Starting Large Synchronous Motors in Weak Power Systems

Kurt LeDoux, *Member, IEEE*, Paul W. Visser, *Member, IEEE*,
J. Dwight Hulin, *Member, IEEE*, and Hien Nguyen, *Member, IEEE*

***Abstract*—Utility company standards for power quality are making it difficult for industrial users to start large induction and synchronous motors due to high inrush current. This paper will present a large oil company's challenges in starting large motors driven by the utility company in a relatively weak power system in East Texas while not violating the utility company's standards. A workable solution is an air-cooled pulsewidth-modulated voltage source variable-frequency drive system designed to start multiple large-horsepower medium-voltage synchronous motors without any measurable voltage flicker. Various combinations of motor design (induction versus synchronous) and starting methods are reviewed, and final design schematic diagrams are documented. Challenges encountered during the design and start-up are described, and solutions with final performance details are provided.**

***Index Terms*—Adjustable-speed drive, motor starting, synchronous motor, variable-frequency drive (VFD), variable-speed drive, weak power systems.**

I. Introduction

A LARGE OIL and gas company undertook a major upgrade of a 1940s vintage gas plant in East Texas, installing four 15-kV electric-driven centrifugal compressors ranging from 8100 to 17 500 hp. The objective of the project was to both increase the capacity of the plant and replace the obsolete and high maintenance large (over 5000 hp) existing gas engine-driven compressors. Additionally, eight new 5-kV compressors were installed, including all requisite 480-V ancillary and lighting system loads. Electrical demand increased over 15-fold from less than 4 MW to about 60 MW, with over 65% of that total attributable to the four new 15-kV centrifugal compressors. Lower anticipated life cycle operating costs (investment versus maintenance and uptime) pointed to electric in lieu of gas drivers for the new compressors. It was desired to start the four compressors loaded or in recycle to eliminate emissions associated with blowing down (unloading) the compressors. Compressor speed turndown was not required for this installation. The existing plant electrical distribution system was upgraded and expanded with a new 138-kV substation and all of the associated 15-kV, 5-kV, and 480-V electrical infrastructures (switchgear, motor control center (MCC), cables, and tray).

Upon project completion, there was essentially a new electrical distribution system retaining only a fraction of the original circuits for the remaining in-service equipment and lighting.

A. Utility Constraints

During front-end engineering design, it was discovered that the utility had the following constraints for the proposed 138-kV substation.

1) Limited available short circuit current: Calculated to be 7459 A (three phase) at 138 kV which would affect the large motor (8.1 to 17.5 khp) starting ability.
2) Strict voltage flicker requirements: Requested to limit voltage flicker (dimming of lights resulting from voltage drops) to 1.5%. This rule limited the ability to start the large compressor motors without special starting methods.
3) Limited available transmission line capacity to the facility: 63 MW at 90% power factor (PF) (per the utility contract) without a major rebuild of the existing 138-kV transmission lines. Note that the total plant demand load is currently over 60 MW and rising at 99% PF.

In summary, the utility did not have a "stiff" system but did have very stringent flicker requirements. A "stiff" system is more immune to flicker during high current inrush when starting large motors. The project had a significant challenge to start the loaded compressor motors and maintain power quality standards imposed by the utility.

II. Alternatives and Final Design

A. Motor Starting Alternatives Considered

Multiple motor starting alternatives were considered to address the voltage flicker limits. Some options were considered only in passing, and others were investigated more thoroughly as follows.

1) *Auxiliary Starting Motors (Diesel or Electric)*: One option considered was to install "pony" motors to bring large motors up to partial speed before transferring to the normal bus. This option was quickly discounted by inspection due to the excessive field equipment requirements, complexities with the required clutch arrangement, and overall reliability.

Manuscript received June 13, 2013; accepted October 16, 2013. Date of publication November 20, 2014; date of current version May 15, 2015. Paper 2013-PCIC-516, presented at the 2013 IEEE Petroleum and Chemical Industry Technical Conference, Chicago, IL, USA, September 23–25, and approved for publication in the IEEE Transactions on Industry Applications by the Petroleum and Chemical Industry Committee of the IEEE Industry Applications Society.

