BEST PRACTICES: PLANNING AND ENGINEERING THROUGH PRODUCTION FOR REPLACEMENT OF 16,500HP ADJUSTABLE FREQUENCY DRIVE SYSTEM

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Abstract — Application and installation of high-power AFD's (Adjustable Frequency Drives) in the oil and gas industry requires a significant allocation of resources and a large "tool box" in the evaluation and deployment of tailing pumps as capital equipment. This paper was authored to describe a single successful installation of a 16,500 HP medium voltage AFD replacing an existing tailing pump AFD in an effort to increase process availability. This case study was written in a manner to provide a roadmap of key performance indicators, AFD design characteristics, life-cycle phases, and target measures used to support the goals and objectives of efforts in engineering, operations, and maintenance planning.

This paper includes an explanation of major life-cycle stages of the project such as: initial planning; design for the purpose of modernization; business case development for funding approval; project execution through detailed engineering; manufacturing and functional testing; project execution; installation; commissioning; trial runs; factory acceptance testing; development of a maintenance strategy and planning for future replacement. The paper also addresses engineering of major AFD elements (power conversion, cooling system, control system and accessories).

Index Terms— (AFD - Adjustable frequency drive, PWM - Pulse width modulation, IGBT - Insulated gate bipolar transistor, THD - Total harmonic distortion, MTBF- Mean time between failures)

I. INTRODUCTION

Tailings are a mixture of fine clay, sand, water and residual bitumen produced during the extraction process that separates bitumen from the oil sand. Tailings are pumped into holding ponds to settle solids from water. When tailings are released to a pond, the heaviest material – mostly sand – settles to the bottom, while water rises to the top. In a continued effort to address economics in oil and gas production, tailing AFD equipment availability improvement was observed to ensure strong production and prevent unplanned outages of tailing process equipment. The 16,500HP medium voltage AFD controls five 2500HP motors which drive the pumps for the tailing process.

II. BACKGROUND

The operations department of one of the oil-sands producers in Alberta, Canada, has highlighted their aging AFD equipment as a production risk. They have performed assessments for replacement of the AFD's used in their tailing pumps. These assessments are most important, since the equipment has reached, or is close to the end of its life expectancy. The tailing pump AFD equipment plays an essential role in ensuring higher availability of tailing pumps for overall production. In the oil-sand industry, the downtime costs are usually much greater than even the fully burdened cost of replacing the drive. Unplanned downtime is devastating and costly.

The older AFD used on the tailing pumps had legacy technology; the onsite spare-parts inventory availability was low due to the age of the technology and scarcity of spare parts. Sporadic faults were occurring with this older AFD equipment, causing availability issues that directly affected productivity of tailing processes. These AFD-related issues were leading to unplanned outages and maintenance work that was untimely and costly. Based on feedback from the maintenance team, the frequency of unplanned outages was approximately 72 hours per year, including production restarting cycle time. The total indirect production losses in one year with old AFD were the following:

Unplanned outages cost calculations-
Total unplanned outages hours are 72 hours
72 hours x 3000 tons/hour = 216,000.00 tons
0.6 barrel oil production per one ton, so total barrels are
216,000.00 tons x 0.6 barrel/ton = 129,600.00 barrels
129,600.00 barrels x $66 ($100 average barrel price - $34 production cost) = $8,553,600.00
Total indirect production losses are equal to $8,553,600.00

The goal is to maximize tailing processing whilst maintaining maximum AFD availability. The decision for AFD replacement was based on reducing the frequency of unplanned outages, and increasing process throughput. Also, another key objective was to continue to optimize operating costs of the tailing pump AFD by enhancing the system's efficiency, lowering harmonics, reducing spare parts inventories and reducing maintenance costs.

This case study was developed to explain the differences between old and new AFD design characteristics, life cycle phases, objectives of the business case, modernization studies, engineering, testing, and operation philosophies. Another intention was to provide measures used to support the goals. The following Key Performance Indicators (KPI's) were considered for the modernization case study to replace tailing pumps AFDs:

Business KPIs: Productivity, quality, safety;
Operational KPIs: Yearly throughput, availability, reliability;
Maintenance KPIs: Ratio unplanned vs. planned outages, maintenance costs, asset condition;

Reliability was considered as the probability that the tailing pump ASD equipment performs its intended function for a specific interval under stated conditions. Availability was considered as a measure of the degree to which tailing pump ASD equipment is operable and committed at an unknown point in time.

Availability [%] = (Planned production time – total downtime by maintenance / planned production time) x 100

Reliability [%] = (Planned production time – total unplanned downtime / planned production time) x 100

III. AFD REPLACEMENT LIFE CYCLE PHASES

Replacement projects for medium voltage AFDs are not simply a purchase of replacement equipment. The approach is complex, including engineering that may be required in order to assess the multiple requirements that allow a newer model to fit physically and electrically. The procurement of equipment also requires the installation, commissioning and testing onsite. Importantly, procurement on its own does not include downtime cost. Downtime costs are usually much greater than even the fully burdened cost of replacing the drive. Unplanned downtime of tailing pumps is devastating; hence, operation and reliability teams started working on the replacement plan together.

A. Planning AFD Replacement

The drive system replacement included a step by step approach with:

- Identification of ongoing issues and solutions,
- Planning tailing pump AFD replacement,
- Economic justification and business case development,
- Specifications development,
- Modernization scope study,
- Detailed engineering,
- Manufacturing of the AFD,
- Test and acceptance,
- Production outage planning,
- Installation and commissioning, and
- Operation and maintenance

Normally, expected average AFD life is 20 years (per manufacturer's AFD product manual) with possible failures occurring normally in the last 5 years of predicted operating life. During those last 5 years, the ongoing and performance related issues for the tailing pump AFD were emergency breakdowns, unit performance issues that increased down-time. In legacy conditions and in this case [equipment 15 years old], spare-parts are often not readily available to apply to the AFD, which contributes toward lower tailing pump availability, and raises concerns about AFD reliability due to aging. The operation and maintenance team had provided feedback to the reliability verification team regarding frequency of ongoing issues in the last 5 years of the subject AFD lifespan. When the subject AFD had aged close to its predicted life expectancy, the reliability verification team then began writing a business case supporting replacement. With the assistance of an AFD vendor, the team completed the case to replace the tailing pump AFD with newer, more modern and reliable equipment. The business case included a comparison of the existing AFD with criteria to contrast the replacement AFD against parameters in order to decide whether to replace the existing AFD or to retrofit or upgrade the existing AFD hardware.

