SLOW ROLLING OF MULTIPLE PUMP MOTORS AT A LARGE PETROCHEMICAL COMPLEX

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Abstract – Slow rolling of rotating equipment has been used for decades to prevent rotating parts such as shafts of large electric turbines, motors, pumps, and compressors from sagging or bending when not in operation. In industrial facilities, such as large petroleum processing plants, slow rolling is often used with stand-by pumps to prevent pump casing distortion and shaft bending. This paper covers an industrial application of a slow rolling scheme for up to two motors driven simultaneously utilizing a single Adjustable Speed Drive (ASD). The control system has been fully automated using a Programmable Logic Controller (PLC) interfaced with an upstream Distributed Control Systems (DCS). The scheme provides a cost-effective solution for multi-motor applications by reducing the number of ASDs required, minimizing the required footprint in the substation, improving energy efficiency by eliminating electric power conversion losses, and reducing the overall installation costs. Attention will be given to the control systems architecture, automated modes of operation, electrical configuration, and mechanical performance.

Index Terms — Slow rolling, rotating machinery, centrifugal pumps, synchronous transfer, Adjustable Speed Drive.

I. INTRODUCTION

Large petrochemical facilities depend heavily on reliable process equipment. One important aspect to maintain high reliability is ensuring that hot standby equipment is always ready to take on process feeds without any interruption. In industrial facilities, such as large petroleum processing plants, slow rolling is used with hot standby pumps to prevent pump casing distortion and shaft bending. These effects are often the result of uneven thermal growth from temperature gradients that develop in the pumps due to stagnant or non-uniform flow of hot process through the pumps when keeping them in hot standby. Without slow rolling, manual shaft barring, or a turning gear, the pump-motor assembly may exhibit high vibrations while in operation exceeding the shutdown threshold established by a monitoring and control system. The high vibrations present a potential for internal damage when stationary and rotating parts are contacting each other. This is particularly of concern for equipment driven by electrical machines that are started across the line.

A. *Reliability Challenges Experienced at a Large Petrochemical Complex*

Oil and gas facilities utilize a wide variety of rotating equipment for various processes, however, one of the more problematic categories are centrifugal pumps in hot service (over ~150°C). These pose several unique challenges including:

- Pipe strain due to piping misalignment, either from original installation or due to thermal movement of piping during operation.
- Shaft misalignment from the cold to hot condition.
- Distorted baseplates and damaged foundations due to stresses from the thermal movement of the pump casing.
- Bent shafts and/or distorted casings caused by excessive or uneven distribution of seal flush or quench flow, leading to internal rubbing and damage of pump components (process seals and bearings due to loss of lubrication and vibrations).
- Non-concentric component problems are compounded with thermal movements.
- Loss of performance due to deformation of pump clearances and rubbing.
- Heat related damage to elastomers, and
- High risk of fires from leaks due to operating near or above auto-ignition temperatures.

One of the most important factors to ensure hot standby centrifugal pumps are available to start without issue is to keep them as close to operating temperature as possible. The temperature must be maintained uniformly without hot or cold spots in the machine. There are a few ways this can be achieved. Possible solutions often involve some combination of the following:

- Insulation, which must be kept tight and uniform around the pump to prevent hot/cold spots.
- Heat tracing process heating, which can contribute but is more often used for freeze protection.
- Slipstream bypass(es) of hot process fluid flowing backwards through the pump from discharge to suction.
- Slow rolling of the pump which must be done at a speed sufficient to maintain the oil wedge on journal bearings without causing high head pressure.
- Manual barring or rotation of the pump prior to starting, but also during the hot stand by period.

B. Description of the Problematic Pumps

Four of the problematic hot service pumps at this facility were the Atmospheric Bottoms pumps (P-2 A/B) and the Vacuum Bottoms pumps (P-6 A/B). They are located in the Atmospheric and Vacuum (A&V) unit of the Upgrader which processes diluted bitumen. Both pump services are critical to the Upgrader operation and their loss will result in a shutdown of the A&V unit, plant-wide rate reduction, and eventual shutdown of the entire Upgrader site.

All four pumps are identical API 610 BB2 double suction axially split style pumps [1]. At one time they were different capacity but due to a Debottlenecking project (DEBO) coinciding with the scope of this paper they are all now identical. The pumps as well as the piping are 316 stainless steel.

The P-2 pumps process atmospheric bottoms hydrocarbon product. The normal operating temperature is 332°C with a maximum of 380°C. Flow rates are 1250 m^3/h, utilizing 968 kW at 1800 rpm. One pump operates at a time, with the other on hot standby.

The P-6 pumps process vacuum bottoms hydrocarbon product. The normal operating temperature is 330°C with a maximum of 375°C. Flow rates are 1245 m^3/h, utilizing 935 kW at 1800 rpm. One pump operates at a time, with the other on hot standby. The P-6A pump had an existing ASD with the necessary capabilities to synchronous transfer, but only used for speed control.

These pumps have been frequent bad actors with multiple seal failures, chronic high vibrations, and frequently plugged suction strainers. The biggest problem has been high vibrations and seizure on startup. The vibrations observed were almost exclusively 1x frequency vibrations, which indicates an imbalance or bending of the shaft [2,3].

II. DEVELOPMENT OF THE PROJECT

In 2016, a full investigation was launched to determine the root cause of the various problems associated with P-2 and P-6 pumps with the objective being to identify corrective actions needed to improve the reliability of these pumps. Causal Learning is the problem-solving methodology used at this facility [4]. The method has been applied to the reliability challenges discussed in this paper.

