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USE OF VARIABLE FREQUENCY DRIVE TO REDUCE ENERGY CONSUMPTION ON A MATURE OIL PIPELINE

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Abstract

Reducing energy consumption has been an ever increasing concern for the oil industry, and the world in general. As energy costs keeps getting higher, any percentage of reduction can become a great economy in the operating costs. This paper analyses a mature oil pipeline. This pipeline has a 24 inches diameter, 360 kilometers, three pumping stations and a single product. All the stations have pressure control valves and pressure relief valves. The first pumping station has four main pumps, arranged in parallel, and the PCV are active during normal operation. All four pumps have slightly different curves from one another. This makes for an interesting analysis, since using a Variable Frequency Drives on one pump can, and will have different results from another. Since the pumps are in a parallel setting, a hydraulic study of the change of frequency must be a priority. This paper will focus on two main subjects: the technical study of using Variable Frequency Drives in one or more pumps at the first pumping station, without changing the operating flow but reducing the energy consumption of the station and an economic analysis to verify if the investment of installing one or more Variable Frequency Drives on the pumps is cost effective. The paper will show that even in mature pipelines, the use of Variable Frequency Drives is an effective and proven method for reducing the energy consumption without having to worry about changing the operating conditions of the pipeline.

1. Introduction

In the last decade, there has being an ever increasing concern with not only the environment, but with operational optimization and cost reductions. The huge energy consumption by electric pumps in transport terminals or refineries to move products through pipelines has a big effect to the environment and motivates the search for new methodologies to reduce its use. This paper focus on increasing the efficiency of these systems using variable frequency drivers (VFD).

Nowadays, the VFDs have became more reliable and have been more widely used in the oil & gas industry as an excellent choice instead of the PCV valves. PCVs use the principle of dissipating part of the energy that was given by the pump or compressor, which is a very inefficient way to control the pressure and flow. The function of the VFD is to control the rotation of the driver to change the head versus flow and the power versus flow curves. Using this method the energy given to the pump is reduced so there's no necessity to dissipate it.

The use of VFD can cause some problems (for instance, the drivers overheat in some cases were the energy supply is provided by generators) .However, in many oher cases the adoption of VFDs, instead of PCVs to control the pressure and flow justify the additional cost on pumping stations.

Some of the main advantages of the VFDs are listed below:

- Reduce the water hammer effects at the starting and shutdown of the pumps;
- Reduce the cavitation problems through the reduction of the rotation, wich reduces the required NPSH of the pump;

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- Reduction of the detrition on the seals and bearings once that, with the lower rotation, the dynamic load on these elements are reduced;
- Improved Process Control: By matching pump output flow or pressure directly to the process requirements, small variations can be corrected more rapidly by a VFD than by other control forms, which improves process performance.

Beyond all these advantages, the most important is the reduction of the electric energy consume. This reduction can justify the big investment on the purchase of this equipment.

This paper analyzes the installation of one, two or four VFDs on the supply station's pumps on a hypothetic pipeline. This pipeline has four stations that pump crude oil. The study will be based on the comparison between the original case (using PCVs) and using VFDs. All the analyses were made with the software Stoner Pipeline Simulator (SPS). To conclude the paper, an economic viability analysis will be prepared to justify or not the installation of the VFDs.

2. Pipeline Overview

The pipeline used for this study has approximately 360 km and a nominal diameter of 24 inches. It has two pumping stations along the pipeline, without strip or injection until the delivery station. The supply station contains two booster pumps and four main pumps, all centrifugal with a parallel disposal. The pumping stations along the pipeline follow the same pump disposal, with four and five main pumps respectively. Both the booster pumps and the main pumps at all stations operate with at least one pump on stand-by for back up purpose. Using the maximum number of pumps on the pipeline, the supply pumps control valves are active, controlling the downstream pressure due to the pipeline's MAOP limitation. The Figure 1 presents a simple flowchart of the pipeline.