Comparison criteria for the existing tailing pump AFD were as follows:

- AFD design characteristics, physical size;
- AFD efficiency, power factor and harmonics;
- Frequency of unplanned outages of existing AFD;
- Frequency of required planned outages to maintain minimal AFD performance;
- Operating time in percent/year;
- Spare-parts availability;
- Required maintenance resources for trouble shooting and repair of parts.

The above parameters of the existing AFD were compared against a new AFD. Planned outages are scheduled outages for the purpose of routine maintenance and to check the equipment health, or to optimize AFD equipment for process optimization. Unplanned outages occur due to unforeseen situations such as emergency break-downs that create unexpected production loss. Unplanned outages represent the greatest loss of production; hence between the two types of outages, also represent the greatest cost. Costs of critical inventory spare-parts, inventory reliability verification, optimization resources, repair, maintenance, tools and/or special resources costs are much lower when compared to unplanned outages (refer to section II unplanned outage cost calculations as per end user).

As shown in Fig.1 the decision was made to replace the tailing pump AFDs. This was the most economical, cost effective and fastest way to improve the reliability and refresh the process equipment. The decision was made based upon the above criteria, the equipment age in its lifecycle, and detailed studies comparing the aged equipment against new equipment.

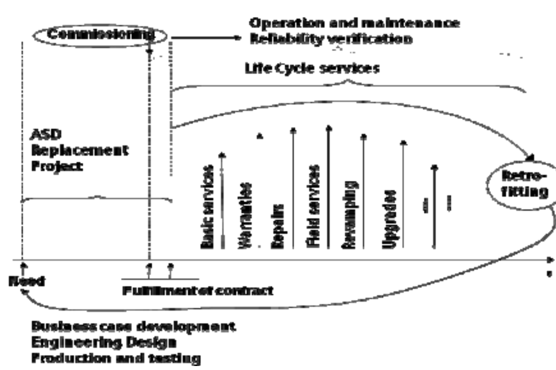

Fig. 1 LIFE CYCLE SERVICES

B. Modernization Study

During this period, a modernization case study was performed to support the installation of a new 16,500 HP AFD. Identified in Fig.-2 are some of most important factors related to AFD design characteristics and life cycle stages that operation, reliability, and project teams considered during their engagement in the replacement of tailing pump AFD equipment of 16,500HP capacity. In this case, the new AFD was selected with an integrated design that results in an AFD with a smaller footprint, simplified design and integral system testing prior to shipment to site.

Previous AFD was traditional in design and had five separate components: harmonic filter, power factor correction components, transformer, power converter (AC/DC, DC/AC and link capacitor or inductor) and motor output filters (as shown in Fig. 2 and single line circuit diagram of old tailing pump AFD in Fig. 3. Fig. 2 is the block diagram view of the old AFD circuit diagram shown in Fig. 3.

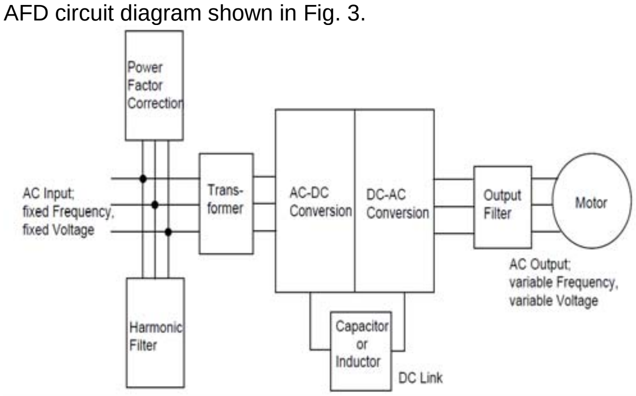

Fig. 2 OLD AFD BLOCK DIAGRAM

The current harmonics at the input of the power conversion section causes additional power losses on the isolation transformer and this consequently required over sizing compared to a scenario with equivalent power ratings but in presence of sinusoidal variables. Propagation of the harmonic contents through the isolation transformer into the power line upstream of the AFD and into the motor downstream of the drive would be detrimental. Current harmonics at the primary windings of the isolation transformer would result in voltage harmonics into the power system feeding the drive and could adversely affect other pieces of equipment connected to the same power distribution system: the higher the short circuit impedance of the line feeding the AFD, the more severe this phenomenon.

The impact to other equipment operating on the same power distribution system could include: erratic operation, additional overheating or even permanent damage. The harmonic content of the voltage waveform at the converter output could overstress the insulation system on the motor resulting in either a lower life expectancy or a relatively rapid degradation and subsequent failure. Due to the inherent low-pass filtering action of the motor windings, low order voltage harmonics could likely generate low order current harmonics which would overheat the motor windings with further degradation of their insulation. These current harmonics circulating through the motor windings would likely result in additional torque pulsations. The low power factor at the input of the converter would require higher current at parity of motor shaft power demand, requiring larger cross section conductors in the transformer and in the feeder to the AFD. Larger conductors are more expensive and installation can be more challenging.