The causal investigation has identified several items that must be addressed to improve the overall reliability of P-2 and P-6 pumps. The vibrations and seizures that occurred at startup were found to be primarily caused by the bending of the shaft and pump casing distortion before startup. Several contributing issues and fixes were identified and implemented to help resolve this problem over recent years:

- The shaft material was upgraded from 316 Stainless Steel to Nitronic 50 material which is less prone to bending.
- Prior to this investigation the wear ring clearances were enlarged above the API recommendations to help prevent rubbing.
- The wear ring design has undergone several changes from replaceable tack welded wear rings, to integrally welded wear rings, and back to replaceable wear rings with a heavy interference fit and Stellite coatings.
- The pump casings were inspected and concentricity of pump components was improved.
- The pump feet hold down bolt design was modified to allow for some thermal movement.
- Additional warm up lines were added to allow the warmed-up fluid to enter the pump from multiple locations to improve the heat flow and uniformity.
- The pump baseplate and foundation were inspected and repaired due to damage from the thermal movement of the casing over time. The baseplate feet were bent outwards and the grout filled baseplate had developed voids.
- Corrections were made to the piping alignment and supports to help alleviate piping strain on the pumps.
- The insulation around the pump was inspected to ensure it is in good condition and installed properly around the pump.
- Temperature gauges were added to the top and bottom of the pump casing to help operations monitor and verify the temperature difference in the pump casing while in standby and before starting.

Following these modifications and repairs the overall pump operation was significantly improved, however, the hot standby pumps still experienced high 1x frequency vibration trips and seizures on start-up.

A. Boundary Condition

This paper is written to specifically present the development of the solution that addressed the "bending of the shaft / pump casing before startup" failure mode encountered on this application.

B. Causal

- While in hot standby, a significant temperature gradient of approximately 50°C exists across the pump casing.
- It was observed that pump internals are touching the wear rings prior to start-up indicating shaft pre-load/rubbing.
- Pump casing distortion exists on all four pumps confirmed by measurement during overhaul inspections.
- To quantify the significance of this opportunity, in July 2014, there were 21 days of limited rates to mitigate the risk of plugging strainers of the then un-spared P-6B (P-6A undergoing repairs), 3 days of which were associated with significant production loss.

C. Slow Roll Test Run

One of the leading contenders for a possible solution which were under consideration was to slow roll the pumps. One of the factors which made this a primary solution to move forward with was the fact that the site already had a dedicated drive on one of the pumps. The original purpose of the existing ASD was to run the P-6A pump continuously at variable speed, with no transfer to Direct-On-Line (DOL) capability. This led to the exploration of the slow roll option. To begin with, as a proof of concept for the slow rolling option, it was relatively easy to reprogram the existing pump P-6A ASD to provide a slow rolling mode of operation as a trial. The programming went further such that the slow roll cycle was followed by a ramp to full speed using a ramp rate of 2.5 rpm/min (12 minutes to full speed). Slow rolling and subsequent ramping of the drive to rated speed using the P-6A pump and drive was found to be successful in preventing the worst of the vibrations from start-up to full speed.

To prevent bearing damage, the pump shaft needs to rotate fast enough to provide an oil wedge and hydrodynamic bearing lubrication. As the pumps have no bypass for extra fluid the slow roll speed was limited to prevent excessive head pressure in the pump. The slow roll speed of 300 rpm was selected, which is suitable to provide enough shaft speed for proper bearing lubrication, but the maximum the site was comfortable running without a bypass line. Inspection following the trial indicated no noticeable bearing damage.

D. Concept Identification, Evaluation and Comparison

To meet the facility reliability objectives, and based on the results of slow rolling trial, it was determined that each complementary pump (A or B) would be slow rolled while on hot standby and accelerated progressively over preferably a five-minute period. Several technical solutions were identified and evaluated; the most important ones summarized below.

Option 1: Use the existing ASD that currently serves P-6A to slow roll up to 2 pumps simultaneously.

This solution can be the most cost effective but also the most technically challenging. To connect the ASD to any motor, a new Motor Control Center (MCC) having four motor starters and an incoming power section is necessary. This option has the potential to provide speed ramp up of a single pump, synchronization, and transfer to DOL power source. Once the transfer to DOL completed, the ASD can return to slow rolling any other pump.

Option 2: Use P-6A's ASD and purchase another equivalent Medium Voltage (MV) ASD to slow roll any two pumps simultaneously.

This option provides an ASD dedicated to P-2A and P-6A pump pair and another for P-2B and P-6B pair. Compared to Option 1, installing a new ASD will provide essentially the same mechanical benefits yet at a higher cost. Option 2 does increase the system reliability as the second ASD could continue to slow roll a pump pair if the other is not available. The increase in system reliability could have minimal impact as the existing ASD on P-6A has been reliable since it has been installed in 2006.

Another challenge for Option 2 is the space constraints to house a second new ASD and MCC set. A constructability field inspection identified the substation's Uninterrupted Power Supply (UPS) would need to be relocated to provide room for the new ASD, resulting in additional costs.

Option 3: Buy 3 fully rated MV ASDs, one for each pump, to slow roll and ramp to full speed without DOL transfer capability.

The main advantage is that each motor can slow roll independently without interruption. The overall system is also simpler to design, build, and operate.

Disadvantages include lower energy efficiency (~97% on ASD due to power conversion) and higher construction, operation, and maintenance costs. As there is no space available in the existing substation, a new building would be required. The new building, 3 ASDs, and their installation and commissioning would add significant cost to the project that are simply not justified.

Option 4: A subset to Options 1, 2 and 3 is to procure Low Voltage (LV) instead of MV ASDs.

The LV ASDs would only be used to slow roll the motors. This is a disadvantage as the speed ramp up sequence would not be possible and is important to detect increasing vibrations and potentially slow or shut down a pump preventing costly pump failures.