K. LeDoux and H. Nguyen are with Toshiba International Corporation, Houston, TX 77041 USA (e-mail: kurt.ledoux@tic.toshiba.com; hien.nguyen@tic.toshiba.com).

P. W. Visser, retired, was with ExxonMobil, Houston, TX 77002 USA. He resides in Spring, TX USA (e-mail: visstex@sbcglogal.net).

J. D. Hulin is with the ExxonMobil Corporation, Houston, TX 77067 USA (e-mail: dwight.hulin@exxonmobil.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIA.2014.2373820

2) *Switched Starting Capacitors*: The installation of large banks of switched starting capacitors common to all motors on the main 15-kV switchgear bus was considered only in passing as a viable option. Capacitors would be switched in and out with vacuum breakers to correct the very low PF of a motor during starting acceleration. This option was discounted due to the potential for electrical system resonance issues, arcing during switching operations, risk of self-excitation of other motors on the bus, and overall system protection issues.
3) *Reduced Voltage Solid State (RVSS) Soft Start Dedicated to Each Motor*: Significant time was invested in evaluating the alternative of using solid-state reduced voltage starters as this was the initial concept select recommendation. A soft start manufacturer performed unloaded motor starting analyses for both large induction and synchronous motors. If the compressors had been loaded (i.e., not vented), the starting calculations would have indicated higher inrush current and/or increased acceleration time. The analysis results for the 14 000-hp synchronous motor were as follows:
    a) RVSS soft start: 375% FLA for a 23.0-s acceleration time and equivalent locked rotor time of 6.5 s.
    b) across the line start: 460% FLA for a 4.3-s acceleration time and equivalent locked rotor time of 3.6 s.

   To summarize, the installation of a soft start system would only reduce the starting current by approximately 20% while increasing the acceleration time by over 400% for synchronous motors. Similar results would be anticipated for induction motors. The marginal reduction in starting current would not have reduced the voltage flicker to the required to 1.5%, and the extended acceleration time at the higher starting current would result in unacceptable rotor heating. Accordingly, this alternative was finally discarded.
4) *Load Commutated Inverter (LCI)*: LCI systems have been available for many years and have been used for large synchronous motor control. This option was not considered due to a number of complexities. Primarily, position sensor feedback was needed for starting that would have required additional hardware on the motor. The rectifier section of the LCI system has a high harmonic content and a low starting PF that would have required additional studies for power line quality to ensure compliance with the flicker limitations.
5) *Reduced Voltage Auto Transformer (RVAT)*: Auto transformer starting methods can be more effective for reducing voltage flicker than the RVSS soft start method described earlier. Said another way, the RVAT produces more torque per line ampere than the RVSS. This is because a transformer is used to reduce voltage to the motor. A transformer transforms the voltage while conserving kilovolt-amperes, whereas other series-type starters (reactor and RVSS) drop voltage and therefore absorb kilovolt-amperes. The impact to the motor is similar between the RVAT and RVSS. Consequently, the RVAT was not considered after the RVSS starting study showed that excessive motor heating would be encountered during starting.

TABLE I
COMPARISONS OF STARTING METHODS

Method	Torque	Flicker	System Resonance	Motor Restarts	Cost/ Simplicity
Across the Line Start	Good	Poor	None	One	N/A
Pony Motors	Good	Good	None	Multiple	High
Starting Capacitor	Good	Good	Poor	One	Low
Reactor	Poor	Fair	Poor	One	Low
RVSS	Poor	Fair	None	One	Fair
RVAT	Fair	Good	None	One	Fair
PWM VFD	Best	None	None*	Multiple	High
LCI VFD	Best	None	Fair	Multiple	High