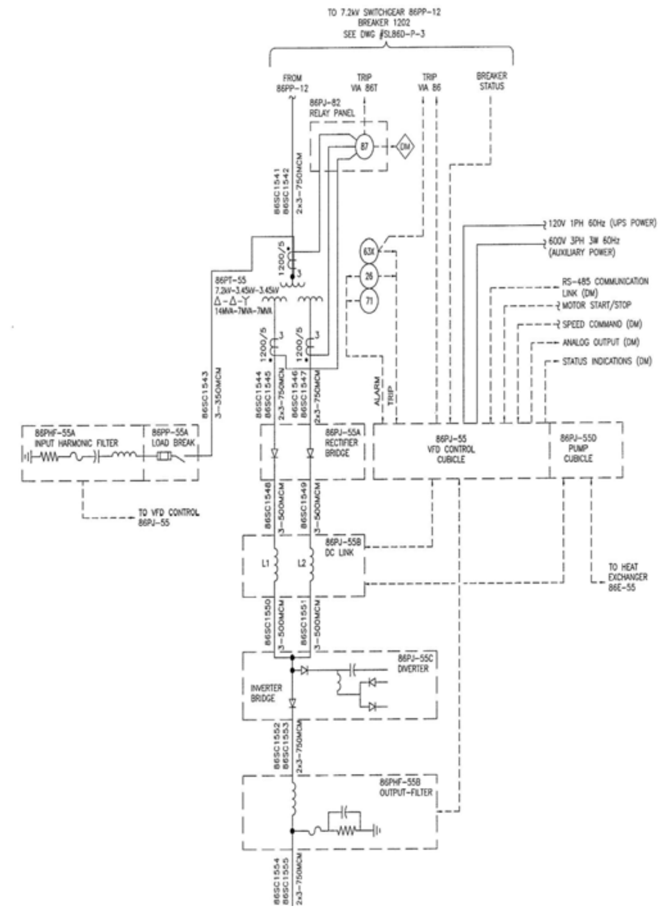

Fig. 3 OLD AFD SINGLE LINE CIRCUIT DIAGRAM

In the old AFD, traditional current harmonics at the input of the drive were confined in the drive itself by using harmonic filters. These were typically comprised of capacitors and resistors whose values were such to make them optimally tuned on the spectrum of the harmonics that need to be attenuated. Power factor correction was achieved using appropriate banks of capacitors, sometimes in conjunction with an active control that varies the number and connections among the capacitors depending on the load on the AFD. Similar considerations were applied to the output filter, where capacitors in parallel to the output busses of the drive and inductors in series to the conductors to the motor could be used for mitigating the propagation of output voltage harmonics and associated currents. Since both harmonic filtering and power factor correcting apparatuses comprise real components, these as such inevitably take real estate for their installation and dissipate some power as well. Their failure rate was affecting both availability and reliability of the old AFD as a system by contributing to unplanned outages.

In this study phase, the reliability project team began investigating elements such as dimensions of new equipment against the existing. A new AFD power enhancement [increase] requirement was examined and a rating of 16,500

HP was calculated based upon the desired future capacity. A total of 5 x 2500 HP pumps were identified for total capacity. The fifth pump was considered only for future expansion of the tailing process. At that point, the upstream power requirements and power scheme was identified. The digital and analog inputs and outputs as well as controls were all identified and documented. Mandatory process interlocks were also designed into the scheme. At this stage of the project, the reliability and sustainable project teams began interfacing with the production team and planned the pump outages. The evaluation was performed for hot transfer or swapping of the new AFD system with the old AFD to minimize the production outage. Installation checks for 16,500HP AFD's with new electrical houses, commissioning, start-up and onsite testing of new AFD were also examined. The planning was initiated to uninstall existing power equipment such as transformers, harmonic filters, controls, and other redundant or unneeded legacy components.

C. Business Case Approval

Due to the high level of this project's value, equipment replacement is either considered under the plant sustainable project budget for reliability, or it is considered as a capital project. The project can sometimes be more difficult to implement under the maintenance budget, especially with a high cost replacement such as this. This project was considered under the reliability and sustainable project budget that was handled by the sustainable projects group at end customer side. The financial evaluation for the project criteria was performed in a business case fashion in order to evaluate whether or not to replace the AFD. In this business case, many cost sources were calculated and compared related to both production as well as the replacement project cost for tailing pumps AFD.

Planned outage costs are mainly defined as lost production due to the element of scheduled maintenance. The regular scheduled maintenance of the AFD equipment is required for preventive maintenance, to optimize AFD system performance, and increase the reliability. Unplanned outages are mainly lost production costs that can occur due to unforeseen emergency break-downs. The frequency of unplanned outages generates losses proportional to financial losses which include both direct losses (production) and indirect losses (downtime resources and process restarting). Capital investment costs are mainly: cost of AFD equipment and the engineering and project resource costs. The inventory costs include: critical spare-parts, inventory reliability verification, and optimization resources cost. Repair and maintenance costs comprises: routine repair resources, routine preventive and demand maintenance resources including tools and special resources costs. Energy costs include: efficiencies, power factor, and other operational losses. These were all calculated for the new AFD installation. All of the costs were considered in the business case. After careful review, the cross-functional team decided to approve the replacement of the tailing pump AFD to, in large part, reduce unplanned outages frequencies. After the project was approved, the plant engineering team developed the AFD specifications based on power and control requirements and procurement was initiated. The detailed engineering was started by both the end user and the AFD vendor's respective engineering teams. The detail engineering effort includes power, controls design and detailed specifications including company, industry standards provided by the end customer. Bid was quoted by AFD vendor as per industry standards and end customer's specifications. Detail proposal review conducted by end customer's engineering teams and contract was awarded to AFD vendor.

D. Engineering and Execution

The engineering and execution phase includes product specification, overall project management with the AFD vendor, detailed design engineering, power and control strategy development, manufacturing of AFD, and functional and acceptance testing.

For the AFD detail engineering design, AFD topology was designed to meet the requirements typical of the industry. A new AFD has an integrated design, with only two major components: an isolation transformer and a power converter. For the successful and effective implementation of an integrated design, these two components have to meet stringent requirements which negate the need for the rest of the components normally included in a non-integrated design (as shown in Fig. 2). Advanced design for a new AFD with multi-voltage level topologies allows generating output voltage waveforms with a less pronounced ripple and consequently, a lower harmonic content. Due to low magnitude of the output voltage ripple; there is no longer need for an output filter without impacting the motor life expectancy [1] (*ref:* IEEE PCIC paper 2012-50 on optimizing motor and drives packages for best cost of ownership, performance & reliability). Additionally, a multi-voltage level topology is designed to cancel most of the current harmonics at the primary windings of the isolation transformer, hence the secondary windings only require over sizing due to distorted current waveforms whereas the primary windings can be sized for regular sinusoidal variables. Input and output filter components, power factor correcting and harmonic filtering apparatuses are no longer required as well. The simplicity of an integrated design results in a more straightforward system with fewer components, thereby increasing availability and reducing downtime.

