The Application of a 3500-hp Variable Frequency Drive for Pipeline Pump Control

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Abstract—**AEC Pipelines, a Division of Alberta Energy Company Ltd., has expanded the capacity of its Bitumen Blend Cold Lake Pipeline from 130 000 barrels/day (bpd) to 185 000 bpd by the installation of a new midpoint booster pump station utilizing a 3500-hp adjustable speed drive. The unit is a variable frequency induction motor drive (VFD) supplied by GE Canada employing gate turn-off thyristors (GTO's). It was the first of its type in Canada and was the largest induction motor variable frequency drive in a crude oil pipeline application in North America.**

Introduction

AEC Pipelines owns and operates two major pipelines in the Province of Alberta, Canada. A 22-in line transports synthetic crude oil from the Syncrude Canada facility near Fort McMurray to Edmonton. The second pipeline is a dual-line system from the Cold Lake area to Edmonton. A 12-in pipeline carries natural gas condensate to the producers in Cold Lake who in turn use it to decrease the viscosity and increase the American Petroleum Institute (API) gravity of the produced bitumen. The blended bitumen is then transported back to Edmonton via a 24-in pipeline (Fig. 1).

In early 1986 a need to expand the capacity of the 24-in bitumen blend pipeline was identified. This would require the addition of a booster station at the hydraulic midpoint of the line near Bellis, Alberta. Colt Engineering was selected to design the facility. Conventional centrifugal pumps driven by two-pole induction motors were to be employed. Future pump change outs were to be minimized while accommodating a flow range between the present 125 000 bpd to the ultimate line capacity of 400 000 bpd. In addition to the large flow range, the bitumen blend properties can vary between 60 centistokes (cst) to 480 cst viscosity and 5°C to 45°C temperature.

The station would be an unattended facility located in a rural area approximately 140 km from any major center. The existing power service was a 25-kV rural distribution system.

VFD Justification

The engineering and operational concerns for the station both encouraged and complicated a decision as to what type of pipeline pressure control device to use. Conventional practice is a fixed speed motor with a throttling control valve on the station discharge. The other option was an adjustable speed drive with no control valve. The major concerns on choosing a variable frequency induction motor drive (VFD) were

initial capital cost versus energy savings
accepted industry practice
reliability
maintenance.

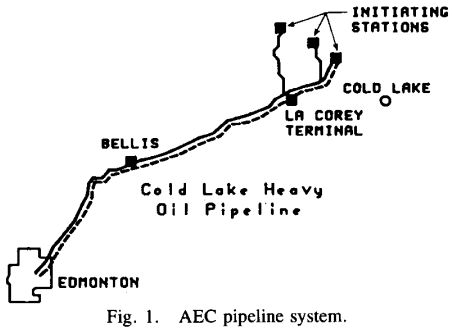

Fig. 1. AEC pipeline system.

The VFD, harmonic filter, associated 5-kV contactors, air conditioning system, spare parts, installation, and engineering would require $800 000 (Canadian) more than fixed speed starters in equipment and installation costs.

The power system in the area had a very limited capacity. It was possible to draw only 3500 kVA starting or operating a motor without building new substations and distribution lines. The use of either reduced voltage or across-the-line starting of a fixed speed unit would have resulted in an inrush in excess of the 3500 kVA allowed. This would then have required an additional capital cost-sharing contribution by AEC to the power utility company to upgrade the 25-kV system of $1 000 000 (Canadian) plus a four-month delay in station startup.

Fig. 2 shows the pipeline system curve plotted on the multispeed head curve for the pump. Present throughput requires the pump to operate at a maximum of 80 percent of rated speed. This results in an overall operating cost savings of approximately $129 000 (Canadian) per year in the first year with a decline in savings as the flows increase in the subsequent years. This provides a discounted cash flow rate of return of approximately 18 percent. Fig. 2 also shows that by proper pump selection, the pump can be continuously operated at its best efficiency point throughout the pumpstation system curve.