*With Sine Filter

6) *Reactor Starting*: Reactor starting was not considered even though it is simpler than RVAT or capacitor starting and without the system resonance issues associated with capacitor starting. As described earlier, reactor (in series) starting provides poor starting torque, and there were concerns with the overall power system stability during the transition to full voltage (i.e., bypass reactor). For large motors of the project's size, large reactors would have been required that may result in power system disturbances. This starting method has the additional issue of excessive motor heating common to low-voltage starting methods.
7) *Voltage Source Pulsewidth Modulated (PWM) Starting Variable-Frequency Drive (VFD)*: Inherently, the VFD starting method results in the highest (100%) torque per unit line current. Several design options were considered using large VFD(s), either dedicated and sized for each motor or one common and switched between motors. The final design recommendation was a shared/common single large starting VFD coupled with a 15-kV switching scheme that proved to be the lowest cost and technically acceptable option. This solution builds upon a similar paper submitted to the IEEE Petroleum and Chemical Industry Committee (PCIC) 2010 which documents the capability of a voltage source VFD to start motors without exceeding motor full-load amperes (1).

   The other alternatives investigated only partially corrected for current inrush and the associated resulting voltage flicker or potentially had significant system concerns. Table I provides a qualitative summary of the various starting methods described earlier.

B. Synchronous Versus Induction Motors

Prior to starting system design, the type of motor to be utilized had to be determined, induction or synchronous. Induction motors are simpler, lower in cost, and easier to control; synchronous motors are marginally more efficient and provide reactive power (vars) to improve system-wide power factor.

The use of synchronous motors was selected in lieu of induction motors even though they are appreciably higher in initial cost and require a more complicated starting system design. However, the selection of the synchronous motors was justified by the 1% improvement of efficiency compared to induction motors. Additionally, once transferred to the power line, synchronous motors allowed for improvement of the overall plant PF, thus increasing the available real power on the current limited utility transmission lines. The utility limited the load to 63 MW based upon a 90% PF; by improving the PF (the plant is currently operating at 99% PF), the project would be able to add an additional 7.0 MW load and stay within the capacity of the existing transmission lines.

C. *Final Design Selected*

After evaluating all of the considered alternatives, the project recommended a single/common starting VFD coupled to four 12.47-kV synchronous motor compressor drivers. This combination addressed voltage flicker concerns, reliability requirements, lowest operating (kilowatthour energy) costs, and extended motor life/maintenance reductions. This was not necessarily the lowest cost initial investment (CapEx) solution, and a premium was paid for this scheme versus some of the other alternatives investigated. However, it was determined that the benefits far outweighed the additional costs and potential risks. This system would result in the lowest long-term operating and maintenance costs (OpEx).

Only air-cooled VFDs were considered as air-cooled units have lower complexity (i.e., no hoses, pump seals, water-to-water heat exchangers, outdoor heat exchangers, or a deionization tank) and subsequent higher reliability than liquid-cooled VFDs. After a long period (up to three months) of inactivity, most water-cooled drives require significant wait time to pump water through the deionization tank to ensure nonconductivity. This is not an issue for air-cooled technology.

Previous experience with starting VFDs had shown that a motor can be started unloaded with a VFD rated at only 25% of the motor horsepower rating. Available air-cooled VFDs are well within that range as the largest motor for this application was 17.5 khp. In order to minimize unloading requirements (venting of compressors), a 60% or 10-khp air-cooled VFD was specified.

Also, a "start duty only" VFD allows savings associated with climate control. The control house was specified with an HVAC system sized only for the ambient temperature and humidity plus the no-load heat losses from the VFD input transformer. The full-load VFD thermal losses were not considered for the HVAC design even though they can be substantial (4% or 300 kW at full load). However, the VFD is only fully loaded for less than 1 min during the start cycle; accordingly, at least ten consecutive large motor starts can be made without an unacceptable temperature rise in the building. This fact was borne out during commissioning and start-up. At the user request, a redundant outside air exhaust fan was provided in the VFD building should the air-conditioning system fail to keep up with the VFD heat load. To date, this feature has never been utilized.

III. APPLICATION CHALLENGES

The end user did impose a number of special technical, testing, and project execution requirements upon the drive vendor which did complicate the design, testing, and execution of this project.

A. *Technical Specifications*

A combination of user operation philosophy, cost considerations, and machinery design requirements dictated that the drive vendor provide the following deliverables.