The LV ASDs procurement, installation and maintenance costs are lower by all metrics. To transition between slow roll and full speed, a new MV MCC would still be required. It appeared that the total cost outweighs the benefits when compared to option 1, 2 and 3. Ultimately, this option was rejected without being fully developed. Other major concerns included electrical insulation ratings in the event the LV ASD output is connected to a MV source.

E. Concept Selection

Based on the concept identification, evaluation, and comparison workshop, Option 1 was selected and fully defined in preparation for investment decision [5]. The selected power system configuration is depicted in Fig. 1 below

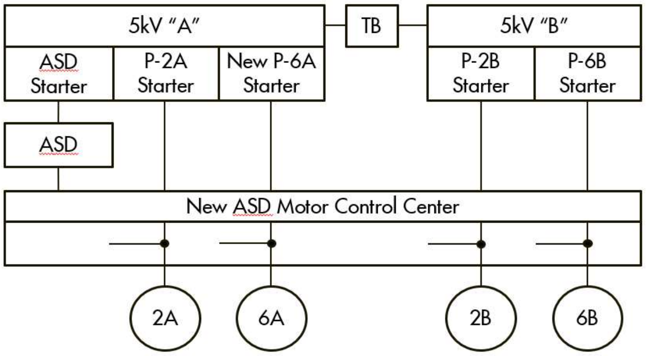


Fig. 1 Block Diagram for Utilization of Existing ASD

Two Motor Bus Transitions (MBTs) schemes from ASD to DOL were considered utilizing the existing ASD:

a) Open transition transfer.
b) Closed transition transfer.

The open transition transfer does not parallel the ASD output with the DOL power source during the transition. Once the ASD is disconnected from the motor, the motor will coast down and is reconnected to the DOL source once the conditions for the applicable method are met. Conversely, the closed transition transfer involves brief paralleling of the ASD output and DOL source, commonly referred to as a "synchronous transfer". Since the DOL source is connected to the ASD output before the ASD output contactor is tripped, the transfer is completed without interruption [6].

An open transition transfer logic scheme based on residual voltage was first considered. It was later found that the time required to establish the residual voltage transfer limit resulted in an unacceptable coast down, posing a significant reliability threat to operations [6].

By utilizing a synchronous transfer scheme to DOL instead, the risk of damaging the pump as well as plugging strainers is minimized.

Despite the facility having no previous experience utilizing a ASD driven synchronous transfer scheme, the technology is known to be well established in industry [7]. The particular drive topology utilized for the slow roll application has been used in over 1200 instances.

F. *Uncertainties, Risks (Threats and Opportunities)*

A list of project risks was compiled in a comprehensive risk register. Below is a summary table of the highest-ranking risks identified at the project development phase. One of the most notable external risks is the concurrent execution of a DEBO Project aiming at increasing the unit capacity by upsizing several pieces of equipment, including the four electric motors driving the P-2 and P-6 pumps.

TABLE I
HIGHEST RANKING PROJECT RISK REGISTER SUMMARY

Risk Event	Effect	TECOP*	Probability	Impact	Mitigation
Risk associated with "on the run" execution	Economic impact and process downtime	E	High	High	Delay execution until 2020 Turnaround
ASD insufficient capacity for new 1500 HP DEBO motors	Replace ASD/ Rework	T, E	Medium	High	ASD upgrade and cost impact on project economics
Transfer out of synchronization	Asset damage and production loss	T, E	Low	High	Robust and proven control system. Fuses.
Insufficient substation floor space due to competing DEBO work	Not enough floor space to install new MCC	T, E	Medium	High	Work in concert with the DEBO project team to optimize floor space.

*TECOP – Technical, Economic, Commercial, Organizational, Political

III. CONTROL SYSTEM DESCRIPTION

The overall control system is a critical engineering challenge of the project. Even with the best hardware, without robust and efficient programs, the overall return on investment can be significantly undermined.

The control system is built on the following subsystems interconnected via digital communication networks and discrete Input/Output signals (I/O): DCS, PLC, Machinery Remote Monitoring and Diagnostics (RM&D), Safety Instrument System (SIS), ASD, and Motor Protection Relay.

The control system manages the three modes of operation: Full Speed (DOL), Sync Ramp to DOL, and Slow Roll. Each are described in detail in Section F below.

A. *Key Control System Subsystems Description*

The key subsystems are briefly discussed below with an in-depth explanation of their interactions in the following subsections.

1) *DCS:* The DCS is used as interface between operations and all the other subsystems, meaning all alarming and commands are typically executed here. The DCS also monitors the health of all the subsystems. The DCS I/O are comprised of mainly process specific I/O while equipment specific I/O are, for the most part, wired directly to the PLC. The DCS allows the system to be operated from a single operator control interface for ease of operation and convenience.

For the four pumps discussed in this paper, the DCS can issue a Stop command at any given time, or a Start command in any of the following modes: Slow Roll, Sync Ramp to DOL, or Full Speed.

2) *PLC:* The PLC is the most critical subsystem as it is responsible for the:

- Control of the DOL contactors
- Control of the MCC ASD contactors
- Interlocking of DOL and ASD contactors
- Transmitting all ASD and DOL contactor statuses to DCS
- Storage of the ASD parameters required for different modes of operation
- Execution of DCS mode request (Stop, Start, Slow Roll, Sync Ramp to DOL, and Full Speed)
- Startup and Shutdown of motors
- Field I/O hardwiring

The PLC is hardwired to the DOL and ASD output contactors for controlling the start / stop functions through opening and closing of MV contactors. Without its proper function, all contactors are at risk of opening and therefore shutting down all pumps. In addition, the start / stop and mode selection sequences are executed within the PLC. The PLC hardware was selected to maximize the compatibility with the field equipment and to provide faster scan rates than the DCS.