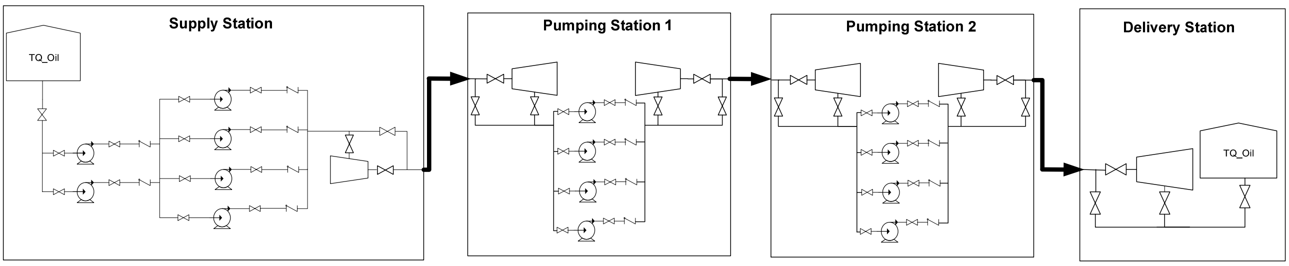

Figure 1 – Flowchart of the pipeline

Each of the main pumps at the supply station presents similar, but not identical curves. This aspect allows for an interesting study using different VFDs options for the pipeline, depending on the number of VFD installed and which pumps they are installed on to. Table 1 shows the main characteristics of each pump at the supply station.

Table 1. Supply Station Pumps Characteristics

Data	Main Pumps			
	MP 1	MP 2	MP 3	MP 4
Type	Centrifugal	Centrifugal	Centrifugal	Centrifugal
Nominal Flow (m³/h)	531	531	531	531
Motor Efficiency (%)	95%	95%	95%	96,5%
Nominal Power (HP)	2800	3000	2800	3000
Power Factor	0.912	0.921	0.912	0.921
Nominal Rotation (RPM)	3585	3585	3585	3585
Nominal Current (A)	336	336	336	336

The oil pipeline used as an example is a dedicated one, using for the most part a single oil blend with very specific characteristics due to the receiving station limitation. Its main characteristics can be found on Table 2.

Table 2. Oil Characteristics

Product	Specify Gravity	Viscosity @ 20 ºC (cP)	Vapor Pressure @ 20 ºC (kgf/cm²)
Oil	0,8907	47,69	0,5

3. Simulation Methodology

To simulate with an acceptable degree of accuracy, a previously created numeric model, created for GL Nobel Denton’s Stoner Pipeline Simulator was used. The model had already been validated with the operating company. The software allows for complex thermal and transient flow equation, using a one dimension simplification. The software has a VFD model for pumps, emulated as an actuator working directly on the pumps current. Four simulation scenarios with different VFD configurations were studied, acting only on the Supply station main pumps:

- No VFD present;
- VFD on one of the four pumps;
- VFD on two of the four pumps;
- VFD on all four pumps.

These scenarios were simulated considering only the maximum number of pumps. To simplify and speed up the simulation, the flow was considered isothermal and VFD power loss considered negligible. The software used simulates the transient flow in pipelines, solving the mass continuity equation, conservation of linear momentum and energy equations using a one-dimensional approximation through finite differential technic. The control valves were kept during all simulations, and there set point can be found on Table 3. The valves opening fraction were used to demonstrate the difference of the VFD usage.

Table 3. PCV Set Points

location	Scraper	Set Point [kgf/cm²]
Supply	Downstream	95.0
Pumping Station 1	Upstream	10.0
	Downstream	91.0
Pumping Station 2	Upstream	5.0
	Downstream	75.5
Delivery	Upstream	5.5

4. Energy Calculation Methodology

The complete viability analysis of the VFDs installation cannot consider only the energy consume point-of-view. The study must analyze also the economic impact caused by the purchase and the maintenance of this equipment and the energy consumption for them. For this analysis, some very common concepts used on project analysis as net present value (NPV) and internal rate of return (IRR) were considered. The Following factors and rates were used for the calculations:

- Discount rate for NPV: 7.9%;
- Annual cost on the investment: 0.5%;
- Annual increase on the electric energy cost: 5%;
- Minimum attractive rate for the investment: 10%;
- Pipeline’s utilization rate: 80%;
- NPV and IRR for a period of 15 years.

To calculate the pumping station's energy use, some average values, based on actual rates from a Brazilian agency of electric energy, were used. These are shown on Table 4.

Table 4 – Energy Costs

Costs	Supply Station	Pumping Station 1	Pumping Station 2
Off Peak Energy (R$/MWh)	230	190	190
On Peak Energy (R$/MWh)	230	300	300
Off Peak Demand (R$/kW)	11	7	7
On Peak Demand (R$/kW)	40	40	40

On off-peak hours, the study was performed for the actual pump's arrangement (3+3+4) but on peak hours, two different cases were considered due to the increase in energy costs: no pumping or 1+1+0 (one pump at the supply station, one at the first pumping station and none at the second pumping station).

