Development of an 11,000 r/min, 3500 hp Induction Motor and Adjustable Speed Drive for Refinery Service

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Abstract - **Faced with the need to revise the refining process to produce reformulated gasoline in compliance with EPA requirements, the Chevron El Segundo Refinery found justification to purchase special high speed electric motors with adjustable speed drives to replace existing steam turbine recycle compressor drivers. This paper explains the decision making process and rationale that led to this purchase. Further, it describes the design/development process and testing/approval procedures to demonstrate the necessary reliability levels for critical refinery service in this "first-of-its-kind" application.**

INTRODUCTION

The steam turbine motorization project was developed as a means for the Chevron El Segundo Refinery to make 150 lb steam available for use on the reformulated gasoline projects. This project, in combination with other steam saving efforts, eliminated the need to install a new packaged boiler. The installed cost for a new 250,000 lb/hr boiler was estimated at $20 million compared to an installed cost of $4.6 million for two high speed motors. (High speed motors are those which operate at speeds above 3600 r/min.) In addition, permitting, operating, and maintenance costs as well as air quality concerns for the new boiler were unattractive compared to the use of electric motors.

A study was made of seven condensing turbines to determine if replacing each turbine with a motor was a viable option while considering operability, safety, and reliability. From the original study of seven turbines, two were chosen as the first to be replaced. The selected turbines drive hydrogen recycle compressors, each of which has a spare turbine/compressor that will remain in service while the turbine to motor conversion is made and will be retained as a spare after the conversion. This reduced the lost production/operating cost involved with installing the motors and minimized the risk associated with the use of new technology.

Each motor would be rated 3500 hp with a maximum speed of 11,160 r/min. The steam savings from each turbine is approximately 40,000-46,000 lb/hr of 150 lb steam. Replacing the two turbines with motors reduced the refinery's Energy Intensity Index (EII) by more than 1.0 point, which translates to an annual cost savings of $1.6 million (difference in energy cost between steam and electricity).

During the early phases of the project, several options for replacing each turbine with a motor were investigated. The options included: 1) install a standard speed motor and gear with across the line starting, 2) install a standard speed motor and gear with an adjustable speed drive (ASD), and 3) install a high speed motor with an ASD. The high speed motor manufacturer was consulted prior to preparing a detailed cost estimate to review motor design and assess reliability issues. Cost estimates were completed for all three options and evaluated based on project objectives. One of the main project objectives was to minimize the modifications required to replace each steam turbine.

Although the first option was the least expensive, the fixed speed did not satisfy the required compressor operating parameters and this option was eliminated. The second option created some difficulties during construction since the compressors were located on the top deck of a three-story structure. The increased length of a train that included a gear and a motor would require extensive modification of the foundation and rework of large diameter hydrogen piping. The added cost of the modifications required for the foundation increased the installed cost of the standard speed motor/ASD option to slightly more than the cost of the high speed motor option. More importantly, the modifications required for installation of the motor and gear were estimated to extend the construction schedule by four weeks with a corresponding substantial cost increase due to the longer plant shutdown.

The third option involved new technology with very limited experience. However, retrofit of the turbines with high speed motors to directly drive the compressors was considered a viable alternative due to the construction challenges stated above and the elimination of any reliability problems associated with a gearbox. Reliability of the high speed motor and ASD was a concern for the project team. Motors of similar design but at lower speeds (5500 r/min) had been successfully applied in other facilities by the manufacturer [6]. This motor would be an extension of these previous designs. After extensive risk assessment and review of preliminary design data, the high speed motor option was selected.

MOTOR DESIGN

These motors are rated 3500 hp, 2800 V and were built to meet all applicable requirements of API Standard 541 [1] with appropriate modifications for ASD application [10]. A maximum speed of 11,160 r/min was required with an operating speed range of 8350-11,160 r/min. The motors are induction type since such high operating speeds are not currently possible with synchronous motors due to rotor construction limitations.

The motors were considered to be the critical item in this ASD system since motors of this size and speed had never before been built. While 3500 hp motors are generally considered "large", the torque requirements are actually those of a standard 3600 r/min machine at 1130 hp because motor size is proportional to torque which equals hp x 5250/(r/min) expressed in ft-lb. Hence, the physical size of the stator and, more importantly, the rotor is relatively small.

Instead of a conventional laminated construction, the rotor design uses a solid, one-piece steel forging for strength, rigidity, and symmetry. Fig. 1 shows a sketch of the rotor. Notice the long slender shape necessary to maintain acceptable peripheral speeds. The bearing span is approximately eight feet, the rotor diameter is less than 13 inches, and the total weight is just over 2300 lb.

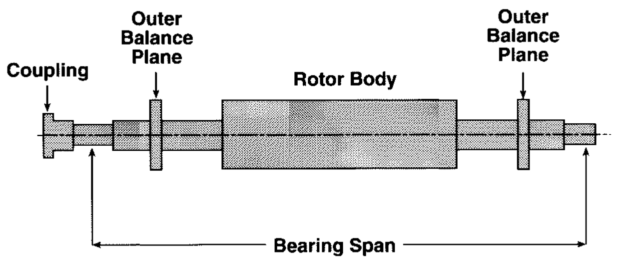
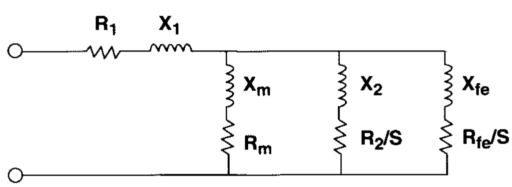


Fig. 1. 11,000 r/min, 3500 hp High Speed Induction Motor Rotor.