3) *RM&D:* The RM&D's primary function is to protect the equipment against damage via continuous monitoring and analysis of vibrations to ensure that all pumps and motors do not exceed specific trip and alarm setpoints. In addition, it is responsible for:

- Monitoring motor shaft rotation (speed feedback)
- Transmitting data to the DCS for indication
- Initiating hardwired trip signals to the SIS
- Enabling / disabling a trip sensitivity multiplier based upon the mode of operation allowing momentarily higher vibrations during Slow Roll startup sequence.

4) *SIS:* SIS is utilized to shut down the motors independently from the DCS based upon a combination of motor vibration, process trip conditions, and operation commands such as Emergency Shutdown (ESD). The SIS trip initiators and outputs are hardwired to the different subsystems and act as an independent layer to monitor and shutdown the equipment.

5) *ASD:* The ASD responds to the PLC commands and drives the motors for two modes of operation: Slow Roll and the Sync Ramp to DOL. To execute the different modes the ASD requires some adjustments to its parameters. The ASD also provides the ultimate permissive for the closing of DOL contactors via discrete I/O connected directly to the DOL contactors.

6) *Motor Protection Relay:* The motor protection relays are only necessary to protect against motor overload and thermal damage via current, windings and bearings temperature, as well as typical start inhibit monitoring functions when the motor is not on the ASD.

B. *Control System Architecture*

The selected control system architecture is shown in Fig. 2. The DCS communicates with the other subsystems via a combination of MODBUS (Ethernet and Serial) and Ethernet IP. Each subsystem has its own hardwired I/O which monitors the field equipment and communicates back to the DCS for alarming or indication through the PLC. Where the subsystem is used to trip equipment, either the DCS will issue a reset command, or a field reset is required to clear the trip / alarm conditions.

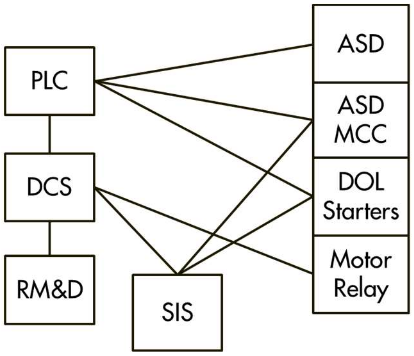


Fig. 2 Simplified Control System Block Diagram

C. Redundancy / Hardware

Due to criticality of the process driven by the pumps, the DCS, PLC, and SIS hardware is fully redundant. These systems monitor the health of their Central Processing Unit (CPU), communications, I/O modules, and power supplies. An alarm event will be raised in the DCS if any hardware malfunction or fault occurs.

Independent UPS and utility circuits are used to provide power to redundant subsystems to mitigate single point failure.

The PLC I/O are comprised of remote I/O modules which are connected to the CPU via ethernet. There is a remote I/O module located at each of the eight ASD outputs and DOL contactors to facilitate their monitoring and operation.

Communication between the DCS and each subsystem is monitored via a watchdog which will alarm in the event of communication time out. Each subsystem is configured to hold its state in the event communication is lost to prevent unnecessary process trips. If a pump was running on DOL, the pump will remain running with either loss of communication between the PLC and DCS or PLC and I/O modules. However, if a pump was running on the ASD (Slow Roll or Sync Ramp to DOL), the pump would stop.

D. Commands / Communication

Exception based messaging is used to limit the amount of traffic between the subsystems. Pulsed, rather than maintained commands, are utilized between the DCS and the subsystems. This reduces the risk of dropped commands and misalignment between the subsystems.

The subsystem feedback status is passed back to the DCS to confirm a command was received. For critical commands a mismatch alarming scheme is configured in the DCS. The DCS displays the “mode requested” and “current mode” as command integrity feedback to ensure a proper handshake between the two systems.

Synchronization of the DCS and PLC is maintained by feedback loops between the systems. The feedback loops are used to confirm commands have been received and executed. Due to the field equipment response time, time out alarms have been programmed to notify the operator of any abnormal sequences.

E. Pump Status of Operation

There are three distinct pump statuses used in the control scheme: Not Ready for Service, Ready to Start, and Running.

1) *Not Ready for Service:* The first pump status is Not Ready for Service. Whenever a pump is in this status, it will not be allowed to start. Any attempt will not execute and will not impact any other motor already in operation.

The following conditions will set the pump in a Not Ready for Service:

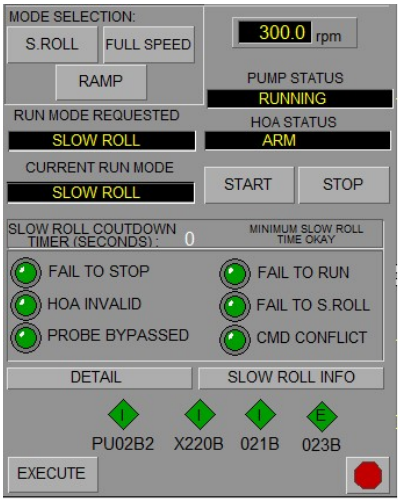
- Field Switch Hand-Off-Auto (HOA) in the OFF position.
- PLC pump permissives not satisfied.
- SIS or DCS interlock trips.
- Motor protection relay trip or lockout.

2) *Ready to Start:* The second pump status is Ready to Start. This status indicates that all the permissives have been met and the pump is ready to start. This status will not impact any other motor already in operation.

3) *Running:* The third pump status is a transition from Ready to Start to Running mode. The transition will occur when the run status feedback is received by the DCS.

F. Pump Modes of Operation

The modes of operation are selectable configurations for each motor within the DCS that allow operators to set how they want to operate the equipment. Each pump overlay displays the mode selection, mode requested, current mode and pump status. The mode selection is only written to the PLC when the mode selection is updated and the execute button is selected as shown in Fig. 3.