To add the additional costs caused by the purchase, installation and maintenance of the VFD, average market values were used. These are reported on Table 5. These values are used in comparative ways.

Table 5 – VFD Equipment Costs

Equipment	Unitary Cost (R$)
3000 CV VFD	956.000,00
Switch for the VFD input	93.000,00
Spare parts for two years operation	96.000,00
VFD's optional	75.000,00
Contactor	80.000,00
Installation material	200.000,00
Installation cost (Overall Cost)	400.000,00

5. Simulations Results

Three scenarios were simulated to compare with the base case, which simulation's results are shown on Table 6, using PCVs to control the discharge pressure. The specific pumps conditions during the base case are shown on Table 7. This case operates with three main pumps, disposed in parallel. The PCV has 49% of fraction opened, the pumps speed is 3585 RPM and the flow in the pipeline is 1321 m³/h. Besides the Supply's control valve, all the other stations control system are inactive. Due to maintenance schedule and a programmed change of rotor, the MP 1 wasn't use in the studies.

Table 6. Base Case Overall Conditions

Location	Scraper	Pressure [kgf/cm²]	Flow [m³/h]
Supply	Downstream	95.0	1321
PS 1	Upstream	10.2	1321
	Downstream	88.5	1321
PS 2	Upstream	18.4	1321
	Downstream	62.2	1321
Delivery	Upstream	6.3	1321

Table 7. Base Case Pumps Output and Overall Power

Supply Pumps	Pump Power [HP]	Pump Speed [RPM]	PCV Fraction Open [%]
MP 1	0	0	0.49
MP 2	2582	3585	0.49
MP 3	2374	3585	0.49
MP 4	3000	3585	0.47

Location	Power [HP]
Supply	8185
PS 1	5556
PS 2	3105
TOTAL	16846

The first scenario simulated was the operation of three main pumps on the supply station. On this first case, it was considered only one VFD on one pump. Considering that the three pumps are not identical, the simulation was done with one VFD, but changing the pump to decide in which the operation could be optimized. The Table 8 shows the results obtained for the first scenario using the VFD on pump 2. The Table 9 shows the results obtained for the first scenario using the VFD on the pump 3. The Table 10 shows the results obtained for the first scenario using the VFD on the pump 4.

Table 8. First Scenario – VFD on the pump 2

Supply Pumps	Pump Power [HP]	Pump Speed [RPM]	PCV Fraction Open [%]
MP 1	0	0	1.00
MP 2	1656	3240	1.00
MP 3	2743	3585	1.00
MP 4	3000	3581	0.47

Location	Power [HP]
Supply	7629
PS 1	5556
PS 2	3104
TOTAL	16289

Table 9. First Scenario – VFD on pump 3

Supply Pumps	Pump Power [HP]	Pump Speed [RPM]	PCV Fraction Open [%]
MP 1	0	0	1.00
MP 2	2970	3585	1.00
MP 3	1562	3285	1.00
MP 4	3000	3583	0.47

Location	Power [HP]
Supply	7762
PS 1	5555
PS 2	3104
TOTAL	16421

Table 10. First Scenario – VFD on pump 4

Supply Pumps	Pump Power [HP]	Pump Speed [RPM]	PCV Fraction Open [%]
MP 1	0	0	1.00
MP 2	2969	3583	1.00
MP 3	2744	3583	1.00
MP 4	1374	3055	1.00

Location	Power [HP]
Supply	7317
PS 1	5556
PS 2	3104
TOTAL	15976

From the results above, it can clearly be seen that the change of pump’s speed can influence positively or negatively on the other pumps that work together in parallel. It’s important to realize that neither the flow in the pipeline nor the pressure changes, as intended.

The first analysis considered the VFD installed on pump 2. The change in rotation caused a great power decrease but also caused an increase on pump 3 power. The power required for this operation was reduced even with the increase of the power on the second pump. The energy differential can be explained due to the lack of loss of energy at the closing PCV. The second analysis considered the VFD installed on pump 3 with similar results from the case above. Through this scenario, it is possible to conclude that the total power consumed is lower than on the first analysis, due to the difference between the pumps in this station.

The third analysis considered the VFD's installation on pump 4 with similar results from the other two cases, but with a much higher power.