The electrical model for this high speed induction motor is similar to that of a normal 60 Hz machine with one addition. The iron parameters of the solid forged rotor are modeled in the equivalent circuit as another parallel rotor path, $R_{fe}/S + jX_{fe}$, as seen in Fig. 2. The modified induction motor equivalent circuit accurately predicts the electrical performance of the high speed motor necessary for design of the ASD.



R_1 = Stator Resistance
X_1 = Stator Reactance
X_m = Stator Magnetizing Reactance
R_m = Stator Core Loss
X_2 = Rotor Reactance
R_2 = Rotor Resistance
X_{fe} = Rotor Core Reactance
R_{fe} = Rotor Core Loss
S = Slip

Fig. 2. High Speed Induction Motor Equivalent Circuit.

The rotor and rotordynamics were the primary area of new design and development. The rotor construction used is very similar to that employed for decades in the production of large turbine generators. These generators are of such size that even at 3600 r/min their peripheral speeds are well above the peripheral speeds required for these motors. Balancing, cooling, and eddy-current reduction methods developed for large generators are employed on these motors. Further, while motors of this size/speed have not been built previously, every refinery has multitudes of compressors of similar (and larger) size/speed. The rotordynamics developed over decades for compressors and turbines can easily be applied to motors. In fact, the rotor of an induction motor is far simpler to model than that of a compressor or turbine and possesses none of the aerodynamic considerations.

The rotor cage is very similar to some of the motor manufacturer's standard designs [7]. The entire rotor cage is aluminum for its low weight (and low centrifugal forces) and high mechanical strength. The bars are shaped and provided with an interference fit to positively locate and firmly fix them within the slots. These bars are connected to the end rings using a continuous automated TIG welding process, which provides high mechanical strength as well as a reliable electrical connection. Stainless steel retaining rings are installed over the end rings to prevent distortion of the overhung bar/ring assembly. There are no shaft-mounted fans on this rotor design. Instead, separate cooling fans are located on the motor enclosure.

The stator design and construction is similar to that of any induction motor. Stator core natural frequencies that could be excited by the ASD were avoided. Design and material selection were the same as for "high efficiency" motors to minimize losses, especially with the higher frequencies involved. The skin effect due to the high frequency supply as well as the electrical field distribution in the stator core and windings were studied and optimized by careful selection of strand dimensions and turn configuration. The insulation system uses glass and mica tapes and solventless epoxy resins in a vacuum pressure impregnation (VPI) process and was designed to minimize risk of partial discharges under high frequency operation. Each coil was individually surge tested prior to connection in accordance with IEEE Standard 522 [5] to eliminate any potentially defective coil. Following VPI, the stator was continually rotated during the oven-bake cycle to ensure consistent resin distribution, which is important to achieve even heat transfer and temperature distribution in the finished stator.

This motor employs base and pedestal type construction where all loads are carried by a heavy steel I-beam base and pedestal bearings as shown by the photograph in Fig. 3. The rest of the motor enclosure is designed to protect the motor from the environment and to provide adequate and evenly distributed cooling. The totally-enclosed water-to-air cooled (TEWAC) enclosure design includes redundant blowers for cooling and internal pressurization.

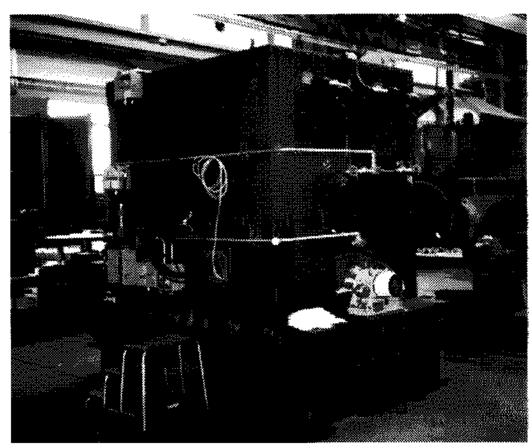


Fig. 3. 11,000 r/min, 3500 hp High Speed Induction Motor.

Hydrodynamic tilting pad bearings (Fig. 4) were selected to meet the requirements of critical speed location, vibration limits, and rotordynamic stability. The bearing pedestals were designed to provide the necessary stiffness for rotordynamic requirements. Also, the coupling characteristics were tuned as another essential part of the rotordynamics. A diaphragm-type coupling specially designed for high speed applications was selected.

A complete rotordynamics study of the proposed system was performed concurrently with the design process. The study included calculation of the lateral and torsional critical speeds, evaluation of shaft stresses, prediction of the expected vibration amplitudes to the specified dynamic unbalances, long-term reliability assessment, unbalance response analysis, and stability analysis [9].

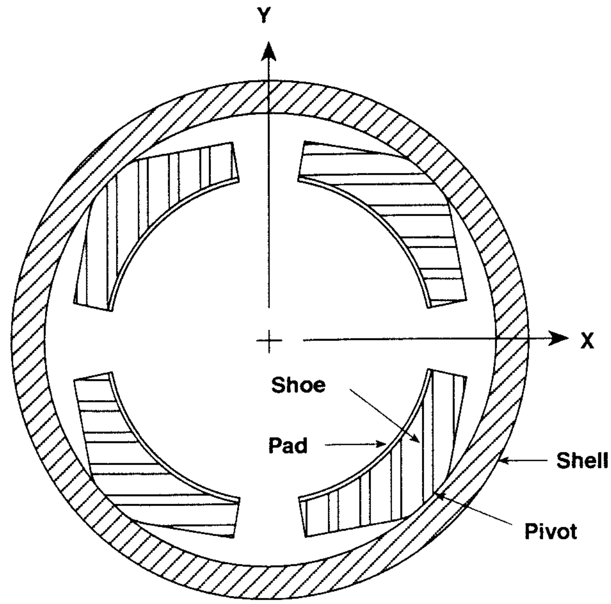


Fig. 4. Tilting Pad Journal Bearing.