300.0 rpm

PUMP STATUS: RUNNING

RUN MODE REQUESTED: SLOW ROLL

HOA STATUS: ARM

CURRENT RUN MODE: SLOW ROLL

SLOW ROLL COUTDOWN TIMER (SECONDS) : 0

MINIMUM SLOW ROLL TIME OKAY

● FAIL TO STOP
● HOA INVALID
● PROBE BYPASSED
● FAIL TO RUN
● FAIL TO S.ROLL
● CMD CONFLICT

Fig. 3 DCS Operator Screen for Pump P-6B

Operations will immediately be notified via the DCS in the event normal operation is not achieved (i.e. command conflict, time-out, missing permissive, failure to run, failure to stop, or equipment trip).

Operators shall be able to Start, Stop, or execute a change in the mode of operation for each pump at any given time. Any operating pump can be interchanged with its respective standby pump when the latter is Ready to Start at the operator’s command.

The three pump running modes of operation are listed and described below: Full Speed (DOL), Sync Ramp to DOL, and Slow Roll. Mode of operation selection is restricted by their sequence such that operations will not be able to transfer from Full Speed to Sync Ramp to DOL or Slow Roll for example. This increases overall control system robustness against incorrect operator command entries in the DCS.

In general, when a mode is executed for any pump, there is no impact to the running status of any other pump. An exception is made only for the Slow Roll mode of operation.

1) *Full Speed:* In this mode the respective pump motor will receive its power from the DOL power source.

Since the process cannot ride-though a pump loss for more than a few seconds, operations must be able to switch the mode request to Full Speed at any given time. Switching to Full Speed mode from Slow Rolling entails shutting down the ASD and opening the ASD output contactor immediately followed by closing of the DOL contactor.

When any of the pumps are started in “HAND” from the HOA field switch, the DCS will automatically set and execute the Full Speed mode.

2) *Sync Ramp to DOL:* In this mode, the pump motor will receive power from its respective ASD output contactor located in the ASD MCC as shown in Fig. 1. Synch Ramp to DOL can be executed, provided that the specified pump status of operation is Ready to Start.

To start on Sync Ramp to DOL, the ASD will start and accelerate the pump to full speed over a 5-minute ramp. Once the pump has reached full speed, the motor will automatically be synchronized and transferred to the DOL source (Full Speed mode).

The ramp time was lowered from 12 minutes during the test run to 5 minutes after it was determined over time that the machine could be brought online faster with the same benefits.

From the initial Sync Ramp to DOL command, there are 10 minutes allotted to accelerate the pump and complete the synchronous transfer. If the transfer does not complete within this time the PLC will abort the sequence and stop the motor.

Initiating Full Speed while a pump is in Synch Ramp to DOL mode entails shutting down the ASD, opening the ASD output contactor, waiting two seconds to let the residual voltage reach the transfer limit, followed by closing of the DOL contactor.

Initiating Sync Ramp to DOL for a pump on Slow Roll with two pumps on Slow Roll causes both pumps to stop and the ASD output contactors to open. Then, the Sync Ramp to DOL routine is immediately executed for the specified pump. At the request from operations, the second pump whose Slow Roll was stopped will remain stopped, it will not be automatically restarted on Slow Roll.

3) *Slow Roll:* When the Slow Roll mode is executed, the pump will receive its power from its respective ASD MCC output contactor. Up to two pumps can be slow rolling simultaneously on the ASD. The DCS will prevent the operator from accessing the Slow Roll mode for the other two pumps once two are running on Slow Roll mode.

Anytime Slow Roll is executed for a pump while another pump is being slow rolled, the slow rolling pump will be stopped. Both motors will then be started in Slow Roll mode. Likewise, when removing a pump from Slow Roll while two were in Slow Roll mode, both pumps will be stopped, followed by an automatic re-start of the other slow rolling pump. The transition to a stop is necessary to update the ASD parameters as well as prevent mechanical resonance.

To protect against motor bearing damage, a speed differential protection will initiate a pump stop command to ensure the bearings have adequate lubrication and prevent excessive pump deadhead pressure.

The Sync Ramp to DOL mode provides the most benefit when preceded by a recommended minimum slow rolling period. The time is set to ensure that all rotating parts have straightened and temperatures stabilized within the pump. The minimum recommended slow rolling time is displayed on the operator console. The timer will not prevent an operator from changing the pump mode prior to the timer timing out to ensure process continuity in the event of an unexpected pump shutdown.

IV. ADJUSTABLE SPEED DRIVE

The existing medium voltage drive is a 1500 HP, 4160 V ASD built in 2004 as shown in Fig. 4. The ASD original design can be applied either as a dedicated single drive / single motor combination or a single drive / multi-motor combination [8]. Some modifications were required to enable the synchronous transfer capability inherent to the ASD control. Once completed the modifications enabled the ASD to perform the needed bump-less transfer as well as drive multiple motors together.

Fig. 4 1500 HP 4160 V Adjustable Speed Drive

V. POWER DISTRIBUTION SYSTEM

The process area substation switchgear is fed at 4160 V from one ‘A’ bus 34.5 kV to 4160 V transformer and one ‘B’ bus 34.5 kV to 4160 V transformer connected with a normally open tie breaker. MV MCCs are close coupled to the ‘A’ and ‘B’ switchgear buses. The P-2 as well as P-6 induction motors are identical and rated 4000 V, 1500 HP, 1800 rpm, WPII frame style.

To share the ASD across all four motors on the system, a new MV MCC arrangement having four motor starters needed to be installed and is shown in Fig. 5. All the starters needed for the scheme were either existing units or spares. These units were modified in the field as required to suit the purpose. Point I/O, remote PLC extensions as well as safety relays have been installed in existing starters to name a few.

