Ensuring Availability of a Large Adjustable-Speed Drive for Process Gas Compressor Application Rated 11 kV 15.5 MW (20 778 hp)

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***Abstract*—Voltage-source inverter (VSI) technology, suitable for synchronous-motor applications, now exists with high power ratings producing high output voltage ($\geq$ 11 kV) with significant benefits over the widely used load-commutated-inverter drives. This paper covers an existing VSI technology applied for the first time at a higher operating voltage. This 15.5-MW 11-kV VSI adjustable-speed drive (ASD) installation is used to soft start three synchronous motors and speed control one of these for a process gas compressor application. Challenges faced during commissioning are described, and associated solutions are presented. A failure analysis of the ASD during commissioning is presented. An ASD design review was undertaken, which has resulted in an improved alternative to the conventional high-voltage busbar design. A protection-coordination study incorporating incoming switchgear and internal drive protection functions is presented. Improved protection schemes and settings are described to obtain faster coordinated fault clearance and improved ASD availability. This paper provides operating experience since the modified ASD has been placed in service in January 2006. Key recommendations are made to enhance the reliability, availability, and performance of medium-voltage drive systems. Also, suggestions are made for additions to the 2006 IEEE 1566 medium-voltage ASD standard.**

***Index Terms*—Availability, failure analysis, high-power-rating adjustable-speed drive (ASD), medium voltage, protection, reliability, voltage-source inverter (VSI).**

I. Introduction

IT IS CRITICAL to ensure that process availability is not compromised when implementing first-of-its-kind medium-voltage adjustable-speed drives (ASDs). Process interruption caused by poor ASD performance could potentially negate their benefits and justification. In 2003, during the conceptual design phase, a project considered several ASD technologies to be applied for soft starting three synchronous motors, each rated 11 kV and 17 MW, and to control the speed of only one of them. The ASD had to be capable of soft starting synchronous motors, synchronization, and bumpless transfer to the utility supply. The ASD design had to be compatible with a standard synchronous motor utilizing an ac exciter. In addition, the ASD had to produce almost sinusoidal output currents. A review was conducted of ASD technologies, including the load-commutated inverter (LCI) that was technically and economically viable for 11-kV 17-MW synchronous motors. The choice of LCI topology was not favored for this application because of the use of input and output three-winding isolation transformer to match the motor voltage as well as the overall system capital cost. Instead, voltage-source inverter (VSI) technology was selected, although no drive at this combined voltage and power rating for synchronous motor has ever been built. The purchased ASD is rated 11 kV 15.5 MW that is suitable to be directly connected to the synchronous motor without the use of output transformer. Due to the critical nature of this application, a spare input isolating transformer and a spare synchronous motor were also purchased.

In late 2004, the new 11-kV 15.5-MW VSI drive underwent complete factory acceptance tests including heat run for the drive and input isolating transformer as well as functional testing. In October 2005, the commissioning work commenced for the ASD train. It was during the early stages of ASD testing that it suffered a failure, causing damage to the drive and power cells. This paper covers the investigation that was undertaken to determine the root cause of ASD failure as well as the measures that were implemented to avoid recurrence. This paper makes recommendations to improve the reliability and availability of high-power and high-voltage (HV) VSI drives.

II. Technology Description and Selection

Each of the three motors is rated 11 kV 17 MW for standardization. This allows the use of a common spare for all the motors. The synchronous motors were oversized for this application, and it was decided to size the ASD at 15.5 MW to match the process load requirement. LCI technology is widely used for large adjustable-speed synchronous-motor applications (e.g., 17 MW) in the petrochemical industry [1]–[3]. Medium-voltage ASD technologies are overviewed in [4]. These include VSI and current-source inverter (CSI) pulsewidth modulation technologies that are readily suitable for standard motors. There has been a strong demand to build inverters at higher voltage

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levels (11–16 kV) [5]. This has significant practical benefits for very large applications due to lower rated current, easier system construction, and reduced cost of system components—e.g., interconnection cabling. Most commercially available related CSI- and VSI-based drives have, until 2004, only been available for application voltages up to 7.2 kV [4]. One topology that can form the basis for larger power and voltage rating is the VSI cascaded H-bridge with advantages described in [4]–[8]. This VSI technology, which has mostly been applied with induction motors, has become a viable alternative to traditional LCI synchronous-motor-based systems [9]. Synchronous motors are, however, more suitable for larger applications above approximately 15.5 MW [9]. In 2004, insulated-gate bipolar transistors (IGBTs) with higher voltage rating were first used with this VSI topology to obtain an increased output voltage of up to 13.8 kV while minimizing the overall component counts. The power density is also significantly improved. This next generation of topology facilitates higher power ratings suitable for higher power synchronous-motor applications.