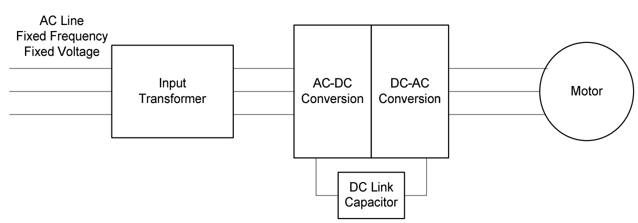

Fig. 4 NEW AFD BLCOK DIAGRAM

Specifically, an integrated design (Fig. 4) also makes it easier for the entire drive system to be thoroughly factory tested and then shipped to the site, as opposed to other designs that are often not tested as a system until all components arrive on-site and are inter-connected. Because the integrated unit has been thoroughly tested and requires no interconnecting wiring on-site, the AFD is assured to work as designed when delivered, reducing commissioning efforts and startup time. Factory testing of the complete integrated drive system also ensures accurate efficiency measurements, which is important for sustainability. Another innovation related to a multi-voltage level topology that increases availability is the use of a series of low-voltage cells ganged together in a building block approach to create the medium voltage power output required by the AFD. Low voltage cells utilize widely used power electronic components characterized by low failure rates. Moreover, if the AFD employs this building-block approach, then it is possible to easily include the bypass feature in the AFD design facilities for quickly bypassing a failed cell while the AFD continues to operate [2] (*ref:* IEEE PCIC paper on five years of continuous operation with adjustable frequency drives, IEEE article by D. Eaton and P. Hammond).

A design feature of the new AFD that improves reliability is fault tolerance, a function that ensures operation in the event of a non-critical fault. This fault tolerance strategy ensures that the AFD resists tripping on a fault of a single device of the AFD, safely awaiting a second confirming indication that a problem actually exists. This fault tolerance strategy can also provide a hierarchical series of warnings of AFD or component failures. Fault tolerance gives an operator significant time to review the situation and avoid a system shutdown. Because the AFD equipment is able to maintain operation in the event of a non-critical fault, fault-tolerant AFDs are used in many critical industry applications in oil and gas production process, other industries, including tailing process in refineries. High-availability medium voltage AFDs with fault tolerance and bypass was preferred for use in the tailing applications which provides the process availability. A new AFD with a higher reliability also has less required maintenance, further contributing to lower operating costs. Figure 4 shows the arrangement of the power section of a new selected AFD for tailing pump.

Figure 5 shows the connection of a new integrated AFD system with upstream power supply. The new AFD is much simpler in comparison to the old AFD shown in figure 3. Detail design engineering of 16,500HP AFD was completed based on technical details and specifications including sizing and selection of components. Control interfaces were identified based on process requirement and existing AFD study.

The following are the power and control specifications of new AFD

1) Specifications:

Ratings: 2500HP, 7200V, 215A each
Total 5 motors operating with 1 x 16,500 HP AFD
AFD input power: 7.2 KVAC, 1176A AC, 3PH, 60Hz
AFD output: 16,500HP, 7.2KVAC, 1250A, 3PH, 60Hz
Control power: 120VAC, 15A, 1PH, 60Hz (6 total)
Heater power: 120 VAC, 15A, 1PH, 60Hz each (3 total)
Cooling Pumps LV VFD power:
518VAC-632VAC, 50A, 3PH, 60Hz (2 total)
MV power sections – NEMA 12/IP54 enclosure
LV control section – NEMA 1/IP21 enclosure

2) Applicable Standards:

All applicable standards were identified and met. Listed below are applicable for the AFD. If the standard is not identified as a requirement, there are no guarantees the product will be design to meet them.

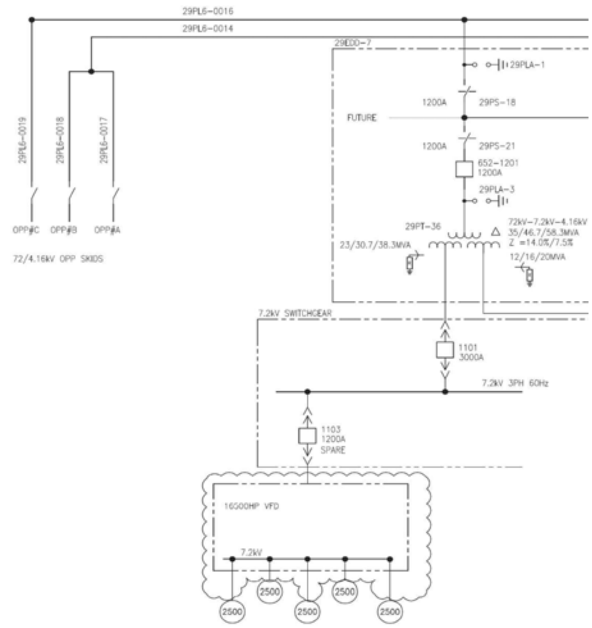

Fig. 5 NEW AFD SINGLE LINE POWER DIAGRAM

3) Transformer:

The new selected AFD transformer has multiple 3-phase secondary windings resulting in a 36 pulse configuration. Secondary windings are properly phase displaced to provide optimal harmonic cancellation and power factor greater than 0.95 at any time on the input line side. Isolation transformers are direct liquid cooled design and windings are made of copper tubing where the coolant flows through. The main transformer specifications are following:

- 16,500KVA, liquid cooled, dry type integral indoor input isolation transformer with 7200V primary
- 95 KV BIL rating
- 7200V, 3 phase 60Hz AC input, 0-7200V output.
- 600V pre-charge winding
- Number of Secondary's (750V) is 18 + 1
- Enclosure size is 125" H x 148" W x 76" D.
- 80 degree and 90 degree thermal switches
- RTDs in each cooling path to monitor temperature
- 12-gauge steel panel and copper tube windings
- Ground pad 4"x 4" for RTD box grounding and panel
- 2000A, Line side, Tin Plated Copper buss with protective boots, bracing and stand offs to meet transformer 95kV BIL rating and short circuit rating

4) No Output Filter:

Figure 6 shows a single line diagram of the new AFD topology which is an integrated design. Complete power converter modules (power cells) are connected in series to achieve the required output voltage. Each module (power cell) is fed from an isolated secondary winding of the input transformer. Each module is virtually a self-contained single phase IGBT-PWM drive. Given the number of pulses (18 or higher) at the output, satisfactory output harmonic content can be achieved with no need for output filters even on applications retrofitting existing motors. Secondary winding voltage is only

750 Vac nominal, hence no high voltage power electronic components are required and the voltage gradient (dv/dt) on motor windings is limited. The available cell bypass feature allows bypassing a cell in case it fails so that the drive can keep operating, which improves tailing pump availability. Multiple cells can be bypassed with the constraint to have at least one functional cell on each output phase.