1) *Redundancy/Backup*: The user recognized that the selection of one VFD for starting four motors meant that one VFD was a single failure point that could result in total plant shutdown. Redundancy in the design was requested of the VFD vendor. The vendor supplied a drive that allowed for 60% output capacity even if a rectifier, transformer, or output phase failed, which could still start the compressors by additional unloading. This required dual transformers in parallel and parallel output phases. Once the motors are running, the drive can be isolated for repair.
2) *Test Mode*: The user required a one-button self-test of the VFD system to ensure that the VFD would be available and operational when called upon. Since the VFD is for starting duty only, it would be idle/offline and unpowered for more than 99.99% of the year. Activation of the self-test performs the following offline functions while the 15-kV motors are running normally.
   a) Close the preselected 12.47-kV switchgear feeder breaker to the VFD.
   b) Close the integral VFD feeder breaker to energize the input transformer and power cells.
   c) Power up the VFD cooling fans.
   d) Energize the power cells.
   e) Perform self-test of the VFD controller.
   f) Issue failure alarm to the operator should any portion of this test fail.
   g) This test does not check the operation of any parts of the system that would conflict with operating equipment; accordingly, the motor breakers and synchronization scheme are not tested. Neither is the output transformer bypass scheme tested as that requires feedback from a motor.
3) *Drive Inrush*: To reduce the 1200% power-up inrush current of the drive internal input transformer, a current limiting reactor with a shorting contactor was utilized to limit the inrush to 75% of the drive full-load current rating.
4) *Drive Output Transformer*: The motor size is large, and most commercially available VFD designs are limited to 4.16-, 6.0-, or 7.2-kV applications. In this instance, the project team and compressor vendor had already determined that 12.47 kV was the most suitable voltage for the motors due to the existing power system infrastructure and the motor size. Accordingly, a step-up transformer was required for the drive design to obtain the proper motor voltage.
5) *Sine Filter*: A sine filter consisting of an inductor and a capacitor was required on the drive output for the following reasons:

   a) *To reduce detrimental effects of output transformer*: Since a transformer can exacerbate ringing and resonance surges from a drive artificial voltage (dc pulses to simulate a sine-wave current), that may damage motor insulation (2).
   b) *To limit liability*: Since the motor supplier was a different vendor from the VFD supplier.
6) *Excitation System*: The motor starts synchronized with drive output frequency and at unity PF. The motor rotor needs excitation before the drive starts. The VFD outputs a control signal to the exciter controller as part of the control scheme, and upon transfer to the line, it hands off control to the exciter to maintain var or PF control.
7) *Output Transformer Response at Low Frequency*: A drive output transformer does not have a linear response from 0 to 60 Hz (simply put, a transformer cannot step up the dc voltage). At low frequency, the voltage output from the transformer and motor breakaway torque performance are very poor. To obtain proper performance, vacuum circuit breakers were installed in the output to bypass the transformer during motor acceleration from 0 to 20 Hz, and then, insert the transformer from 20 to 60 Hz. This stepped approach requires the drive to switch between two different drive V/Hz settings to maintain the motor's fixed 12.47 kV to 60 Hz ratio.
8) *Application Concerns*: The compressor selected was a high-speed centrifugal unit that required a speed increaser gear box. On a four-pole synchronous motor, the rotor could rotate up to 90° either forward or backward to get in synchronous position. However, reverse operation would damage the compressor. A ratchet could be installed, but this requires mechanical servicing and adds complexity. Without the use of encoders, the VFD determines the exact rotor position by measuring the stator transient voltage during rotor magnetization and adjusting the drive voltage at start-up to ensure only forward rotation.

B. Interface Coordination and System Responsibility

The user assigned system responsibility to the VFD manufacturer. However, the 15-kV switchgear was purchased directly by the user and the 12.47-kV motors were purchased by the compressor packager which is typical (mechanical/machinery issues drive that decision). The VFD manufacturer proved to be the optimum choice for system responsibility for the following reasons:

1) It provided the most critical and complex components of the system (VFD with synchronizing logic to the utility, breaker switching logic (BSL) programmable logic controller (PLC), and synchronous motor exciter controller in addition to the VFD building).
2) It provided design guidance and one-line requirements to the user to obtain bids from switchgear vendors.
3) It is the only entity willing and technically able to provide a complete string test utilizing both the provided equipment and representative switchgear and synchronous motor to prove the total system during the factory acceptance test (FAT).
4) It participated in the switchgear vendor's FAT after the installation of the VFD vendor's switching logic PLC in the switchgear building to prove the PLC control of the 15-kV breakers.