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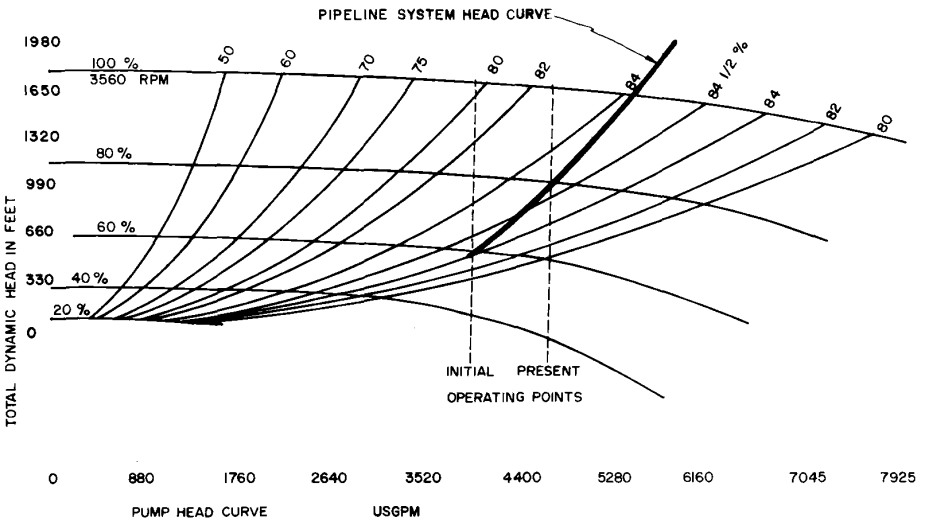

Fig. 2. Pipeline system curve.

An extensive review of similar pipeline applications essentially agreed with the findings of a survey presented at a recent Petroleum and Chemical Industry Committee (PCIC) Conference [3]. There was very limited use of VFD's with induction motors in the oil pipeline industry, certainly none of comparable hp rating in North America. However, based on wide general industry acceptance of VFD's, the technology was considered to be well established and accepted, and not of a "prototype" nature.

The VFD had to perform at least with the same degree of reliability as a control valve so as not to reduce the pipeline service factor. Of key importance in reducing this risk factor was that it was a booster station, and therefore its outage would only cause a reduction in line capacity, not a complete shutdown of the line. Maintenance and troubleshooting of the VFD would be required of pipeline maintenance staff. Vendor support and service had to be readily available for more complex problems. Training was provided both in-house and at the vendor's facility. The VFD was a microprocessor-based system; hence diagnostics are essentially a software function and therefore plentiful. Spare parts totalling approximately 10 percent of the drive cost were purchased.

The final decision was made to use a VFD rather than a control valve due to a lower overall capital cost (the difference between the utility capital cost contribution and the additional equipment costs.) It was felt that the required reliability and maintainability could be achieved.

Description of Operation

The booster pump station is an unmanned fully automatic facility, which is remotely controlled through a supervisory control and data acquisition (SCADA) system. It is designed to incorporate two parallel trains of two series pumps, with a fifth pump being a common spare (Fig. 3). The initial installation consists of one 3500-hp VFD and two 3500-hp centrifugal pumps (P2 and P3). Ultimately the station will be equipped

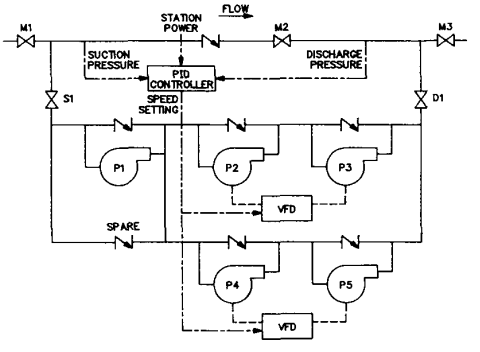

Fig. 3. Pumpstation configuration.

with five pumps and two VFD's. Each pump motor is rated at 3500 hp, 3600 r/min, 4160 V with a 1.15 service factor. The VFD will normally operate a motor between 60 and 105 percent of the rated 3600 r/min.

The VFD will vary the speed of a pump to control the pipeline suction pressure. The pipeline initiating stations use control valves to control flow (Fig. 1). As the flow increases there will be an increase in pressure drop between Bellis and Edmonton that results in a pressure rise at Bellis. The microprocessor-based proportion–integral–derivative (PID) controller then increases the speed of the VFD to reduce the suction pressure back to the set point. This circumvents the need for the traditional control valve and thereby improves station efficiency [6]–[8]. Suction pressure control was used to avoid pump cavitation and provide the simplest operation of the initiating stations.

The VFD is capable of operating only one pump at a time. Separate motor starters were designed and purchased to allow the VFD to start, run, or synchronize to the line either motor. A programmable logic controller (PLC) performs the logic for controlling these starters, the VFD, and all pump station logic [4].

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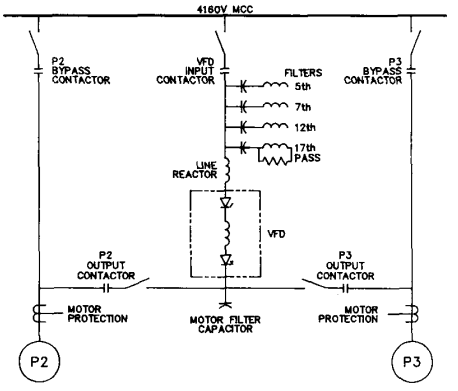

Fig. 4. Simplified single line diagram.