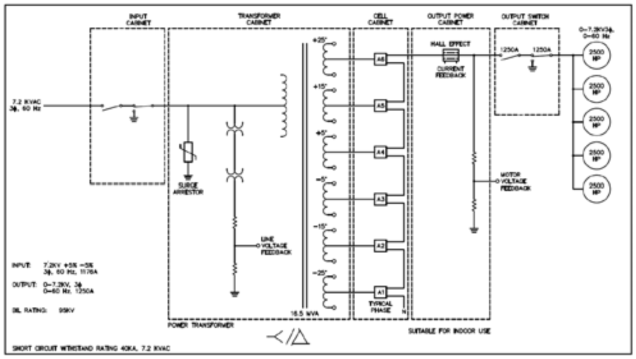

Fig. 6 NEW AFD SINGLE LINE DIAGRAM

5) Cooling System:

The cooling system is an integral part of the AFD. The liquid cooling systems of AFDs are more complex than their air-cooled counterparts. Liquid-cooled systems are engineered specifically for the application, considering outdoor ambient temperature, cooling water availability, criticality of the driven process and the level of redundancy required. By nature, liquid-cooled ASD systems are applied to large (multi-megawatt) motors and loads. Since these tailing pumps are mission critical, they demand the highest levels of safety, reliability, availability, and efficiency. AFD cooling systems typically include the following equipment and instrumentation:

- Motor driven coolant pumps
- Control system
- Instrumentation and sensors for conductivity, temperature, pressure & flow
- Coolant reservoir or tank
- Deionizer cartridge & filter
- Pipes, valves, & actuators
- Heat exchanger

The cooling system of the AFD is designed to provide redundancy for single point failures of any of the following components: pumps (motors, inverters, blades, housing), valves (relief), sensors (pressure, temperature, flow), and filters / deionizers. The AFD cooling control system is capable of detecting failures in the identified components. The coolant cabinet is designed with 60 inches width. The coolant flow is maintained by means of two fully redundant coolant pumps. Both pumps operate during normal operation. If one fails, the other shall increase speed to maintain required total system flow. Each pump motor has a separate power source through small low voltage AFDs to maximize energy efficiency and better flow control.. Pump speed and resulting flow rate is closed loop controlled, based on cell modules and transformer temperature set point and feedback. The coolant flow required by the transformer is determined by the transformer KVA rating, number of secondary windings, and resulting design losses. Vertical centrifugal pumps with a higher efficiency are used and the pumps selected for this application has suction and discharge ports in the same plane. Pumps, check valves, sensors, the deionizer tank, and the cooling control system are configured in such a way that isolation is possible and components in the cooling system can be removed and replaced during AFD operation. The cooling and ventilation are both designed for the worst case heat load (50°C drive ambient temperature with 40°C drive coolant inlet temperature or 40°C drive ambient temperature with 47°C drive coolant inlet temperature, concurrent).

The deionizer tank was designed as follows:

- Deionizer tank includes a visual indicator to show flow rate for deionizer circuit. The deionizer tank is designed to hold resin with 20,000 grains / gallon for a single tank system, 50,000 grains / gallon for a dual tank system.
- The deionizer tank assembly is configured in such a way that it is not possible to mount and install the tank backwards, resulting in reverse flow and restricts the conductivity to one (1) micro-siemens
- An option is provided for dual expansion tanks, which is required when coolant volume exceeds the capacity of a single tank. A single expansion tank system shall support up to 250 gallons of coolant. Dual expansion tanks shall support between 250 – 500 gallons of coolant.

Separate coolant fill and coolant drain pipe lines are provided near an access door for a service-person to add or drain coolant as necessary, regardless of operating condition. Isolation valves and swing valves are placed in series with these fill and drain pipe lines, making it possible for coolant to be added or removed while the AFD remains in operation. The cooling liquid used in the coolant cabinet system is de-ionized water with 0 to 60% propylene glycol. The coolant cabinet system is designed to create rated flow with 60% glycol and inner loop temperature of 25°C.

6) Cooling Controls:

The cooling control system is connected to sensors in the coolant cabinet including flow meter, temperature sensors, pressure switches, conductivity meter, coolant cabinet leak detector, and water tank level switches through expansion I/O modules. The following are descriptions of the individual parts of the coolant control system:

a) *Leak detection:* A leak detector is installed in the coolant cabinet to detect the presence of liquid coolant on the cabinet floor. If coolant is detected, the leak detector sends a signal to the control system to trigger an alarm.

b) *Flow and pressure sensing:* Flow and pressure sensors provide the flow and pressure actual values to the control system which uses this data to control pumps and generate alarms if necessary. If either a 'loss of flow' or an 'over-pressure' fault is detected, the control system will shut down the faulted pump and initiate the associated alarm. The logic also identifies a failure of the flow sensor.

c) *Temperature sensing:* The temperature sensing logic is used for combination of inlet water temperature, cell outlet temperature and transformer outlet temperature monitoring to monitor the effectiveness of the coolant system and to identify component faults. This logic also recognizes when a sensor has failed.

d) *Coolant level monitoring:* Coolant level monitoring is continuously checking the level of coolant in the coolant tank reservoir. Very low levels may indicate a leak in the coolant control system. High levels in the tank may indicate an over-pressure situation. This logic checks sensors to determine the level of the tank and provides signals for ‘High’, ‘Low’, and ‘Low-Low’ water level conditions.

e) *Conductivity monitoring:* Conductivity monitoring logic is constantly monitoring the water conductivity for high and very high conductivity situations. A 4-20ma readout signal is provided to indicate coolant conductivity to the cooling control system which uses this data to send alarms for High (> 3 micro-Siemens) and High-High (> 5 micro-Siemens) conductivity level detection.

f) *Heat exchanger fan control and voltage monitoring (air-to-water heat exchangers):* The heat exchanger fan control function monitors temperature levels in the coolant system and determines the number of heat exchanger fans needed to maintain the acceptable temperature range within the AFD. Logic is always set to prevent excessive cycling of heat exchanger fans. Turn-on temperature thresholds and the cycling time schedule are programmed through the HMI.

g) *Alarm handling:* Alarm handling logic detects faults in the coolant system. Event logging is maintained to store a complete record of all alarms and events that have occurred in the AFD. Data Logging is also maintained as a record of the cooling control system operation data.