Accordingly, the end user issued three separate purchase orders from different vendors for the following: 1) switchgear/power building; 2) VFD, VFD building, exciter controllers, and switching logic PLC; and 3) compressors/motors. Meetings were held with all parties, and drawings when released were shared to ensure equipment and control compatibility. The VFD vendor developed and manufactured the drive, purchased and programmed the user-specified BSL PLC, and purchased a commercially available dedicated synchronous motor ac exciter controller from a third party.

C. Factory Acceptance Test (FAT) Events

In keeping with the user's "system responsibility" approach, the VFD vendor was required to functionally "string test" the full system. This included not only the provided equipment but also the representative switchgear and synchronous motor to be utilized in the field. During the user-specified FAT string testing, all of the major components (VFD, switching logic, switchgear, and exciter controller) worked together to start the synchronous motor to the user's satisfaction. However, the exciter controller failed multiple times with circuit board damage. The failure occurred during transition/switching from the the VFD/motor period (i.e., 0–20 Hz) to the VFD/output transformer/motor period (i.e., 20–60 Hz). This result was completely repeatable (all four exciter controllers were damaged), and it was assumed that a surge was occurring in the motor exciter winding. When the exciter controller manufacturer was unable to determine the failure cause or offer a solution, that exciter controller was abandoned, and a different exciter controller manufacturer was selected.

The new exciter controller design (one required for each motor) used a commercially available low-voltage VFD (by the main VFD vendor) with modified software. Normally, this product provides variable voltage and frequency with a fixed V/Hz ratio. The software was modified to maintain the frequency fixed at 60 Hz with an output infinitely adjustable up to 460 V. This simulates the same performance of a thyristor controller starter output. Additional equipment added to the low-voltage VFD included a sine-wave output filter, a var and PF controller, and a PLC for the control of the synchronous motor PF after the drive has transferred the motor to the normal power line.

Testing of the electrical system components individually and together in a string test proved to be very important in identifying and resolving what could have been a very serious problem in the factory before field installation.

D. Site Acceptance Test Events

Once all equipment was installed in the field with compressors and testing had begun, four minor unanticipated issues occurred.

1) *Exciter Controller*: During the check out of the VFD and motor, the motor was stopped while running on power line. During coast down of the motor, the capacitors on the dc bus of the newly designed low-voltage exciter failed dramatically. This would happen even if the exciter controller had no power. Exciter winding voltage would not decay as normally expected and would actually increase.

   Referring to Fig. 2, the exciter circuit was designed without isolation contactors as originally configured. During nonpowered coast down of the motor, the capacitors (B) in the sine-wave filter on the low-voltage VFD exciter controller were in resonance with the motor exciter windings (A). The resulting ac voltage (C) would go to high levels exceeding the VFD capacitor rating (D). Voltages on the exciter are normally 420 VAC or less but were documented over 700 VAC, exceeding the limits of the motor exciter winding insulation.