The acceptable vibration levels were those defined in API Standard 541 [1] with some modifications by the user specifications (see Table 1). Hence, at 11,160 r/min the allowable unfiltered shaft displacement relative to the bearing housing is 1.0 mil_{p-p} (0.001 inch peak-to-peak). Calculations showed such levels to be achievable.

API Standard 541 [1] and the user specifications required that the critical speeds of the motor maintain a separation margin from the operating speed range to avoid excessive vibration. Lateral and torsional resonances were required to be separated by 20% from running speed and 10% from twice running speed, electrical line frequency, twice electrical line frequency, or any ASD excitation frequency.

Although a rotor of smooth cylindrical shape without rotating fans does not have the destabilizing sources typical to a compressor, the high speed increases the potential for vibrational instability. A ratio of the maximum continuous speed over the first lateral critical speed above 2.0 is a warning of possible unstable vibration. For this motor the speed ratio is approximately 5.0. Tilting pad bearings used in these motors have the capability to minimize destabilizing forces (i.e., oil whirl) at high speeds. The bearing geometry, clearance and preload were adjusted to maximize the rotor stability while meeting the specified requirements pertaining to critical speeds.

The undamped critical speed map for the rotor mounted on its two bearings is shown in Fig. 5. This figure shows the rotor must pass through the first two critical speeds during starting and will operate between the second and third critical speeds for the expected support stiffness of approximately 750,000 lb/in.

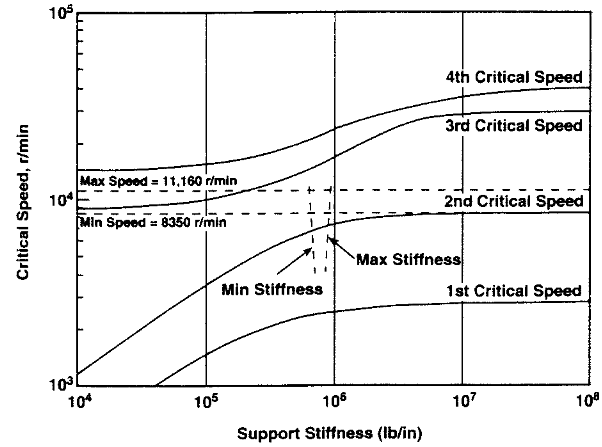


Fig. 5. Lateral Analysis Undamped Critical Speed Map.

A damped response analysis of the rotor/support system was performed to more accurately predict the location and vibration response of each critical speed. Unbalances prescribed in API Standard 541 [1] were simulated at locations on the rotor to excite the various critical speeds. The analysis was made for the full range of bearing clearances, preloads, temperatures, and unbalance locations. The vibration response at the shaft proximity probes versus rotor speed for each unbalance condition is calculated to identify the location of each critical of interest. Later this analysis is compared to actual unbalance response test results.

Fig. 6 shows a sample calculated rotor response with the unbalance weights applied at each end of the rotor in phase with each other, which excites the first critical resonance (as well as the third). For the expected range of support stiffness, bearing clearance, and oil temperature, the calculated first lateral critical speed varies from 2160 to 2200 r/min. Response at this critical is satisfactory as it is well removed from the operating speed range and has a very low maximum vibration amplitude of less than 0.2 $mils_{p-p}$.

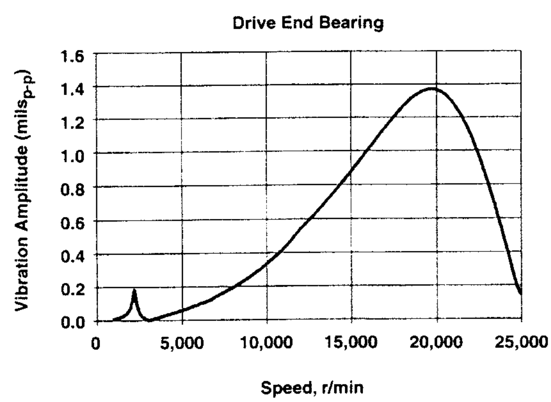


Fig. 6. Calculated Rotor Response With Unbalance Weights Applied at Each End of the Rotor and In Phase With Each Other.

Fig. 7 shows a sample calculated rotor response with unbalance weights applied at each end of the rotor 180° out of phase with each other, which tends to excite the second and third critical resonances. The calculated second lateral critical speed varies from

6680 to 6840 r/min. The highest calculated speed for the second critical is separated from the operating speed range by only 18.1%, instead of the user required 20%. However, the maximum calculated vibration amplitude from Fig. 7 is 0.9 $mils_{p-p}$ with the rotor unbalanced. If the maximum response for this rotor does not exceed 1.6 $mils_{p-p}$, the response is considered well damped [1]. Thus, the rotor response at the second critical is satisfactory. The third lateral critical speed is apparent in both Figs. 6 and 7 at approximately 20,000 r/min, which is well removed from the operating speed range and not of concern.