Fig. 5 New 4160V ASD Motor Control Center

VI. FACTORY ACCEPTANCE

The project team was tasked to design and build a realistic control panel to fully test the control system during the factory acceptance test sessions. The testing platform included actual digital controls: PLC, DCS, I/O, as well as hardware mimicking the ASD and DOL contactors, interlocks, safety relays, and isolation switches. This could be justified because of:

- Experience with other projects based on complex control systems necessitating brown field wiring modifications resulting in higher commissioning hours than scheduled and budgeted thus increasing project execution risk.
- Proactive field tests as well as work procedures review through realistic simulations help identify gaps and programming errors, minimizing required field troubleshooting time ensuring efficient execution.
- Increased operation and maintenance personnel knowledge and skills through learning sessions utilizing the simulator before commissioning and turnover.

There are several other benefits of utilizing simulation over other traditional passive testing methods. The main advantage is how each component or subsystem can be tested as a fully integrated control system (controls and power) [9]. It is uncommon to have the spare MCC or ASD equipment required to complete offline function testing. Since the project included complex controls, such as automatic start of Slow Roll and Full Speed routines, interlocks and numerous I/O, such equipment was required for testing purposes. The MV components were represented with LV devices in the realistic testing platform.

The facility believes that one way of reducing a project execution risk is keeping field work to a minimum. In general hands-on-tools time is limited and difficult to coordinate. This limited time results in low field execution efficiency. These challenges can be reduced by completing as much work as reasonably possible in a controlled environment such as the one offered by the testing platform.

Despite best engineering practices and reviews, errors occur which are only discovered during actual testing and commissioning activities. Depending on the issue, errors can pose a significant execution risk, such as the out-of-phase connection of ASD output contactor with the DOL power source.

The testing platform shown in Fig. 6 was found to be an excellent troubleshooting and learning tool. Nearly all features were enabled and fully tested. The test plan included the validation of the following before the final programs were uploaded into the actual DCS, PLC, and ASD.

- Testing of discrete inputs and outputs.
- Testing of communications as well as data mappings.
- Protective functions (electrical / mechanical / interlocks).
- Automatic start routines and manual commands.
- DCS console displays and alarm / status annunciations.

The project team engaged plant electricians and instrumentation technicians by hosting information and testing sessions. These sessions offered a great opportunity to gain skills and knowledge in the project. They were introduced to all control scenarios, going beyond the standard control narratives. A review of the logic diagrams was completed, clarifying how the different modes of operation are decoupled while still interacting with each other. This resulted in a clear understanding of what troubleshooting activities can be accomplished while the system is in full operation. The gained skills were further improved later-on when completing the actual commissioning activities.

Fig. 6 Factory Acceptance Test of PLC Hardware and Program

VII. IMPLEMENTATION PERFORMANCE REVIEW

A. *Electrical Synchronization*

The oscilloscope screen photo in Fig. 7 shows the voltage waveforms at the drive output (1) and the DOL supply (2) one second prior to the output contactor being closed. The ASD adjusts the output voltage both in terms of magnitude and phase relationship to match the source to which its being synchronized with a slight lead on the phase angle to allow for the sub-cycle transfer time during the transition. The result is a smooth transfer with minimal disturbance to the mechanical and electrical systems.

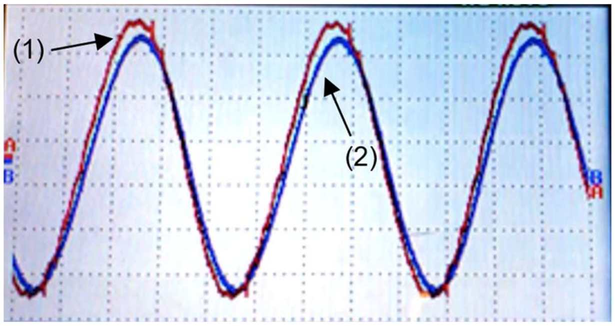


Fig. 7 ASD Output (1, red) and DOL (2, blue) Voltages

B. *Mechanical Performance*

Before implementing the slow roll and other improvements the pumps were commonly plagued by high vibrations and rubbing on startup. The machines would frequently trip or seize due to these issues. Fig. 8, Fig. 9 and Fig. 10 show a startup of P-2B pump with typical high 1x base vibration where one of the probes passed the trip value. The machine did not trip during this particular start as it requires 2 out of 2 probes to exceed the trip threshold to trip. The figure shows the orbit and spectrum are dominated by the 1x base frequency which indicates an imbalance or bend and supports the idea that the shaft was bent during the startup.

Following the ASD slow roll implementation, the vibrations when starting up a pump were generally improved, resulting in higher reliability performance. Fig. 11, Fig. 12 and Fig. 13 show the same pump during a start from 300 rpm to full speed, 1800 rpm. The plots show a clearly reduced 1x base frequency component which indicates a minimal to acceptable level of shaft bending during the startup. The result varies across the four different pumps but is generally improved compared to starts prior to the ASD slow roll implementation. The orbit and spectrum in this example appear noisy and indistinct because the 1x rpm component is no longer dominating the signal and is allowing the runout and other noises to be seen more clearly.