A motor will be started through the VFD and output contactor and accelerated to 60 percent speed. At this point the speed set point from the PID controller is fed to the VFD with the 4-mA minimum signal representing 60 percent or 2160 r/min and the 20-mA maximum signal representing 105 percent or 3780 r/min. If the first pump cannot get down to the required suction pressure at full speed the operator can remotely request the motor to synchronize. The PLC then brings the VFD to within three percent of the rated speed, checks that there is still adequate suction pressure and low enough discharge pressure and power draw, then commands the VFD to synchronize. The VFD will now synchronize the motor to the supply line and then, in conjunction with the PLC, close the bypass contactor and open the output contactor (Fig. 4). This pump will now operate as a fixed speed unit. The operator can then command the second pump motor to start. The second unit will now operate off the VFD the same as the first unit had. Both pumps are in series allowing for continued suction pressure control. The future second train of pumps (P4 and P5) will perform identical to the first.

The VFD speed is set by a PID controller that monitors station suction pressure, station discharge pressure, and station kW power draw. The controller then performs a low select on these three variables, that is, controls off the signal, which would require the slowest speed. The operator will remotely set the suction pressure he would like to achieve and the VFD will be ramped up in speed to achieve this set point. The PID controller monitors all three variables, and if either discharge pressure or power draw reaches the internally programmed preset values, it will control the VFD speed with that variable rather than suction pressure. The discharge pressure is important because, at flows below the rated station maximum, the maximum operating pressure (MOP) of the pipeline could be exceeded. The discharge pressure set point therefore is set near the MOP. The power draw set point is used to prevent setting a higher kW demand than the station normally requires. In Alberta the power company charge on kW demand is normally 50 percent of the overall bill and, once a new demand is set, it remains in effect for twelve months. The kW set point in the PID controller is adjusted periodically if increased flow rates are forecast to be required on a continuing basis.

Equipment Description

The variable frequency drive is a General Electric induction motor drive. It is rated at 3500 hp with the capability to drive the 3500-hp motors to their full 1.15 service factor. The drive is a current source inverter (CSI) with silicon-controlled rectifiers (SCR's) utilized in the rectifier section and GTO's in the inverter end. The supply to the VFD is 4160 V fed through line reactors but without an isolation transformer. The control for the drive is a microprocessor-based digital system. This allows very flexible application, specific control, and excellent diagnostics. The total unit is air cooled with fans exhausting into the electrical room. It was felt that liquid cooling presented greater risk due to coolant leakage and the associated maintenance, although air cooling results in a noisier environment and increased air conditioning costs.

The motors are 3500-hp 3600 r/min units with WP II enclosures. They are a rigid shaft design to eliminate the problem of operating at critical frequencies. The motors have class F insulation and a 1.15 service factor. This provided a safeguard if harmonic heating was higher than anticipated. It also allows future pipeline operational flexibility for variations in viscosity and flow. The motor protection included bearing vibration and temperature, stator temperature, differential current, ground fault, extreme overcurrent, and overload. All motor protective devices were active during VFD operation as well as during across the line operation. The VFD also provided current related protection.

In Alberta the utility applies a strict standard which limits permissible harmonic currents to very low values. This necessitated the installation of a large harmonic filter. The filter contained 3.04 Mvar of capacitance. It consisted of 5th, 7th, 12th, and 17th high pass filters. The 12th was designed to remove the 11th and 13th harmonic currents. Due to the physical size of the filters they were designed as outdoor substation type of structures.

The VFD, motors, and filter were all purchased as a single package. By using a single vendor, we avoided the need to act as a coordinator between the VFD supplier and the filter and motor suppliers. This also squarely placed the responsibility on one vendor to meet the utility's harmonic specification. This proved invaluable as precise values of harmonic currents generated by the drive to both the motor and the filter were difficult to define. The motor contactors and PLC were purchased and programmed separately to provide the customized application required.