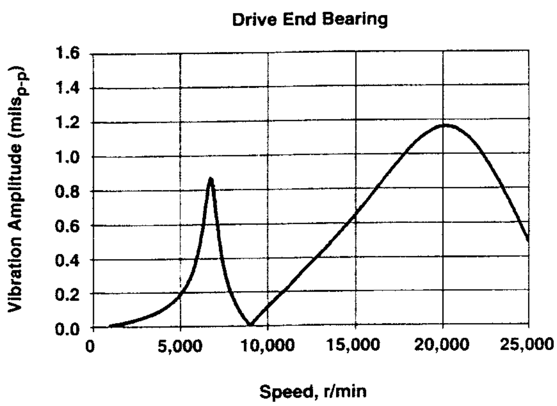


Fig. 7. Calculated Rotor Response With Unbalance Weights Applied at Each End of the Rotor and 180° Out of Phase With Each Other.

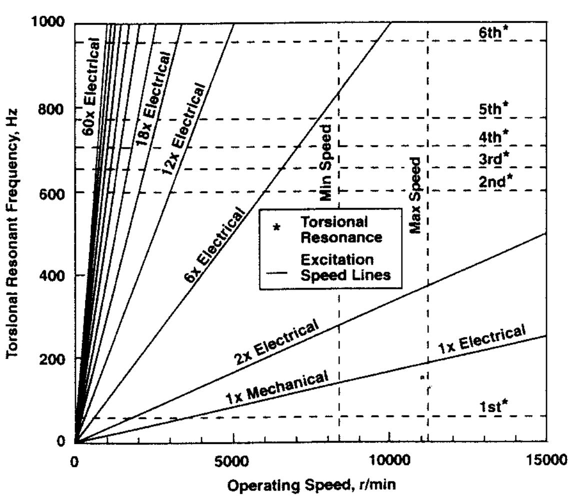


Fig. 8. Torsional Resonance Interference Diagram.

A torsional analysis of the motor/coupling/compressor/ASD system was performed to assure excessive torques associated with torsional natural frequencies would not occur. This is especially important with an ASD application because of the multiple torsional excitations generated by the drive. Fig. 8 shows the interference diagram of torsional resonances for this system. Notice the excitation frequencies include integer multiples of 6X electrical frequency from the six pulse ASD inverter in addition to the normal 1X running speed and 1X and 2X electrical excitations. The 6X excitation frequency intersects the fifth and sixth order torsional resonances within the operating speed range including the 10% separation margin, indicating a potential problem. However, the stresses associated with these higher order torsionals were calculated and found to be well within the motor and compressor shaft endurance limits and the coupling continuous torque rating.

Along with the torsional analysis, a transient analysis was performed for a phase-to-phase short circuit and a three-phase short circuit to evaluate the peak shaft stresses/torques as well as normal operating stresses. As usual, the phase-to-phase short circuit produced the highest stresses in the system components, but these stresses were not high enough to significantly affect component fatigue life.

With the successful development of these motors, the range of high speed induction motor ratings and speeds available has been extended. Fig. 9 shows the approximate horsepower and speed range of large ASDs which presently have been built by a limited number of manufacturers.

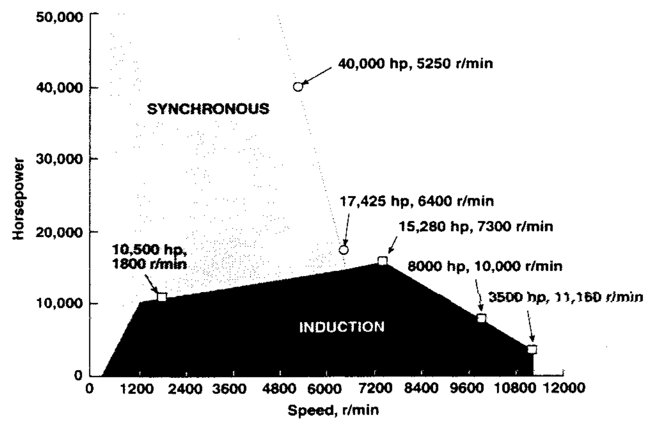


Fig. 9. Present Experience Range With Large Adjustable Speed Drives.

ADJUSTABLE SPEED DRIVE DESIGN

The decision to use a high speed motor for this application required a reliable ASD capable of operating the motor continuously from 139-186 Hz or 8350-11,160 r/min motor speed. This frequency requirement was not a major concern for the ASD because the drive manufacturer had a 167 Hz ASD design with 2.5 years running experience. The same drive design could also be applied to 186 Hz operation. This ASD was designed to deliver a maximum of 3500 hp at 11,160 r/min. The motor electrical parameters necessary to design the ASD were provided by the motor manufacturer (see Fig. 2).

Fig. 10 shows a circuit diagram of the current source inverter ASD used for this application. The rectifier of the ASD is designed the same as lower speed drives because it operates on the 60 Hz system. The two 6-pulse thyristor controlled rectifier bridges in series operate with a 30° phase shift by using the three winding isolation transformer delta and wye connected secondary windings. This produces an equivalent 12-pulse rectifier as seen by the system at the primary of the isolation transformer. This 12-pulse input is desirable because it significantly reduces the harmonic distortion on the electrical system [4].

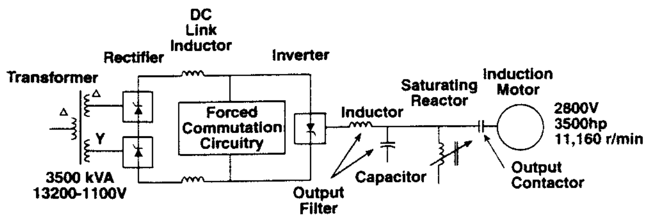


Fig. 10. Adjustable Speed Drive Circuit Diagram.

The inverter bridge is 6-pulse design with 60 μs turn-off time thyristors. These thyristors are twice as fast as the rectifier thyristors, allowing the drive to operate at higher fundamental frequencies while producing approximately the same operational margins as a standard 60 Hz inverter.