7) Heat Exchangers:

The water to air heat exchangers are used to exchange the heat to cool the new AFD. The AFD heat losses are mainly removed using a mixture of de-ionized water and propylene glycol. Heat exchangers for this AFD are designed to meet CRN (Canadian Registration Number) requirements which include a special manifold design. Also the heat exchangers are CSA (Canadian Safety Authority) certified with below specifications:

- Total capacity: 1730,898 BTUH
- Airflow: 98,096 CFM
- Elevation: <3300 FT AMSL
- ENT fluid temp: 131.8 deg F
- LVG fluid temp: 116.6 deg F
- Fluid flow rate: 264 GPM
- Fluid: 50% propylene glycol
- Fluid pressure drop: 28 FT H2O
- Ambient air temp: 104 deg F
- Max working pressure / temp: 150 PSIG@200 deg F
- Fan speed: 1140 RPM
- Fan Type: Composite
- Fan motor Qty-HP: 10 - 3HP
- Fan motor voltage/freq./ph/amp: 575V/ 60HZ/ 3ph/ 3.53A
- Fan motor type: TEFC

As shown in Fig. 7, the liquid-to-air heat exchangers include the following construction features:

- Headers / manifolds are furnished installed on each exchanger such that the customer supply and return connections are via single, separate 3 inch, 150 lb, flanges incorporating an isolation valve in each connection.
- Construction of 62 inch legs on each heat exchanger.
- Heavy Duty Heat Exchanger; with 5/8”x 0.025 AW copper tubes, 0.010”Aluminium Fins (9 fpi), with the stainless steel heat exchanger manifold, nitrogen purged during fabrication, 2.5” shutoff valves isolation manifold with 3”CTS flanged “inlet and outlet connections, 1”drain / vent connections.
- The heat exchanger is designed for 150psig operating pressure and tested at 225psig and designed to operate outdoors in an unprotected environment
- Special shutoff valve designed for isolation manifold with 3” CTS flanged “inlet and outlet connections per customer specifications

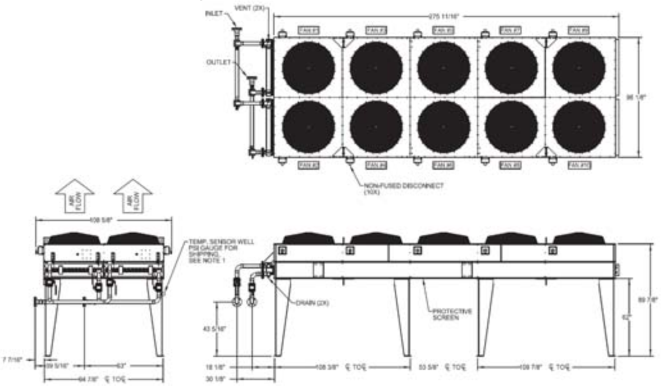

Fig. 7 HEAT EXCHANGER

A 60 percent propylene glycol / 40 percent de-ionized water AFD cooling fluid is being circulated through each heat exchanger. This mix is referred to as the liquid coolant. The maximum heat load to be conveyed to each exchanger by the liquid coolant is 507KW [1,730,898 Btu/Hr] for each AFD. A nominal liquid coolant flow rate into each exchanger is designed to be 264 US GPM. The operating ambient air temperature range is -40 deg F [-40 deg C] to +103 deg F [+39.4 deg C]. The designed maximum temperature of the liquid coolant leaving each exchanger is not exceeding 116.6 deg F [47 deg C]. The resultant maximum temperature of the liquid coolant entering each exchanger is not exceeding 131.8 deg F [55.4 deg C].

Required are ten Non-Fused Electrical disconnects mounted and wired adjacent to each fan. Electrical disconnects are rated 65 KAIC. There are ten 36” fan blades with OSHA approved fan guards. Dimensions are shown in figure 6. The heat exchangers are capable of operating at an elevation < 3,300 feet above mean sea level and also capable of maintaining full rated heat transfer capability with N-1 fans in service.

8) Process Protection:

A fault protection scheme is implemented so that sudden AFD protection trips are minimized. The goal is to maintain the AFD (and consequently the process to which it is applied) in operation as long as possible while concurrently preventing any permanent damage to the equipment. Key AFD parameters and variables are constantly monitored and alarms of different degrees of severity are issued in case any of them exceeds a predefined range. The operator is thus notified of abnormal conditions and can initiate proper corrective actions. Automatic corrective actions related to the nature of different applications are standard for the process protection, whereas some additional corrective measures specific to particular requirements can be customized or ad hoc developed.

9) High Availability:

The new AFDs are also offered by vendors in "high availability". The increased availability of the drive, which translates in longer MTBF is achieved by means of: duplication of the control system (AFD control hardware, including transducers and on-board instrumentation), duplication of the I/O with active I/O management, enhanced isolation transformer monitoring: temperature of each cooling path is continuously monitored by means of one RTD backed up by one thermal switch. However, there is little impact on foot print and cost in case of ordering high availability option.

10) Safety Key Interlocks Design:

A special key interlocking scheme was designed to meet CSA safety requirements. As shown in figure 8, lockout capabilities and the key interlocks were designed to tie up with upstream input circuit breakers, AFD input and output disconnect switches and different AFD cabinets (transformer cabinet, cell cabinet, pre charge cabinet, cooling cabinet and motor protection cabinet) for the safe access after all power is removed from the AFD.

