7204

reduce energy consumption by 78% while keeping operation regular without being affected. In addition, all pumps with variable flow rates have an average payback period of 0.58 years which is very encouraging to pursue in the project.

A fired heater damper or throttling on air blower discharge does not supply the exact flow for the optimized combustion. VSD is more sensitive and accurate in adjusting the flow rate required for the complete combustion process. Energy savings were achieved from two sides. First, energy consumption for blowers at reduced flow rates would decrease without throttling. Second, it would adjust the required air to guarantee complete optimized combustion. VSD of air blowers could be connected to flow gas sensors to measure the concentration of flue gases as an indicator of combustion efficiency to increase or decrease the amount of air supplied. Heater efficiency improvements were not included in calculations as it is difficult to predict efficiency accurately without a flow gas analyzer. Installation of VSD for the heater will save 110 MWh /year; it has a payback period of 0.9 years without including efficiency improvements of the heater. Results have indicated that VSD will be feasible for blowers of fired heaters with a payback period of fewer than 11 months.

Energy savings were calculated for installing VSD on all air cooler fans to match fan speed with ambient temperature. The airflow rate was designed for 42 °C, but the ambient air temperature is 24 °C. Therefore, we had an opportunity to decrease the amount of cooling to 40% of the current rate on average operation around the year. It would reduce energy consumption by 78%. Installation of VSD for the air cooler fans would save 845 MWh/year, and the payback period was 0.32 year. Results have indicated that VSD will be feasible for fans of air coolers with a payback period of 4 months.

The air compressor at Qarun is a reciprocating compressor. The compressor discharge is connected to the receiver air storage vessel. It works on start and stops cycles. When the receiver tank pressure decreases, the compressor starts and keeps running until the pressure achieves the set high pressure in the receiver tank. Receiver tanks play a significant role in compressor operation, minimizing the compressor's start and stopping as an air reservoir. In addition, it is redundant for peak demands from the air that exceeds compressor output. Energy savings in a reciprocating compressor is not achieved directly as reducing rotation speed does not have any energy reduction in compression energy. Fortunately, from Eq. (9), reducing receiver tank pressure will reduce energy consumption. But reducing receiver tank air pressure will increase the start and stop cycles for the compressor. Here is the function of VSD, we could decrease the compressor rotation speed to minimize start and stop cycles at reduced receiver tank pressure. For the current operating conditions of the compressor and air distribution system, the pressure of the air receiver tank could be reduced from 120 psi to 90 psi without interrupting operation. VSD will regulate the compressor's rotation speed to keep the start and stop cycles within acceptable limits. Energy consumption was reduced by 15% and saved 58 MWh/year. The payback period is 6.2 years, which is not attractive, especially when funds are limited.

Table 4. Economic evaluation for energy savings with VSD.

Equipment	No. of VSD Units installed	VSD price in USD/KW	VSD Cost (USD)	Energy savings MWh/year	Payback period (year)	Emissions reduction kg/year
Pump shipping	3	110	148500	2551	1.17	1,146,214
Pump-disposal	1	110	82500	2144	0.77	963,342
Open drain pumps	1	90	900	4	4.5	1,796
DSD	2	90	3780	59	1.29	26,509
Heater A	2	90	10080	350	0.58	157,262
Heater B	2	90	10080	314	0.64	141,086
Heater C	2	90	10080	429	0.47	192,757
Utility	2	90	8100	218	0.75	97,951
Potable	2	90	2700	122	0.44	54,817
Air blower	11	150	4950	110	0.9	49,426
Air cooler	6	90	13500	845	0.32	379,675
Compressor	2	90	18000	58	6.2	26,061
Total			313170	7204	0.9	3,236,896

*Payback period was calculated on industrial electric prices of 50 USD / MWh. * Emissions reductions include carbon dioxide and sulfur and nitrogen oxides.

CONCLUSION

Oil processing and refining plants have great potential for energy saving by widely applying VSD to electric motors. An energy audit was done on the Qarun oil processing plant, and energy-saving calculations were performed on applying VSD. Applying VSD to all equipment will save 7,204 MWh/year, 360,150 US$/year, and reduce GHG total emissions by 3,236,896 kg/year or 67% of current emissions. The average payback period is about 0.87 years. The calculation procedures used could be applied to any refinery unit or oil processing facility, considering the process limitations of operating variables like operation schedules, pressures, and flow rates.

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NAUČNI RAD

EVALUACIJA POGONA SA PROMENLJIVOM BRZINOM ZA POBOLJŠANJE ENERGETSKE EFIKASNOSTI I SMANJENJE EMISIJA GASOVA: STUDIJA SLUČAJA

Pogoni sa promenljivom brzinom su najperspektivnija tehnika za smanjenje potrošnje energije elektromotora. U ovom radu se govori o uštedi energije ugradnjom pogona sa promenljivom brzinom za upravljanje rotirajućim motorima opreme, kao što su pumpe, kompresori, duvaljke i ventilatori u postrojenjima za preradu nafte. Pored uštede energije, pogoni sa promenljivom brzinom će poboljšati ukupnu efikasnost opreme, povećati pouzdanost i smanjiti emisije gasova sa efektom staklene bašte. Energetski pregled je urađen na studiji slučaja da bi se ispitala potrošnja energije za sve elektromotore. Razmotrena su tehnička i operativna ograničenja za ugradnju i rad pogona sa promenljivom brzinom. Instalacija zahteva prilagođavanje rasporeda i parametara rada kako bi se smanjila potrošnja energije. Studija slučaja je ilustrovala kako izračunati uštedu energije za cevovode, hladnjake za vazduh, ventilatore za peći, pumpe sa promenljivim protokom i klipne sisteme za kompresiju. Pogoni sa promenljivom brzinom su tehnički i ekonomski prihvaćeni u vazdušnim duvaljkama, ventilatorima i pumpama. Potrošnja energije i emisija gasova sa efektom staklene bašte smanjeni su za 67%. Period otplate za ceo projekat je kraći od godinu dana, osim za klipne kompresore čiji period otplate je 6,2 godine.

Ključne reči: energetska efikasnost, optimizacija pumpi, emisije gasova staklene bašte, pogoni sa promenljivom brzinom.