   The sine-wave filter capacitors (B) were removed from the VFD exciter, and the resonance problem disappeared. However, harmonics from the VFD-based exciter controller (2-kHz PWM) output became unacceptably high, and the motor exciter manufacturer required that the sine filter capacitors be retained. Surge arrestors were tried without success (continued to experience unacceptable voltage spikes). The final solution was both simple and inexpensive; an output contactor was added to instantaneously isolate the exciter controller from the motor whenever the motor was tripped.
2) *Power Factor Control Handoff*: During the start sequence, the VFD maintains the PF at 1.0 via the exciter controller. However, upon completion of the motor start sequence, the VFD was to hand off PF set point control to the distributed control system (DCS) to permit the plant DCS operator to maintain overall plant PF. That was a mistake; it was one interface not assigned under the VFD vendor's "system responsibility" mandate. The DCS output was missing, subsequently driving the PF to extremely lag (close to -0-) and trip the motor on a PF fault. The DCS was removed from the control circuit. Upon completion of the starting sequence, PF set point control was handed over to the exciter controller PLC which was reprogrammed to only accept manually entered PF values between 1.0 and 0.8 leading.
3) *Potential Transformer (PT) Location*: The manufacturer of the VFD had installed a 5-kV PT for feedback on the drive output as part of the original design. When the drive was directly connected without the step-up transformer accelerating the 12.47-kV motor to 20 Hz at 4 kV, the drive V/Hz relationship was not compatible with the PT, and it overheated. PTs are designed for full voltage at 60 Hz and not for extended periods of 20 Hz at full voltage required for testing and commissioning. The PT wiring was relocated to the primary of the output transformer circuit so that it only operated above 20 Hz and then only for 2 min before reaching 60 Hz.
4) *Relay Settings*: An independent 25 relay (synchronism check) used for permission to transfer to the line was set at too tight of a tolerance and created nuisance transfer failures on some of the motors. The problem appeared to be on the motor with larger torque variances. It was difficult to troubleshoot because it is not a latching device and is independent of the VFD diagnostics.

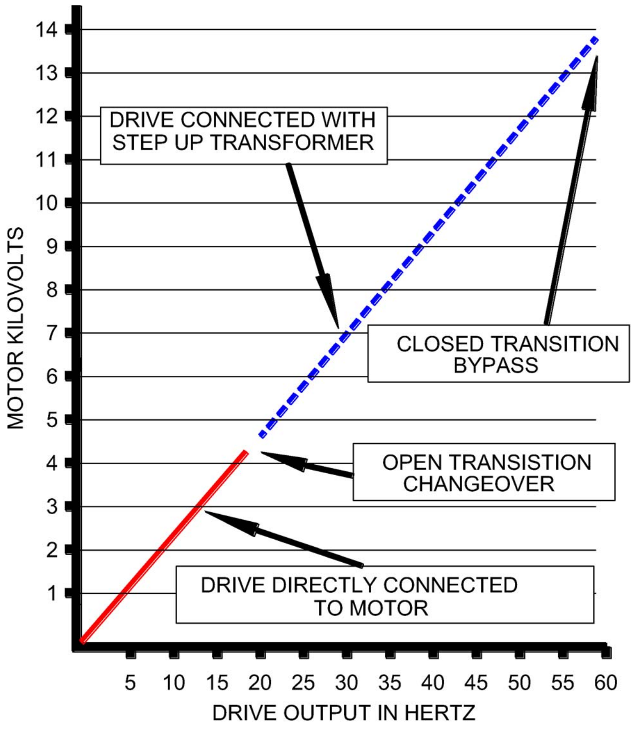

Fig. 1. Two-stage acceleration.

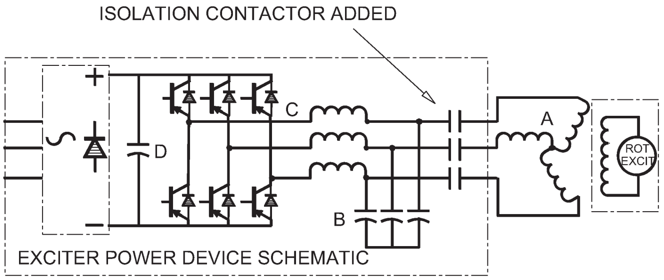

Fig. 2. Exciter controller to motor interface.

E. Final Observations and Performance of the Package

The VFD method of starting limits motor starting current inrush to much less than 100%; in fact, during the 4-min starting sequence, the motor starting current typically never exceeded 40% over the full speed range since the compressors were started either fully unloaded (for the largest 17.5-khp nitrogen compressor) or only partially loaded for the rest. Hydrocarbon compressors were in recycle and not blown down for starting. This compares with about 300%–375% inrush using a reduced voltage soft start.

Please refer to Fig. 1 Two Stage Acceleration and Fig. 3 Starting VFD System Schematic for an explanation of the motor start-up sequence described hereinafter. This sequence can be monitored on the BSL PLC human–machine interface (HMI).