Application Complications

Harmonic Currents

The first difficulty that arose when the decision was made to use a VFD of this size was how to meet the power utility harmonic specification. The basis of their specification is telephone interface factor current product (TIF-IT) outlined in [1]. In this installation the measured percent total harmonic distortion (THD) percentage of the voltage was 1.5 percent resulting from the harmonic current levels, which just met the TIF-IT limits. The consequence of this specification was that harmonic current distortion, which normally have been

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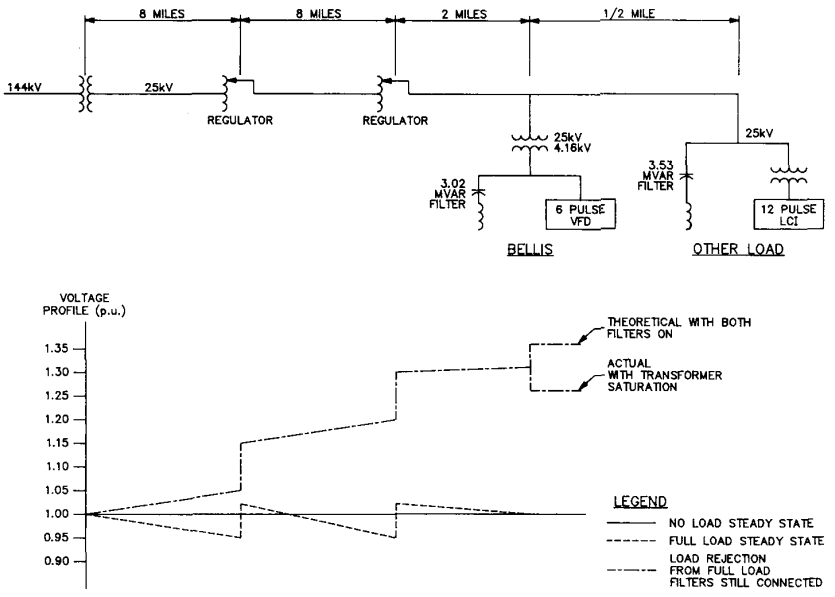

Fig. 5. Distribution system voltage profile.

found acceptable in most locations in North America, had to be filtered out. Due to the specialized nature of filter design it was decided to have the source of the harmonics, the VFD manufacturer, engineer and supply the filter equipment. The vendor still required information from the utility on harmonic impedances of the supply and sources of other harmonics. This proved time consuming and difficult to obtain due to the limited availability of good computer models and the lack of utility measured harmonic data.

Adjacent Loads

A major reason for purchasing the drive was the weak power distribution system in the area. The pump station was to be serviced from an 18-mi 25-kV distribution line. The only other major load was an 8000-hp twelve-pulse load commutated inverter (LCI) drive located one-half mile from the new station (Fig. 5). The adjacent load not only provided for harmonic current interaction but also incorporated a 25-kV 12th high pass filter with 3.53 Mvar of capacitance at the fundamental frequency. With a properly designed filter it was possible to limit the harmonic current interaction. At the 60-Hz frequency the filters acted as straight capacitance. Although the power line had voltage regulators on it, when the 3.53-Mvar filter was energized a 10-percent voltage rise was seen on the 25-kV line. The regulators raised automatically when the 8000-hp LCI drive was operating to compensate for line voltage drop. Upon stopping the LCI drive these regulators provided a further 10-percent rise above the capacitive reactance rise of 10 percent for the one half second prior to the filter also being disconnected. These large voltage swings would be further irritated by the Bellis 4.16-kV 3.04-Mvar filter capacitors. The Bellis station was fed from a 25- to 4.16-kV transformer. The voltage rise on the 4.16-kV side due to the Bellis filter was a further 15 percent. When this transformer was modeled it was found that the transformer saturated at these high voltages and acted as a barrier between the two systems. Therefore rather than experiencing a 35 percent or more voltage rise, it would be limited to 25 percent for one half second as the 3.53-Mvar filter is disconnected then dropped to below 20 percent. The line regulators would then tap down from there to below 10 percent over 45 s. Tests performed during commissioning verified these results. All 4160-V equipment was specified to withstand these over voltages.

Mechanical Resonances

The specification for the VFD motor package included a requirement that the motor be of a stiff shaft design. This was done to avoid the motor operating at any critical frequencies normally encountered on a 3600-r/min motor. It became apparent immediately that different manufacturers disagree on whether a motor can be built with no natural frequencies over this operating range. It was possible though to purchase a motor that had no critical frequency in the range although it had a highly damped natural frequency (i.e., an operating speed which would normally create resonant oscillations but through motor design were damped such that they would not increase in amplitude). Shop tests later done on these motors proved that no increase in vibration could be detected when the motor was run at its natural frequency point.

A more difficult problem was the torsional analysis. Reference [2] outlines the potential torsional vibration problems of applying a large VFD to a motor. The high speed pump had a mass of only one tenth that of the motor, which helped

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to minimize the concern. The VFD generated the harmonic current produced torques and the motor was affected most; therefore the VFD vendor was commissioned to do the torsional analysis. The pump and coupling were provided by a separate vendor, resulting in a slow transfer of technical information between the two vendors. The torsional analysis did prove useful and removed concerns over potential equipment failures.