The second scenario considered the VFD's installation on two pumps at the supply station. Like the first scenario, this was divided on three possibilities. The Table 11 presents the results for the VFD installed on the pump 2 and 3. The Table 12 presents the results for the VFD installed on the pump 2 and 4. The Table 13 presents the results for the VFD installed on the pump 3 and 4.

Table 11. Second Scenario – VFD on the pump 2 and 3

Supply Pumps	Pump Power [HP]	Pump Speed [RPM]	PCV Fraction Open [%]	Location	Power [HP]
MP 1	0	0	1.00	Supply	7300
MP 2	2019	3330	1.00	PS 1	5556
MP 3	2051	3400	1.00	PS 2	3104
MP 4	3000	3508	0.67	TOTAL	15960

Table 12. Second Scenario – VFD on the pump 2 and 4

Supply Pumps	Pump Power [HP]	Pump Speed [RPM]	PCV Fraction Open [%]	Location	Power [HP]
MP 1	0	0	1.00	Supply	7026
MP 2	2025	3330	1.00	PS 1	5555
MP 3	2747	3585	1.00	PS 2	3104
MP 4	2034	3200	1.00	TOTAL	15684

Table 13. Second Scenario – VFD on the pump 3 and 4

Supply Pumps	Pump Power [HP]	Pump Speed [RPM]	PCV Fraction Open [%]	Location	Power [HP]
MP 1	0	0	1.00	Supply	7113
MP 2	2969	3585	1.00	PS 1	5555
MP 3	1973	3380	1.00	PS 2	3104
MP 4	1940	3180	1.00	TOTAL	15772

If considered purely the energy consume reduction, the results show that the installation of two VFDs on the supply station's pumps regardless of which one will be installed is better comparing with the first scenario. The worst case on the second scenario is 16 HP lower than the best case on the first scenario.

The last scenario analyzed is the installation of three VFDs, one in each pump working. In this case there is only one possible VFD's arrangement. The results obtained for this scenario are show on Table 14.

Table 14. Third Scenario – VFD on the pump 2, 3 and 4

Supply Pumps	Pump Power [HP]	Pump Speed [RPM]	PCV Fraction Open [%]	Location	Power [HP]
MP 1	0	0	1.00	Supply	6948
MP 2	2312	3400	1.00	PS 1	5555
MP 3	2214	3440	1.00	PS 2	3104
MP 4	2191	3240	1.00	TOTAL	15606

As done before considering only the consumed power, the third scenario shows that the reduction caused was bigger than the first and the second. Instead of consuming energy on the pump and the dissipation on the PCV the case causes a reduction on the power consumed.

6. Simulations Results

To have a clearly comparison for the obtained results on the energetic and economic studies of the VFD's operation instead of PCVs to control the pump's discharge pressure at the supply station for the analyzed pipeline several cases were considered as show bellow:

- **Case 1:** Installation of only one VFD on a specific pump, without the possibility to change the pump during the operation. This case was divided into three depending on the analyzed pump:
  - Case 1.1 VFD acting only on the pump 2
  - Case 1.2 VFD acting only on the pump 3
  - Case 1.3 VFD acting only on the pump 4

- **Case 2:** Installation of only one VFD but with the possibility to work on any pump by the use of the contactors. This case was divided into three depending on the analyzed pump:
  - Case 2.1 VFD acting only on the pump 2
  - Case 2.2 VFD acting only on the pump 3
  - Case 2.3 VFD acting only on the pump 4

- **Case 3:** Installation of two VFDs on specifics pumps, without the possibility to change the pump during the operation. This case was divided into three depending on the analyzed pumps:
  - Case 3.1 VFD acting only on the pumps 2and 3
  - Case 3.2 VFD acting only on the pumps 2 and 4
  - Case 3.3 VFD acting only on the pumps 3 and 4

- **Case 4:** Installation of two VFDs on specifics pumps, but with the possibility to work on any pump by the use of the contactors. This case was divided into three depending on the analyzed pumps:
  - Case 3.1 VFD acting only on the pumps 2 and 3
  - Case 3.2 VFD acting only on the pumps 2 and 4
  - Case 3.3 VFD acting only on the pumps 3 and 4

- **Case 5:** Installation of four VFDs one for each specific pump. There is only one possibility on this case.