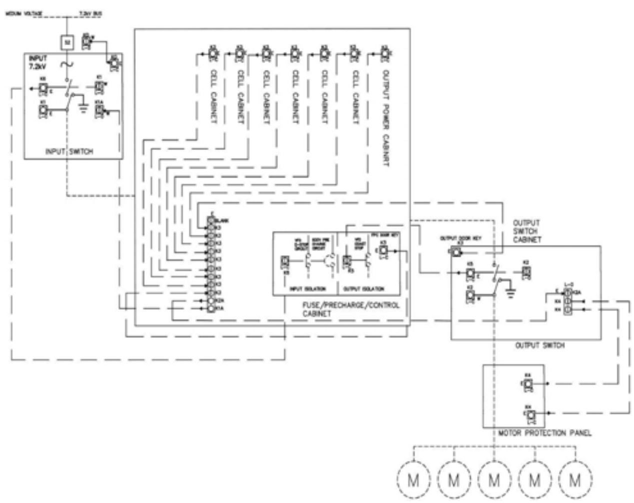

Fig. 8 SAFETY KEY INTERLOCK BLOCK DIAGRAM

The AFD design was developed based on an onsite power and control study, detailed specifications and the above key process features. The detail engineering design drawings were issued by AFD vendor to EPC company and end customer for engineering approvals. The long lead items were released for procurement after the design and drawing approval by EPC company and end customer. The final design was released for manufacturing after final quality checks, completion of the drawings and receipt of long lead items. The AFD had been set-up for detail functional and system testing after assembly was completed.

E. AFD System Testing and Acceptance

The AFD test procedure was defined for the scope of non-standard customer witness testing. The testing was performed at the AFD manufacturing plant as per manufacturer's testing guidelines which includes visual inspection, insulation tests, functional tests, cooling system testing, system no load / load test. The test procedure was developed to comply with end user's specifications based on testing criteria including special testing requirements.

1) VISUAL INSPECTION AND OPERATIONAL CONTROL OVERVIEW

The input power cabinet was checked with input section, input attenuation, input disconnect switch, customer line and load cable connections, motor connections, bypass contactors, cable access and input fuses. The transformer cabinet was checked to include the location of the nameplate, ratings, phase shifts, wiring, electrical and mechanical highlights. Cell cabinets were checked for the function of the power cells in the system and identification of cell components. The control cabinet was checked for the function of the keypad and their interaction in the system, the communications link to the power cells, control input section, blower control or water cooling operation, any additional customer interlocks or options, voltage attenuation and current transformer feedback. The cooling cabinet section was checked for water cooled control including filling operation and fault logic. All the safety features were tested including personnel safety, circuit breakers and disconnect switches, lockout capabilities and key interlocks, safe access after all power is removed from the drive, AFD protections, air flow switches, thermistors and thermal switches and electronic overload protection.

2) AFD OPERATION NO LOAD TESTING:

Rated drive voltage is applied with no load. The tested features included keypad navigation, overview of menu access, AFD and motor parameter adjustments, AFD operation and fault display, AFD fault logic operation with over-temperature, cell fault, blower fault and user defined faults. AFD and customer control logic Interface with operation of customer control logic and AFD logic specific to the AFD. Cell bypass operation at no load and full speed, demonstration of redundant cell operation and demonstration of power factor regulation.

3) SYSTEM LOAD RUN:

The AFD was loaded with a motor and reactor to test if it meets capability and scheduling criteria. Typical Input and output waveforms are observed on an oscilloscope at the circuit board level. The AFD load run (4 hour standard) system temperatures were monitored for temperature stability testing. Additional testing was performed including AFD efficiency test, harmonics test, AFD power supply testing, thermal testing, extended load run, cooling pressure testing, ground fault testing, output phase-to-phase fault testing.

4) TEST EQUIPMENTS:

Updated calibration records were provided for the test equipment. These included insulation tester, voltmeter, oscilloscope, voltage transformers, current transformers, power quality meters, variac, test computer and other testing equipment.

5) COOLING SYSTEM DESIGN:

Cooling system testing includes testing of valve positions, level switches, coolant cabinet conductivity, sensor programming, coolant leak pressure test, relief valve test, coolant filtering, pump rotation test, coolant cabinet timer, circuit breakers trip test, coolant system controller logic testing and coolant pump logic testing for liquid to air heat exchanger.

F. Installation and Commissioning

Figure 9 shows the general layout of all three sections of the electrical house where all three AFDs were installed. The AFD was accepted by end user after satisfactory completion of system testing. All three AFDs were shipped to the electrical house vendor location in Calgary, Alberta. The integrated design of the new AFD (i.e. isolation transformer integral to the drive) simplifies the AFD installation. Only one medium voltage three-phase incoming line is required. The production team along with the reliability and sustainable project teams decided to develop the new electrical houses to install three new 16,500HP AFDs and performed the swapping of the new AFD system with old AFD system to reduce the production down time. The e-house was installed as an extension of the existing building. The e-House was developed into three sections to house three AFDs.

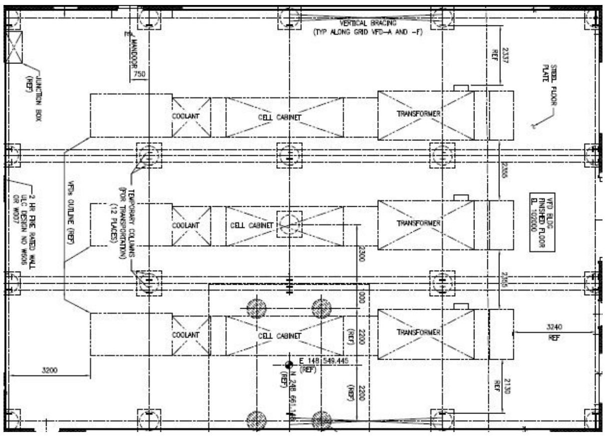

Fig. 9 ELECTRICAL BUILDING WITH THREE AFDS

The construction walk down for step by step approach for installation was performed. The pre-commissioning team inspected the installation including interfacing and torque checks of the cabinet connections. The control wire plugs at each shipping split were reconnected and tie-wrapped per the cable schedule. The ground bond jumpers were reconnected to ensure that the entire system is earth grounded at one of the system grounding points. Confirmed the shielded cables were used for the motor connections. Only one end of the shield was grounded at the AFD end. The ground for the transformer neutral was checked. The cell input power cables were then reconnected to the cell input back bus, tightened and torque marked. Inspected for all primary, secondary and power connections on the transformer to ensure each cable lug aligns with its winding terminal. Interconnect piping was flushed prior to interconnection between AFD and heat exchanger. Piping interconnection to the external heat exchanger was checked and completed. All the control power and auxiliary power sources were connected per the AFD schematics to allow the pre-commissioning process to continue. All electrical connections were torque and marked.