Film capacitors, instead of electrolytic capacitors, have been introduced in the dc link of the higher voltage IGBT-based inverters with an expected associated improvement in drive reliability. Based on a review of the various ASD technologies available in 2004 for high-power HV synchronous motors, it was decided to select this VSI multilevel technology for this application. The selected topology is shown in Fig. 1 that consists of 15 power cells, each rated 1375 V 800 A, configured to produce 30-pulse ASD system rated at 11 kV 15.5 MW.

Five cells that are connected in series per phase were selected to provide 11.9-kV line-to-line voltage. The ASD system is specified with a cell bypass feature [10] so that, upon loss of one power cell, the ASD is still capable to soft start the synchronous motor and transfer to utility frequency.

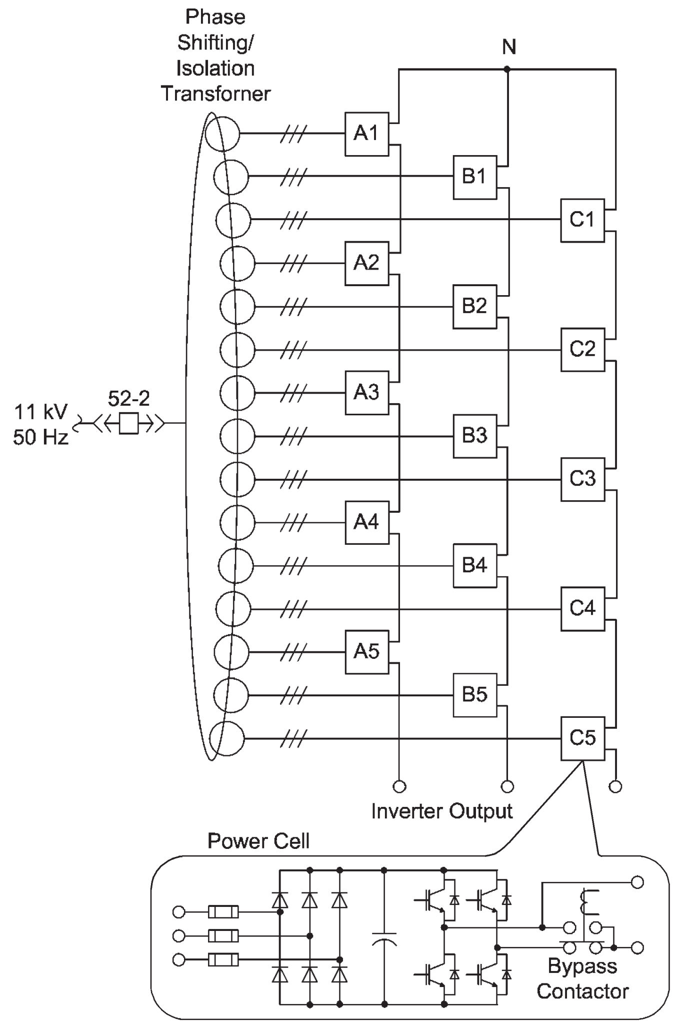

Fig. 1. Simplified multilevel converter topology to obtain project requirement of 11 kV (phase-to-phase) output voltage.

III. Installation Overview and Challenges

The system installation was completed in September 2005 (see Fig. 2). The ASD system consists of the following main components:

1) an 11-kV feeder breaker; 52-2;
2) a water-cooled isolation transformer rated 22 MVA 11-kV input;
3) fifteen power-cell drives resulting in 30-pulse configuration; each cell consists of six-pulse rectifier using diodes, dc capacitors, and inverter using IGBTs;
4) bypass transfer scheme to soft start the individual synchronous motor and then transfer it to a 50-Hz supply;
5) an output reactor;
6) excitation scheme.

In October 2005, the entire ASD system was energized to conduct functional testing and to check the water-cooling system. Start-up plans were in progress to bump start one of the synchronous motors but due to excitation problems, this was not possible, and the ASD was left energized in an idle mode, namely, the input transformer was energized without the power cells gating. The ASD was in this mode for several hours when it suffered a failure, causing the 11-kV feeder breaker (52-2) to trip.