This ASD uses two large dc link inductors sized to filter the dc current ripple. The dc link inductors also serve to isolate the rectifier and inverter bridges to minimize the effects between the ASD input and output.

The ASD output filter contains a bank of capacitors that is designed to reduce motor full load current harmonic distortion to approximately 5%. Consequently, no derating of the motor is required due to harmonic heating. Fig. 11 shows typical output voltage and current waveforms for this ASD.

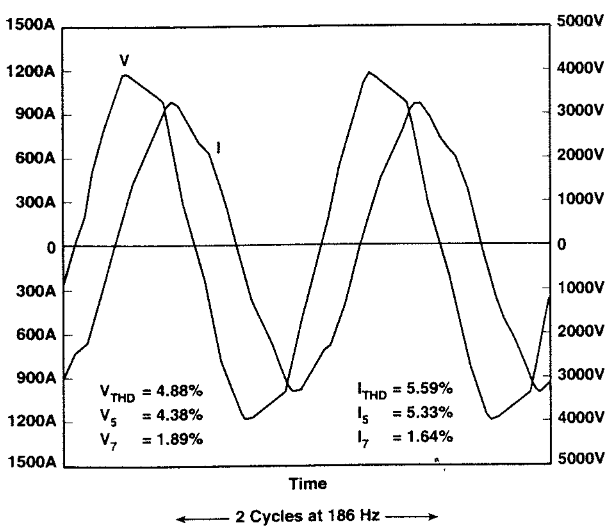


Fig. 11. Typical ASD Output Voltage and Current Waveforms.

The capacitive output filter also allows the inverter to be load commutated at higher frequencies. The ASD is designed with forced commutation of the inverter during startup. At a point below minimum operating speed, the inverter load becomes capacitive which enables natural load commutation, and the forced commutation circuit is turned off. This results in lower dc current requirements and a higher drive efficiency.

The compressor and the refinery process require a constant torque of approximately 1650 ft-lb throughout most of the speed range with a maximum of 1730 ft-lb at 8500 r/min. Since the drive was designed in conjunction with the motor, it was decided to operate on a higher than nominal volts per hertz (V/Hz) curve below rated speed. The drive operates at a constant V/Hz below 142 Hz, 2600 V and then reduces the V/Hz linearly down to the nominal 2800 V at 186 Hz. The higher V/Hz increases capacitor current in the output filter, ensuring that the inverter operates in the load commutated region throughout the operating speed range despite the higher torque requirements at minimum speed.

The ASD is designed with several special features to enhance reliability. The latest technology digital control module is used and is powered by an uninterruptible power supply (UPS). All bridge cells are built with 200% peak voltage margin with an additional N+1 thyristor per bridge leg. With this design, the drive can withstand 200% peak voltage with one failed thyristor in each leg. The ASD is installed in an air conditioned control building supplied with a pressurization unit. The pressurization unit is filtered to remove dust particles, thus increasing the life of the drive and decreasing maintenance. The ASD bridge cells are cooled by an internal water supply with a water-to-air heat exchanger mounted outside the control building to expel 77% of the losses to the outdoors, reducing air conditioning requirements. Redundant cooling pump and blower motors are used with automatic transfer circuitry.

Because the input isolation transformer has to work in conjunction with the drive system, the secondary voltage can be chosen to optimize the power factor of the drive system at full load. Analysis showed the power factor in the operating speed range to be 0.89-0.91 at the transformer primary with the two secondary windings feeding the rectifiers at 1100 V_{ac} each.

SYSTEM TESTING

Since this application involved the use of new technology in critical service, it was essential to very thoroughly test the equipment. The challenge was to avoid problems after startup. Also, the time available for installation, commissioning, and final tuning of the ASD was relatively short. Thorough testing could help assure a reliable installation with minimum commissioning time. The ASD was first tested without the motor at the drive manufacturer's factory. The complete drive was shipped to the motor manufacturer's factory where a system test under full load, rated speed conditions was conducted. The ASD was shipped back to the drive manufacturer's factory where final factory tests were conducted. Final system tests will be conducted during commissioning at the refinery.

The transformers and reactors, being proven equipment, were given only routine electrical tests required by applicable ANSI standards. The only additional tests were a heat run at rated frequency and a sound test conducted on the saturating reactor. These tests were made to verify an acceptable temperature rise (85°C measured) and noise levels (85 dBA at one meter measured) when operating the reactor at 186 Hz.

Original tests on the ASD conducted at the drive factory include verification of control logic, protective features, and alarms; heat run; and insulation high potential tests. The heat run was conducted at reduced input voltage but with rated current and frequency using the inverter output capacitor as a load since the high speed motor was not available. Some of the control logic tests were conducted using the factory test facility motor. However, these tests could only be made at a maximum of 60 Hz and 800 hp, the rating of the test facility motor.

At the motor manufacturing facility, the motors were arranged in a back-to-back configuration as shown by Fig. 12 for load testing the ASD systems [8]. One ASD system is operated in the normal mode as a motor while the other is operated as an induction generator to provide the necessary load. The test facility generator provides only the system kW losses as well as substantial reactive power. In this manner, both the ASD and the motor can be operated at rated speed and power for testing purposes. The losses can be directly measured for determining the efficiency of the ASD and the motor.

It should be noted that the back-to-back arrangement is an abnormal configuration for operating the drives since one drive is operating in the regenerative mode, a condition which will never exist in service. Also, the drives are being supplied by the test facility generator which has limited capacity. A sudden change in load could result in instability of the test system with substantial overvoltages due to reactive power changes on the relatively small generator. Thus, it was necessary to avoid tests which cause sudden load changes while operating in the back-to-back configuration.