Two hypotheses were considered for each case for peak hours, as shown on item 5. The initial costs are the same, beyond the considered hypothesis. The Figure 2 presents these investments. As the energy cost increases during the peak hours, an analysis that involves kWh costs must consider the operational changes during these periods:

- **Hypothesis 1:** The pipeline works only during off peak hours, using the maximum number of pumps (3+3+4);
- **Hypothesis 2:** The pipeline operates during the peak hour with a different pump number (1+1+0) as described on item 5.

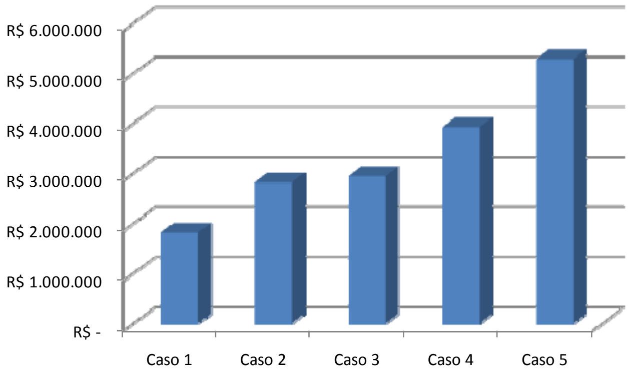

Figure 2 – Initial Investment

For the first hypothesis, the pipeline's utilization rate is 80% because it doesn't work on peak hours, so it only operates with 3+3+4. This hypothesis results into 538 operational hours per month and a monthly energy cost varying for each case. These costs were measured and presented as comparison graphics between the cases. The Figure 3 presents a comparison for each case for the payback and IRR in 10 years, considering the hypothesis that the pipeline doesn't operates at the peak time.

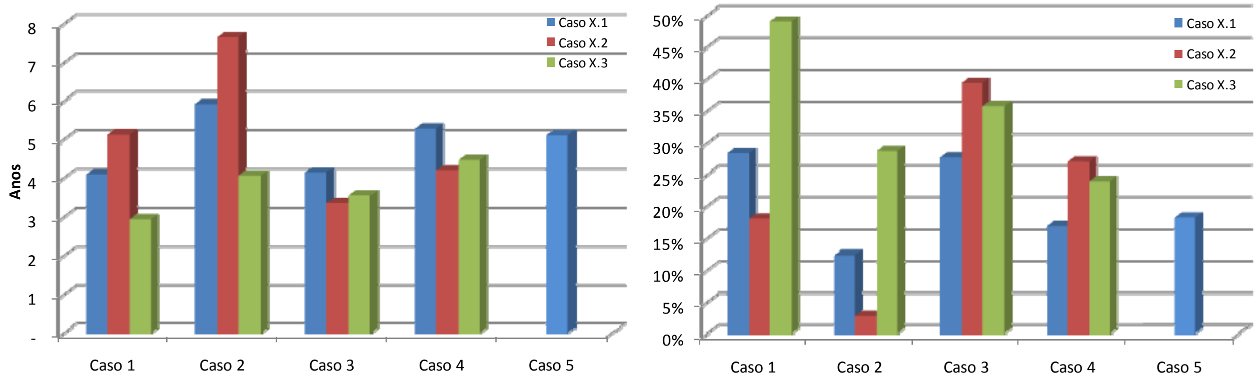

Figure 3 – Payback (left) and IRR in 10 years (right) for each case, considering the first scenario

The Figure 4 illustrates the comparison between NPV's five cases in 10 years considering the hypothesis of stopping the operation at the peak time.

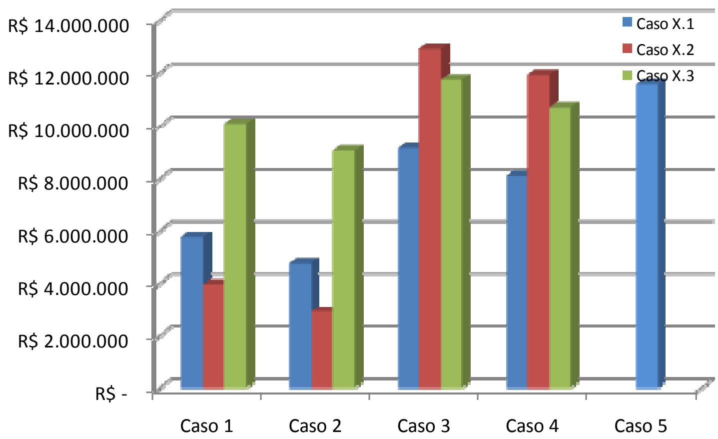

Figure 4 –Comparison between the NPV in 10 years for each case, considering the first scenario

The second hypothesis considers that the pipeline works during all day long (also during the peak hour) but during the peak hour the pumping system is 1+1+0. Based on this hypothesis, the operational time is 542 hour per month operating with the original arrangement (3+3+4). Figure 5 presents a comparison for each case for the payback and IRR in 10 years considering that the pipeline operates with an exclusive arrangement during the peak hour.