1) Assuming that motor M1 must be started, the operator in the field pushes the start button on the selected

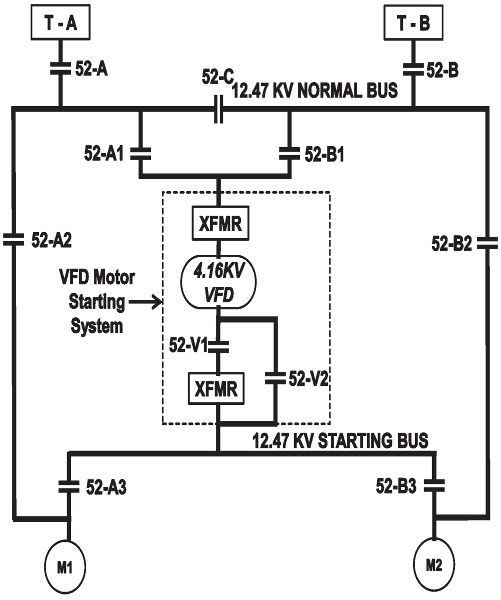

Fig. 3. Starting VFD system: Example for two motors.

compressor control panel which only operates if multiple permissions, including "VFD Ready," are received from BSL PLC.

2) BSL PLC closes the VFD feeder breaker 52-A1 and integral VFD input transformer soft start breaker to energize VFD cells and start VFD cooling fans.
3) BSL PLC closes the motor starting breaker 52-A3 and output transformer bypass breaker 52-V2 and ensures that the normal bus breaker 52-A2 and output transformer breaker 52-V1 are open.
4) The VFD controller takes control and ramps the motor from 0 to 20 Hz (33% of full speed); approximately 2 min are required up to this point.
5) At 20 Hz, the BSL PLC performs open transition switching of the output transformer bypass scheme by opening 52-V2 and then closing 52-V1.
6) Motor speed coasts down to about 15 Hz, and the VFD controller "catches" the motor and ramps the motor from 15 to 60 Hz.
7) Upon reaching 60 Hz (full speed) at rated voltage, the drive microprocessor located compares the voltage, frequency, and phase angle of the utility/normal bus with that of the VFD output and makes corrections to the VFD output as necessary.
8) When the normal and VFD starting buses are synchronized and receive independent confirmation from the "25 Sync Check Relay," the VFD controller directs the BSL PLC to initiate a closed transition transfer by closing the normal bus breaker 52-A2 and then opening the starting breaker bus breaker 52-A3. A total time of 4 min is typical from the initial start command to transfer.
9) VFD remains energized for 30 min during which time steps 1) and 2) are bypassed and the VFD is immediately available to start another motor by going to the step 3) breakers for the following motor (i.e., 52-B2 and 52-B3).
10) There is only a marginal temperature rise in the VFD building during this 4-min starting sequence.

This VFD starting method completely eliminated any potential for voltage flicker. Additional benefits of this starting system were complete elimination of all motor and coupling stresses as well as motor heating concerns during starts; in fact, the Max Starts/Hour feature in the motor protection relays for the four VFD started motors was turned off. Compressors were started multiple times per hour during the commissioning and start-up period with no rotor heating concerns.

These advantages provided by VFD starting over other starting methods reduced the commissioning time on the compressors; no starting delays were required for cooling time for the motors during the multiple shutdowns and restarts that occurred during the testing of the compressor controls and surge protection. There was never any wait time between starts required for the motor to cool down.

A single/common starting VFD was the most cost-effective solution versus dedicated starting VFDs. The cost for four dedicated VFDs, one per compressor, far outweighed the additional investment required in switchgear and controls. The VFD was sized to about 60% (10 000 hp) of the largest motor, knowing that, if it could start the largest 17.5-khp motor, all of the other compressors would definitely start. In fact, the selection of sizing was overconservative on the VFD as the compressor models showed that only 25% (4400 hp) of the largest motor horsepower was needed to start any compressor fully unloaded. The larger 10-khp VFD was selected in order to start some of the smaller methane gas compressors partially loaded to minimize any venting. The largest compressor was for nitrogen for which venting is not a concern (air is 78% nitrogen).