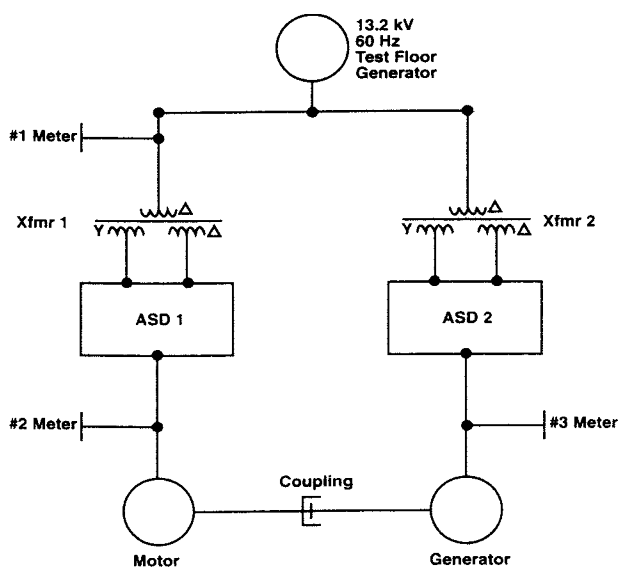


Fig. 12. Back-to-Back Configuration for Load Testing the ASD Systems.

Comprehensive testing of the ASD completed at the motor factory includes:

- Complete startup checklist
- Verify protective features and alarms
- Verify V/Hz, current balance, and load versus speed characteristics
- Verify drive stability and control under all load conditions
- Perform rated power and speed heat run and determine efficiency
- Record input and output voltage and current waveforms
- Verify system voltage disturbance ride through
- Determine motor/capacitor self-excitation voltages

All tests were satisfactorily completed. The ASD efficiency, including the input transformer but not the motor, is 95.8% at rated load and speed. However, a few problems were found and corrected as discussed below.

The ASD was designed to "ride through" an input voltage disturbance of less than 10 seconds without tripping. Upon sensing less than 70% input volts, the ASD goes into a "pause" state. During the pause, the ASD stops dc current while keeping the output contactor closed in order to track the speed of the motor and maintain the ability to catch the spinning motor if the input voltage returns to normal. During testing, it was found that the motor and output capacitor were self-exciting to produce an unacceptable overvoltage. Self-excitation occurs during an ASD pause when the stored energy in the motor nonlinear magnetizing inductance and the output filter capacitor interact to produce an overvoltage as the energy is dissipated [11].

The high speed motor is designed with low magnetic flux levels to keep iron core losses low at the high operating frequencies. This allows the motor to self-excite to a greater percentage of rated voltage when compared to a normal 60 Hz motor. Because damage to the drive components or the motor insulation is possible, a saturating reactor was added in parallel with the motor and capacitor (Fig. 10). The saturation characteristics of the reactor are lower than those of the motor, thereby limiting the self-excitation voltage to acceptable levels. Although this required some delay in the manufacturing schedule, the reactor addition was accomplished and satisfactorily tested at the motor factory.

Another problem which occurred during testing was the failure of thyristors in the forced commutation (diverter) circuit during a high speed trip. The failure mechanism was overvoltage. Although the diverter circuit had proven successful for 60 Hz operation, when operating at higher frequencies an unanticipated overvoltage was produced in the diverter circuit during a trip. Modifications to the circuit were made to reduce the overvoltage and to increase the voltage rating, which corrected the problem. The drive was successfully tested without further difficulties with the diverter circuit.

One of the most important tests for the ASD is the ability to ride through a voltage disturbance. Voltage disturbances always occur on an electrical system, resulting from local or remote faults, motor starting, etc. Reliability problems associated with many previous drive installations have included frequent trips due to system voltage disturbances. This test required the drive to ride through complete voltage interruptions of 0.05 to 0.10 seconds and one to two seconds. It was also required to ride through a voltage sag to 80% and immediate recovery. This test was not conducted with the motors loaded in the back-to-back configuration due to concerns over the test system stability with sudden load changes as previously discussed. A single motor was operating unloaded during this test. However, the total current of the drive was near rated due to the load presented by the large output capacitor. Tests under actual load conditions will be conducted during commissioning.

The ride through capability had been previously verified on a motor operating at 60 Hz. This test also worked with the high speed motor operating at 139 Hz (8350 r/min). However, the initial test on the high speed motor at the rated 186 Hz (11,160 r/min) was unsuccessful; that is, the drive tripped when subjected to a voltage disturbance. Modifications to the control logic were required to accommodate the rated speed conditions. After these modifications, all voltage disturbance ride through tests were completed without incident.

The problems encountered with the ASD illustrate the importance of system testing. Unanticipated problems were found and corrected at the factory before shipment to the refinery. As a minimum, these problems would have caused a significant delay in the commissioning time, making it difficult to complete installation and startup within the available time. In the worst case, some of these problems may not have been found during the limited commissioning time and ultimately caused an unnecessary trip and plant upset. Although it is costly in both time and dollars to conduct a system test, it is usually worth the cost if in-service problems can be avoided. Only time will tell if we were successful.

After completion of testing at the motor factory, the ASD was shipped back to the drive manufacturer for final assembly and installation in its control house. Final factory tests were conducted after installation in the control house. These tests include verification of control logic and protective features, 24-hour heat run, user interface checks, and insulation high potential test.