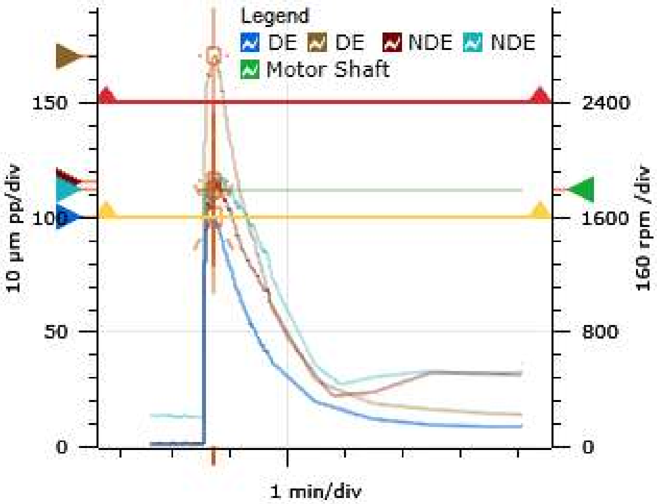


Fig. 8 Startup from Hot Standby Before ASD Slow Roll – Vibration vs Time

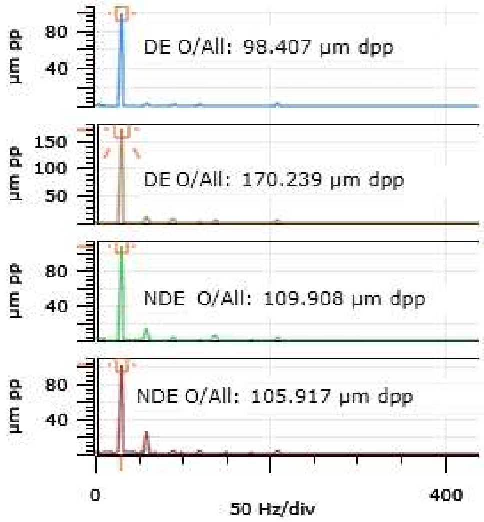


Fig. 9 Startup from Hot Standby Before ASD Slow Roll – Spectrum

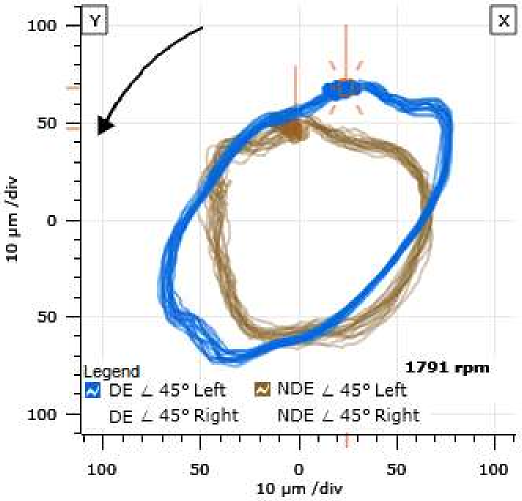


Fig. 10 Startup from Hot Standby Before ASD Slow Roll - Orbit

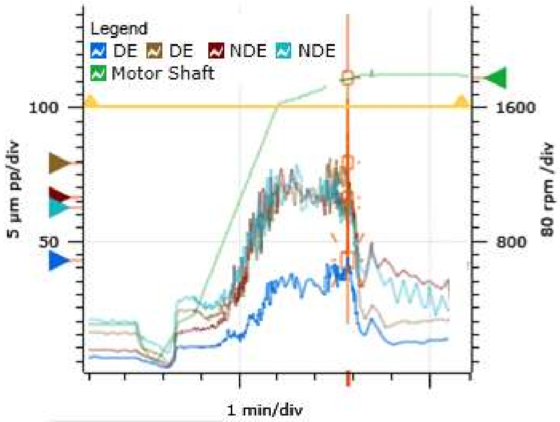


Fig. 11 Startup from 300 rpm Slow Roll – Vibration vs Time

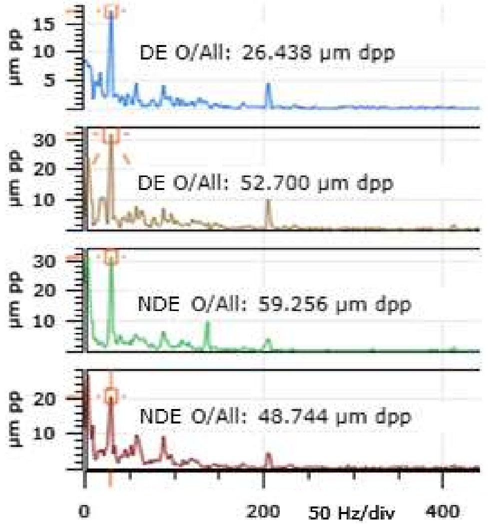


Fig. 12 Startup from 300 rpm Slow Roll - Spectrum

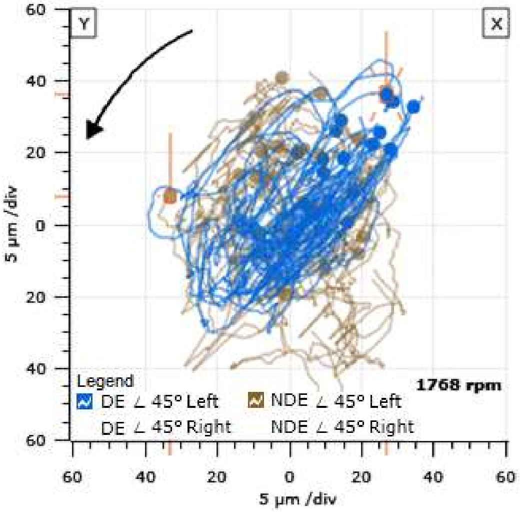


Fig. 13 Startup from 300 rpm - Orbit

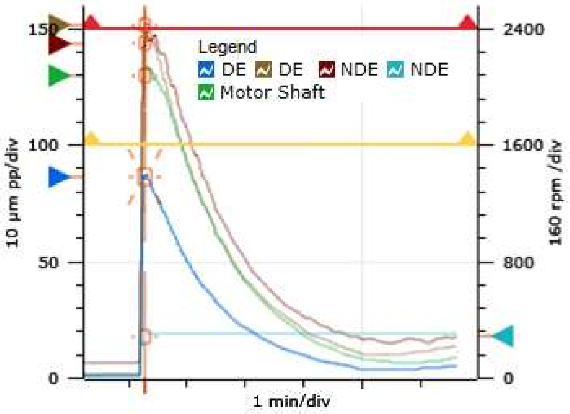


Fig. 14 Startup from Stopped to 300 rpm - Vibration vs Time

Interestingly, when starting up from stopped to 300 rpm in Slow Roll, the pumps are often still seeing high vibrations. This is shown below in Fig. 14, Fig. 15 and Fig. 16 where the vibrations hit trip thresholds but did not trip due to 2 out of 2 voting. This is obviously not ideal but is more acceptable for operations when starting on Slow Roll than when transitioning from zero to Full Speed for production use. If a pump trips while starting on Slow Roll it will not have any impact on production because the main process pump is already running.