The deionized water and glycol mixture was checked. The mixture was filtered through a ten-micron filter as defined in the user manual of AFD manufacturer. The commissioning team filled and purged the system according to the filling procedure from the user manual. Auxiliary 120 VAC and three-phase power to the cell blowers was energized to verify the rotation and/or phase sequencing of the residual heat exchanger cooling fans. Sequencing for the cooling pumps was verified and initial fill and venting process was completed. The system test pressure was brought to around 120PSI for one hour to check for system leaks. The coolant pumps were started and cycled at least three times to assure that the pumps were primed and the coolant conductivity was monitored for its range. Verified the pump motor starter and set the overload. The cell bypass contactor transfer time was checked during initial commissioning. The AFD was energized via the pre charge source and cell modulation was verified. The system was allowed to operate overnight to support the final venting process after no leaks were detected. The pre-commissioning, commissioning and integration test with the tailing pumps, trial run and final acceptance procedure were performed successfully onsite. The system was handed over to production team by sustainable project team and AFD vendor onsite team.

G. Operation and Maintenance

The maintenance and reliability team defined the tailing pump AFD equipment maintenance strategies that include the regular monitoring of the AFD, with daily, monthly, yearly and five yearly frequencies. The daily and monthly checking is being performed per check list through the maintenance team. Where six monthly, yearly and five yearly checking is being performed through AFD experts for preventive and demand maintenance.
Operation of the tailing pump AFD system was monitored by reliability and maintenance team on daily, weekly, monthly, six monthly basis. A significant reduction was found with the frequency of unplanned outages. The frequencies of unplanned outages reduced to two hours per year. The total indirect production losses with the new AFD since commissioning were the following:

Unplanned outages total 2 hours
2 hours x 3000 tons/hour = 6,000.00 tons
0.6 barrel oil production per one ton, so total barrels are
6,000.00 x 0.6 barrel/ton = 3,600.00 barrels
3,600.00 barrels x $66 ($100 average barrel price - $34 production cost) = $237,600.00
So total indirect production losses are equal to $237,600.00

The 24/7 service agreements are defined with AFD vendor to support ongoing critical operation of the tailing pumps. Critical spare parts and inventory levels are regularly verified and managed as defined by reliability guidelines. After the AFD equipment approaches its defined 20 year life expectancy, planning for upgrades and/or future retrofits or replacement will occur through by way of business cases by the reliability project team.

IV. CONCLUSION

There is a growing need to evaluate larger capacity adjustable frequency drive systems for more reliability and higher availability in the oil and gas Industry. This paper was written to demonstrate the critical nature AFD design during the modernization and the engineering stages of the respective project. In order to ensure the best replacement practices required to replace large AFDs in an effort to maximize up-time and minimize execution risks, the following elements are recommended: a detailed replacement plan: comparison of old and new AFD design, selection of right AFD, functional and integration testing, installation, commissioning and detail maintenance plan for AFD system. In the case of these tailing pumps, the frequencies of unplanned outages were significantly reduced from 72 hours to 2 hours per year.

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VI. VITA

Nilesh Patel graduated from Gujarat University, India, in 1995 with a bachelor of engineering in instrumentation and control. Nilesh began his career in 1996 as a service engineer for industrial drives and automation system with Siemens India Limited. He migrated to Canada in 2002 and joined Leading Edge Automation Inc, Mississauga as an application specialist and project engineer for drives system. In 2004, Nilesh joined GN Packaging as a project engineer and then moved to Siemens Canada in 2005 as a business developer for Drives system. Nilesh held various drives related positions and is currently working as a business operation manager within large drives division of Siemens Canada. Nilesh is a licensed professional engineer from professional engineering Ontario and certified project management professional from project management institute, Pennsylvania. Nilesh led the team which was awarded as top industry team in 2012 for Siemens Canada. Nilesh likes to volunteer for community work. He presented life cycle cost of medium voltage drives with Christian Coetzee of Suncor Energy at ESTMP 2012 workshop, Edmonton, Alberta and volunteered at IEEE ESTMP 2014 workshop Calgary, Alberta.

Don Wilson graduated in 1985 from RRC, Winnipeg, with a Diploma in Electronic Engineering Technology. Don completed his Master of Business Administration at Royal Roads University, Victoria, BC, in 2001, and his Doctor of Business Administration in Global Leadership in 2009. Don is employed as Canadian Business Unit Manager of Large Drives at Siemens Canada in Edmonton, AB.

Giovanni Vignolo graduated from the University of Genoa, Italy with an MSEE in 1988. He started his career with Ansaldo Sistemi Industriali in Italy in the application engineering department dealing with drive and automation systems mainly for the metal and paper industries. With Ansaldo, he moved to USA in 1997, then through company reorganizations and acquisitions to ASI Robicon in 2000, to Robicon in 2003 and finally Siemens in 2005. For 11 years he has been dealing with MV adjustable speed drive based applications with the application engineering department as engineer first and then as engineering manager since 2009.

Ashok Mangukia graduated from Saurashtra University (India) with bachelor in electrical engineering in 1996 and began a career as a production and maintenance supervisor with Nugen Machineries Ltd. After working with Nugen for 6 years, he moved to Canada in 2002 and started his career as a service engineer with Haco Canada. In 2007, Ashok moved to Fort McMurray, Alberta to enhance his career in the oil and gas sector and started his career at the Suncor Energy site with Laird Electrical as a quality control supervisor and joined Suncor in 2010 as a project engineer and is presently working as a project manager.