For the high speed motors, the full complement of factory performance tests required by API Standard 541 [1] were performed in accordance with IEEE [2] and NEMA [3] requirements. These tests include:

- Stator sealed winding conformance test
- Rotor residual unbalance verification
- Measurement of winding resistance and no load current and speed
- Determination of locked rotor current and power factor
- Determination of efficiency, power factor, and rated current and slip
- No load and rated temperature mechanical running tests
- Rotor unbalance response test to verify critical speeds
- Sound test
- Insulation high potential, resistance, and polarization index tests
- Bearing inspection and insulation resistance check

Performance of these tests are described in [1], [2], and [3] and are not discussed in this paper. The locked rotor and breakdown torque determination required by [1] is not applicable for a motor operated on an ASD and was not performed.

Some additional tests required by the user specifications were also performed. A temperature rise test with the loss of two out of four blowers was performed to verify the motor could successfully operate without excessive temperature under this condition. Also, a hot rotor stop and restart test was performed to evaluate the thermal stability of the rotor during a sudden stop with complete loss of cooling air. Finally, a bearing housing resonance test was performed to assure no structural resonance exists at any running speed or multiple of running speed which could be excited under normal operation.

All performance tests were satisfactorily completed. The motor efficiency is approximately 94.4%. The stator temperature rise is approximately 55°C by RTD, which is well within the 85°C Class B design limit. Furthermore, the motor still operates within Class B temperature rise with two of four cooling fans off. The maximum noise level is 87 dBA compared to a 90 dBA limit. Vibration levels are summarized in Table 1 and are within specified limits. Vibration data is shown only for a hot rotor condition; however, there was very little change in vibration from a cold to a hot rotor condition.

During testing, a relatively low magnitude subsynchronous vibration was observed in the frequency spectrum taken from the shaft proximity probes and oil leakage through the bearing seals was discovered. These problems were corrected by modifications which routed the oil flow more directly to the bearing pads to improve development of the oil film and by adding an air purge to the outer seal on each bearing. After these modifications, all testing was completed without further incidents.

Table 1
Measured Vibration Data[1]

Location	Vibration Limit	Measured Vibration	
		Motor Speed 11,176 r/min	Motor Speed 8360 r/min
DE Bearing Housing			
Vertical	0.10[2]	0.08[2]	0.05[2]
Horizontal	0.10[2]	0.09[2]	0.07[2]
Axial	0.15[2]	0.13[2]	0.04[2]
ODE Bearing Housing			
Vertical	0.10[2]	0.08[2]	0.08[2]
Horizontal	0.10[2]	0.09[2]	0.09[2]
Axial	0.15[2]	0.13[2]	0.08[2]
DE Shaft			
X Probe	1.00[3]	0.48[3]	0.59[3]
Y Probe	1.00[3]	0.45[3]	0.55[3]
ODE Shaft			
X Probe	1.00[3]	0.29[3]	0.45[3]
Y Probe	1.00[3]	0.34[3]	0.58[3]

[1]All data is taken with the motor hot and loaded in the back-to-back test configuration.

[2]Unfiltered velocity in inch/second, zero-to-peak. User axial limit is 0.15 in/s_{o-p}; API Standard 541 axial limit is 0.10 in/s_{o-p}.

[3]Unfiltered displacement in $mils_{p-p}$.

One test of special interest is the rotor unbalance response test. This test was performed to verify the location of the rotor critical speeds and the vibration response as the rotor passes through each critical speed. The test, which is fully described in [1], involves intentionally unbalancing the rotor with prescribed weights to excite the rotor resonances. With the weights applied, the rotor is driven to approximately 120% of rated speed and allowed to coast down to stop. The vibration amplitude and phase angle versus speed from each shaft proximity probe is recorded. The response clearly indicates the actual location of the critical speeds as well as the rotor response to a modest level of unbalance. Figs. 13 and 14 show sample rotor responses from this test. The first and second criticals are located at approximately 2200 r/min and 6800 r/min, respectively, very close to the analytically predicted values. Also, the vibration response at each critical is within the acceptable limit of 1.6 mils for a well damped response as defined by [1].

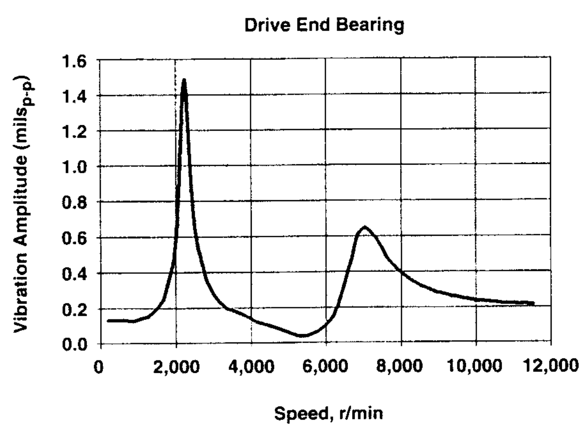


Fig. 13. Unbalance Response Test Results. Weights Applied at Each End of Rotor In Phase.

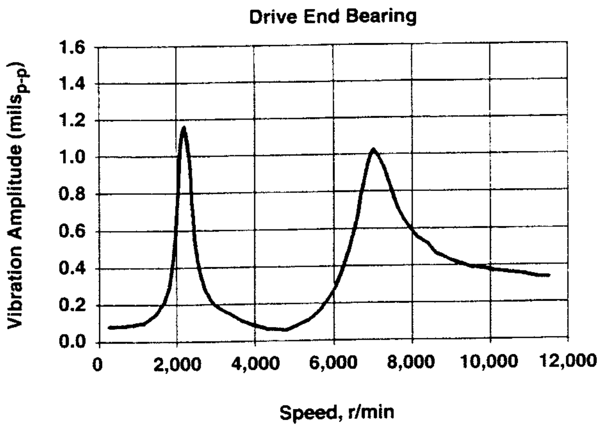


Fig. 14. Unbalance Response Test Results. Weights Applied at Each End of Rotor 180° Out of Phase.