Displaced Neutral

A CSI drive shifts the neutral with respect to ground. Reference [5] outlines how this occurs on an LCI drive. The same phenomenon is seen in a CSI drive. The drive used at this station incorporated two dc link inductors and therefore had an anticipated worst-case neutral-to-ground voltage of 90 percent of the normal line-to-ground voltage. This would result in a neutral-to-ground voltage of 2100 V or line-to-ground voltage of 4200 V. In this installation it was anticipated that these voltages would actually be lower since the drive output voltage was not 4160 V at full speed and the rectifier side firing angle at full speed was below 45°.

This voltage stresses the insulation on the motor and all equipment on the load side of the VFD. To limit this an ungrounded isolation transformer can be used on the input to the drive and the motors grounded. At Bellis this was not done because the motors must be able to operate either off the VFD or across the line. Grounding the motors would then have introduced multiple ground paths and defeated the effectiveness of the high resistance ground resistor on the 4.16-kV transformer. The motors were instead designed to withstand the higher neutral-to-ground voltages. All cabling and contactors were rated for 5 kV to ground so there was no problem with the equipment.

The only difficulty came in the application of surge capacitors on the motors. These would normally be wye connected with a ground on the wye. When the motors operate on the drive this would have resulted in a ground current. The motors could be tripped by an across-the-line contactor, so it was felt that some surge protection was required. As a result, wye connected surge capacitors isolated from ground were used.

Cooling

The drive package was air cooled with fans drawing air through the rectifier and inverter modules. The dc link was convection cooled. This resulted in approximately 60 kW of heat rejection into the building. Two air conditioners were installed in the building each rated at 240 000 Btu. In the future when a second drive is installed a third air conditioner will be added. At the present one air conditioner can maintain the building to a safe temperature. The second unit brings the temperature down to a comfortable level on very hot days and acts as a backup for the first unit.

Future Installations

The Bellis pumpstation installation was designed very conservatively. It was the first application of a VFD of this size for both the pipeline company and the consultant. The result was that the power system and all the electrical equipment were thoroughly analyzed. Any areas where it was deemed that there was a potential for a problem, an alternate solution was planned in advance.

For future VFD's at this horsepower or larger, serious consideration would be given to liquid cooling. This would reduce the amount of auxiliary equipment required for the VFD and thereby the installed cost. It would introduce new technical complications for avoiding leaks and condensation.

In Alberta, under the present harmonic specifications, a twelve-pulse rectifier bridge would be considered. The twelve-pulse design reduces the amount of harmonic filtering required [1]. This not only reduces the filter cost but also simplifies the installation. The decrease in the amount of capacitance would eliminate the voltage rise problems.

In the long term as industry and utilities gain experience with large rectifier loads, a better understanding of harmonics will become available. This will allow more precise modeling and smaller filter designs. At the present time the tools for analyzing harmonic currents, voltages, and their angles produce data that only partially define the sources of possible problems. The result of more experience will also promote realistic standards.

Results

The station and drive commenced operation in July 1987. We have yet to experience an outage caused by the VFD itself or associated equipment. In addition to the economic benefits the VFD has provided many less tangible benefits:

- greatly reduced wear on mechanical equipment and seals due to slower operating speed and acceleration,
- expanded range of overall line flow control,
- unlimited number of repetitive starts,
- greatly improved suction pressure control particularly during startup,
- elimination of surging during startup,
- reduced noise levels due to slower speed operation and absence of a control valve,
- avoidance of annoying power dips for other rural customers.

The VFD concept has been well received by the pipeline operating and maintenance groups.

Conclusion

We believe that variable frequency drives will gain wider acceptance in the oil pipeline industry. While their application has to be studied on a case-by-case basis, they are particularly suited to a pipeline system such as this, which is providing for significant growth in the next five years. The justification, however, should consider more than just the economics, particularly in Canada where electric power is still relatively inexpensive. Our concerns regarding reliability, proven technology, and maintainability continue to diminish. AEC, along with Colt, are presently installing a 5000-hp variable frequency drive at the LaCorey Terminal for startup in January

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1989. This unit was justified on energy costs and a strong preference by the operating group.

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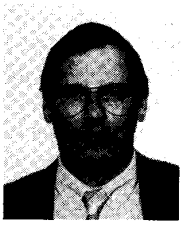

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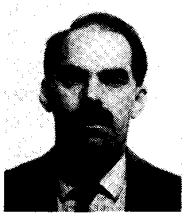

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