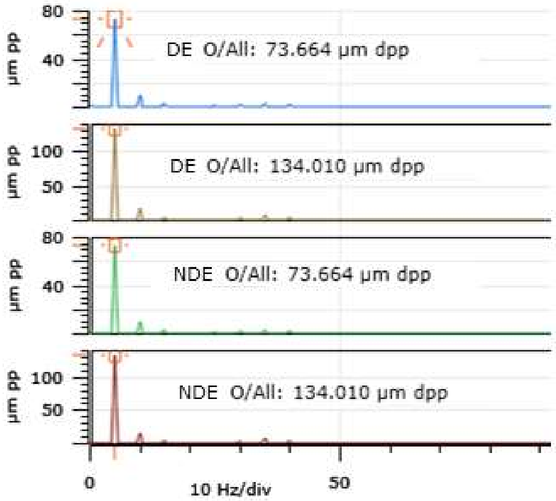


Fig. 15 Startup from Stopped to 300 rpm - Spectrum

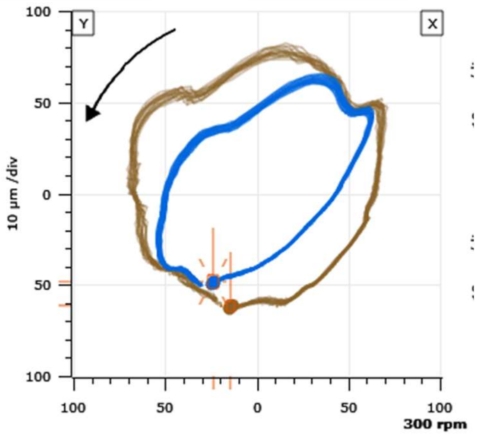


Fig. 16 Startup from Stopped to 300 rpm – Orbit

VIII. CONCLUSIONS

Overall, the reliability of P-2 and P-6 pumps has been improved by the implementation of the slow rolling and speed ramp up features utilizing an existing ASD. There is still room for additional improvements to reduce vibrations. Possible considerations for the future should include the following:

- Reconsider how longer ramp time from 300-1800 rpm could help reduce the 1x rpm vibration response.
- Adding a ramp time to the 0-300 rpm slow roll starting sequence to help reduce the 1x rpm vibration response. This option may pose a risk of damaging the bearings from running below the speed necessary for sufficient hydrodynamic lubrication of the journal bearings and therefore must be carefully assessed.

- Investigate whether it would be more effective to not constantly slow roll the standby pumps but instead use the ASD for slowly ramping up a single pump speed over a longer period when needed.
- Inspect the bearings for signs of damage from running at 300 rpm with possible marginal lubrication for extended periods of time at the next maintenance opportunity.
- Investigate implementing de-synchronization to ramp down pumps from Full Speed to Slow Roll. This will provide a bump-less transition when removing a pump from service, reducing the likelihood of dislodging hard by-products known to accumulate in pump suction strainers.

IX. NOMENCLATURE

Hot standby - Hot standby is a means to ensure a critical process can continue to work uninterrupted even if one or more system components should happen to fail. This will often involve some form equipment redundancy such that there are primary and secondary systems running simultaneously.

Bump-less – To transfer sources in such manner as to not cause any damage to the motors, couplings, and connected loads.

X. ACKNOWLEDGEMENTS

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XI. REFERENCES

[1] API STD 610 - 2010-09, *Centrifugal Pumps for Petroleum, Petrochemical and Natural Gas Industries*: Washington, DC: American Petroleum Institute (API).

[2] S. Yedidiah, *Centrifugal Pump User’s Guidebook*, Boston, MA, Springer, 1996.

[3] W. R. Finley, M. M. Hodowanec and W. G. Holter, "An analytical approach to solving motor vibration problems," *IEEE Transactions on Industry Applications*, vol. 36, no. 5, pp. 1467-1480, Sept/Oct 2000.

[4] G. Stockholm, “Insight from hindsight: A practitioner's perspective on a causal approach to performance improvement,” Safety Science vol. 49, pp 39-46, 2011.

[5] E. John, R. Turner & R. Müller, “Maximizing strategic value from megaprojects: The influence of information-feed on decision-making by the project manager,” *International Journal of Project Management*, vol. 30, no. 6, pp. 639–651, Aug 2012.

[6] J. Gardell and D. Fredrickson, “Motor Bus Transfer Applications Issues and Considerations,” *J9 Working Group Report, IEEE-Power System Relay Committee*, 2012

[7] G. Seggewiss, R. Kottwitz and D. J. McIntosh, "AFD synchronizing applications: identifying potential methods and benefits," in *IEEE PCIC Conference Record*, 2001, pp. 83-89.

[8] *PowerFlex 7000™ Synchronous Transfer Commissioning Guidelines*, Cambridge, Ont: Rockwell Automation Inc. March 2005.

[9] E. Tremblay, A. Kachurowski, D. Leschert and K. Busby, "Protective Relay Upgrade Utilizing Real-Time Simulator Technology: Application in an Industrial Facility," *IEEE Industry Applications Magazine*, vol. 27, no. 4, pp. 57-68, July/Aug 2021.

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