ELECTRICAL SYSTEM

The single line diagram of the electrical system which supplies these high speed motors is shown by Fig. 15. The two ASDs are connected to the operating unit's main substation 13.2 kV buses. There are three buses, each fed from a Southern California Edison utility transformer, normally tied together through a synchronizing bus. The substation is designed to operate without any load shedding with one transformer out of service. One high speed drive is connected to Bus #2 and one to Bus #3.

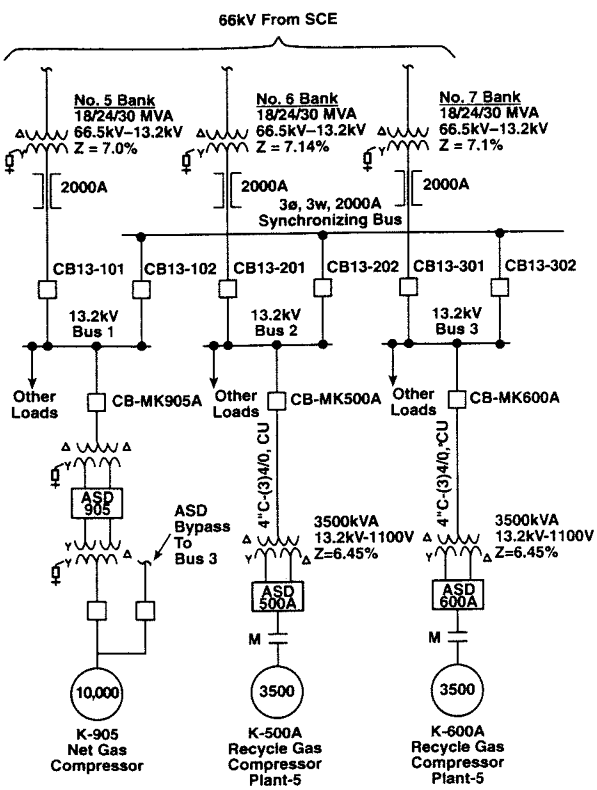


Fig. 15. Electrical Single Line Diagram.

The addition of these motors represents a relatively small load increase for the substation. However, since there is a 10,000 hp ASD already connected to Bus #1 of the main substation, a harmonic analysis was performed to predict harmonic distortion with all three ASDs on line. With one transformer out of service, the total harmonic voltage distortion (V_{THD}) on the 13.2 kV system was calculated as 2.8%, which is under the 5% limit recommended by IEEE Standard 519 [4]. In addition, V_{THD} for the 66 kV utility system caused by the ASDs was calculated as 0.6%, which is within the [4] recommended limit of 5% and acceptable to the utility company. It should be noted that more stringent harmonic limits for the 66 kV system have not been imposed by the utility since this system is dedicated to the user's facilities. On this basis, a harmonic filter was not required. Harmonic measurements to verify the calculations will be made after the drives are placed in service.

COMMISSIONING AND STARTUP

All equipment has been delivered to the refinery and installation is in process at the time this paper is being completed in May 1995. The original startup was planned for December 1994; however, the schedule has slipped to approximately June 1995. Comprehensive commissioning and startup procedures will be followed before placing the equipment in service and are essential to minimize future reliability problems during operation. These procedures will include verification of ASD control performance, protective features, performance under expected load conditions, and voltage disturbance ride through under load conditions.

One potential problem, which became known at the time this equipment was being commissioned, is the difficulty the ASD may have in handling a compressor surge. A similar induction motor ASD, except with conventional motor speed and analog controls, is in service at the user's refinery. This ASD is also driving a compressor which was inadvertently allowed to surge on several occasions. The ASD was unable to handle the rapid power swings associated with the compressor surge. Several unplanned shutdowns occurred as well as some thyristor failures on one occasion. It is also undesirable from the compressor viewpoint to allow surging and precautions have been taken to minimize this possibility.

For the high speed ASD application, anti-surge controls are included with the compressor to avoid surge. However, it is still possible for a surge to occur under some abnormal process conditions but only for a very brief period before the anti-surge control takes effect. As a precautionary measure, the ASD will assume a protective mode if the compressor approaches surge. This is accomplished by activating the forced commutation circuitry to assure commutation failure does not occur. The ASD will continue to operate in this mode while maintaining the required compressor speed and will return to the normal load commutated mode when the compressor moves away from its surge line.

In any ASD application, it is essential to consider both normal and unusual operating conditions which may be experienced. It may be necessary to enhance the performance capability of the drive or provide additional protective measures to reliably satisfy the demands of the particular application.

CONCLUSION

While the application of engineering practice and principles is always part of new product design and development, the application of new products requires more than just sound engineering. It also requires faith and confidence to pursue that which is not "tried and true". The human element needs a frame of reference within which to place that which is new. The fact that much that was "new" to this application had been tried and proven in practice on other types of equipment made the leap much easier. This combined with the thorough testing, intended to prove all aspects of system operation, eliminated much of the anxiety usually associated with such innovative applications. The successful development of these motors has extended the size and speed range of high speed induction motors available for refinery service where economic or other justifications are present. However, successful application of these or any large ASDs will depend on proper system engineering and comprehensive testing to achieve the required reliability for the intended service. The degree of success we have achieved will be determined after placing the equipment in service and gaining operating experience.

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