IV. CONCLUSION

Starting large motors has always been a challenge for multiple reasons. There are more constraints for the design engineer than ever before: emissions requiring loaded starts, limited utility capacity, and voltage flicker requirements. VFD technology is improving and is a viable alternative for the industrial user to mitigate the constraints without the reduction of motor life while allowing multiple restarts. This design of one single VFD with limited redundancy for starting multiple motors balances capital investment with system performance. It allows a motor to start with the most available torque with the least impact to the electrical system.

This innovative design installed in deep East Texas combines the use of the following:

1) starting duty drive with a rating below the motor voltage and current rating;
2) multiple differently sized motors with different protection settings and multiplexed breaker controls;
3) synchronous motor with associated individual excitation controllers;
4) online uncoupled test mode for confirming VFD availability.

As a result, this starting system has been performing as designed ,consistently starting up each motor without any failed starts or need for electrician assistance.

ACKNOWLEDGMENT

M. Colosino, owner of Crescent Power Systems with locations based in New Orleans, LA, USA, and Houston, TX, USA, was instrumental in bringing parties together for a successful implementation. T. Morishita, T. Oka, M. Daskalos, and M. Rayner with Toshiba International Corporation were key design engineers for the variable-frequency-drive system and exciter package.

REFERENCES

[1] K. Ledoux and F. Haydock, "New technology assists the design of outdoor rated medium voltage drives," in *Proc. PCIC*, Toronto, ON, Canada, Sep. 2011, pp. 1–3, Paper T-00.

[2] B. Pelton and K. LeDoux, "Performance testing of a sine wave ASD in submersible pumping applications," in *Proc. Gulf Coast Section Elect. Submersible Pump Workshop*, Houston, TX, USA, Apr. 2002, pp. 4–11.

Kurt LeDoux (M'10) received the B.S.E.E.T. degree from DeVry Institute of Technology, Dallas, TX, USA, in 1978.

He started his career with Reliance Electric as a Service Engineer on Drive Systems. He moved to Toshiba, Houston, TX, USA, in 1982 and has held various drive-related positions in manufacturing, service and repair, engineering, and quality control. He is currently Business Director, Medium Voltage Motors and Drives at Toshiba International Corporation. He has authored many technical papers, most regarding voltage stress issues using drives with long motor cables and step-up transformers for the Society of Petroleum Engineers Electric Submersible Pump Workshop. He is currently still with Toshiba working as Product Manager for Medium Voltage Drives.

Paul W. Visser (M'86) received separate B.S. degrees in electrical engineering and in nuclear engineering from Texas A&M University, College Station, TX, USA, in 1969.

Upon graduation, he went to work with Humble Oil and Refining Company (now ExxonMobil), performing various electrical, controls, and even drilling and workover engineering assignments onshore and offshore in the U.S. and on loan to Saudi Aramco. He retired from ExxonMobil and is now an independent Consulting Engineer.

Mr. Visser is a Registered Professional Engineer in the State of Texas.

J. Dwight Hulin (M'79) received the B.S.E.E. degree from Texas A&I University, Kingsville, TX, USA, in 1982.

He joined Exxon Pipeline Company immediately after graduation as a Design Engineer in the computer and communications group and then in the electrical group designing power and automated controls for pipeline facilities. In 1994, he transferred to Exxon Production, Houston, TX, USA, which subsequently became ExxonMobil Production, where he has continued serving as the Electrical Technical Lead for U.S. Operations. He coauthored and presented a technical paper on distance protection schemes at the 2007 IEEE Industry Applications Society Conference.

Mr. Hulin is a Registered Professional Engineer in the great state of Texas.

Hien Nguyen (M'13) received the B.S.E.E. degree from Kansas State University, Manhattan, KS, USA, in 1982 and the M.S. degree in electrical engineering from Prairie View A&M, Prairie View, TX, USA.

He held positions at Western Electric and General Electric before starting at Toshiba, Houston, TX, USA, in 1988, where he currently works as a Design Engineer and PLC Programmer.

Mr. Nguyen is a Registered Professional Engineer in the State of Texas.