Fig. 2. (Left) ASD. (Right) Excitation and control panels.

Fig. 3 shows the recorded fault current measured on the 11-kV primary side during the ASD failure that caused the feeder breaker to trip.

The ASD was taken out of service and thoroughly inspected. The visual inspection revealed considerable damage to the power cell A2 rectifier and capacitors and signs of arcing on most cell input busbars.

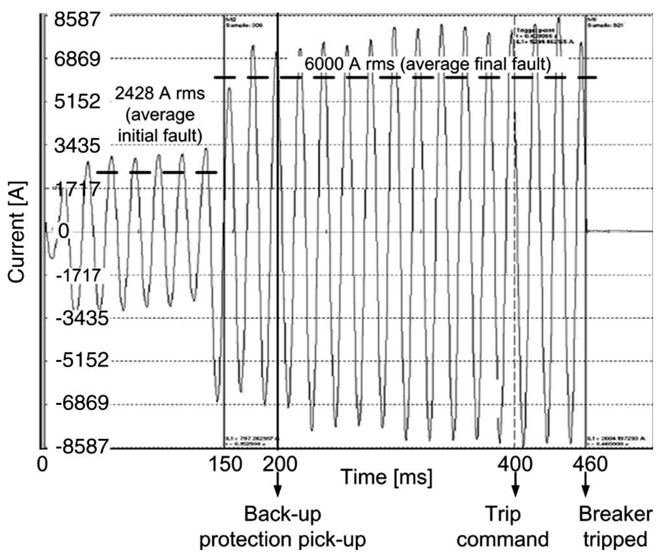

Fig. 3. ASD Feeder (52-2) fault recording at 11-kV side.

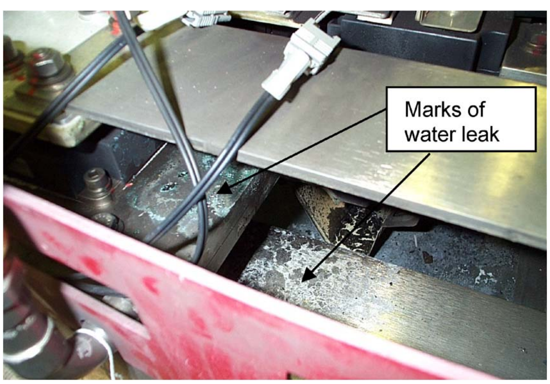

Fig. 4. Power cell A2 showing water marks.

Maximum transformer secondary short-circuit current is calculated at 6438 A rms at 1375 V, based on the lowest winding impedance at 1.47 MVA. This short-circuit current with reference to 11 kV is equal to 805 A rms. An initial analysis of the captured current waveform indicated that the fault first occurred in one power cell (i.e., cell A2), which is represented by the first half-cycle shown in Fig. 3. The fault then progressed due to arcing to two other power cells via the common busbars, resulting in an average initial fault current of 2428 A, as shown in Fig. 3. Further arcing to additional cells resulted in escalation to an average final fault current of 6000 A, as shown in Fig. 3.

IV. ASD Failure Analysis

This incident called for a full investigation to determine the root cause of ASD failure, to review the ASD internal protection which did not operate properly, and the ASD's incapability to isolate the faulted power cell.

The initial findings were that the ASD has suffered severe damage to power cell A2 and associated busbar (see Fig. 4). The incoming 11-kV feeder breaker (52-2) tripped and isolated the ASD. It was decided to ship all 15 power cells to the original manufacturer for detailed inspection and testing.

The faulty power cell A2 was dismantled by the manufacturer and fully examined. It revealed signs of cooling-water leak that possibly existed for some time and eventually compromised the dc-link insulation, causing flashover. It was not possible to determine how long this leak had persisted because the location is not easily visible as it is covered by power-cell components. In fact, when the faulty cell was subjected to standard water-pressure test at the factory, no sign of water leak was noticed. However, when the test was repeated at 150% standard test pressure and the cell was left under this pressure for several hours, a minute leak from one location in the cold plate was observed. Based on these results, it was decided to subject the cold plate for faulty cell A2 to further testing at a specialized material-testing laboratory. The follow-up laboratory testing verified that there was a leak in the cold plate. It also showed a very small crack. The cold-plate manufacturer was consulted, and it became apparent that a new cold-plate design had been used for this ASD that is more compact and effective for thermal conduction. For comparison purposes, a healthy cold plate was subjected to a similar high-pressure water test, and no water leak was detected.