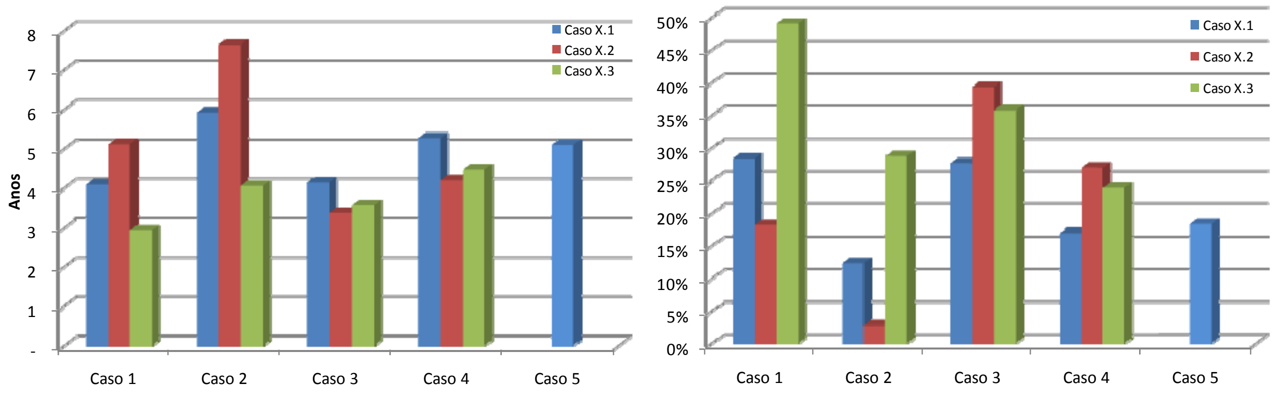

Figure 5 – Payback (left) and IRR in 10 years (right) for each case, considering the second scenario

The Figure 6 illustrates the comparison between NPV's five cases in 10 years considering the hypothesis of operation at the peak time.

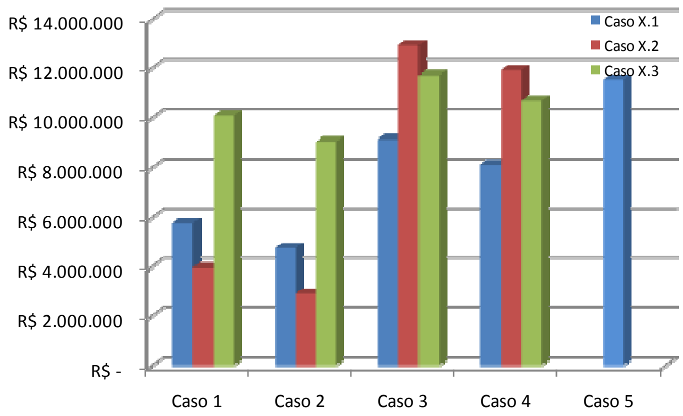

Figure 6 –Comparison between the NPV in 10 years for each case, considering the second scenario

7. Conclusions

As shown above, this paper concludes that the PCV control is not an efficient method to control the discharge pressure. Using this method, the energy loss on the valve means a big loss for all scenarios. Using VFDs was more energy efficient than the base case.

The simulations proved that the most energy efficient possibility was using the VFD on all the operating pumps. The costs involved on the maintenance, equipment and installation represents a huge investment that must be further studied.

The economic analysis shows the best option as the use of two VFDs, not exchangeable (case 3). The case 4 presents an interesting case because the exchangeable VFDs can create a better technique option. Using the case 4 the project will have a better operational flexibility than in case 3 and still be inside acceptable values for the project viability at the considered period.

8. References

IRVINE, G. e GIBSON, I.H. The Use of Variable Frequency Drives as a Final Control Element in the Petroleum Industry, Australia, 2000.