It was impractical to change the cold plates for the 15 power cells or even institute a method to detect such a minute water leak with the ASD in service. Instead, it was decided to implement the following measures to contain any future power-cell-failure damage.

1) Full testing of the remaining 14 power cells and the two spare cells at the factory under water pressure and establishing no cooling-water leak.
2) Replacing the uninsulated busbar work of the ASD with cable bus. Also, installing additional barriers and spacing to avoid arcing between cells and the bus. The damage to this ASD could have been minimized had it not arced to the common bus work. Although a power-cell failure is a rare occurrence, the ASD should be designed to limit damage to a faulted cell.
3) Conducting comprehensive review of the ASD internal protection to ensure very coordinated fast tripping in the event of a cell failure. A review of the field-protection data (Fig. 3) showed that the 11-kV feeder breaker (52-2) tripped on a backup protection within 460 ms due to power-cell failure rather than initiated by a trip signal from the ASD. This ASD design has two internal-protection schemes that are intended to adequately detect a power-cell or a secondary-winding transformer failure and initiate a main-breaker trip in a shorter time than 460 ms to limit potential fault damage. The ASD protection scheme is fully discussed in the next section.

It should be noted that, since January 2006, when the ASD was placed in operation, no further cold-plate cooling-water leaks has been experienced.

V. ASD Protection Coordination and Settings

Fig. 5 shows a simplified single-line diagram with the main protective devices. Fig. 6 shows the associated protection-coordination curves based on the ASD internal protection, feeder-protection settings, and cell-fuse selection.

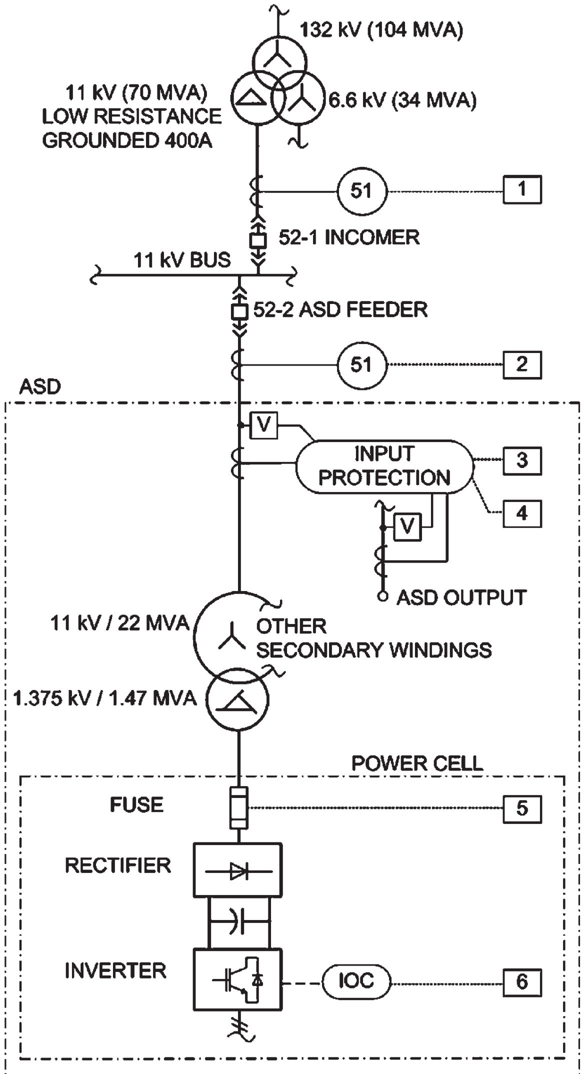

Fig. 5. Protection-coordination single-line diagram.

A. ASD Overcurrent Protection

Due to the multiple transformer secondary windings, conventional protection schemes are not adequate to protect against transformer-winding and cabling faults. Conventional differential protection is impractical due to the amount of current transformers required. The fault current on transformer secondary windings (high impedance and small megavoltampere rating compared with the primary) is low, and conventional protection schemes will be sluggish to clear a secondary fault. The ASD manufacturer has developed a novel input-protection scheme to detect secondary fault current. The input-protection scheme consists of a reactive-power function and a differential real-power function suitable for the detection of short-circuit and arcing faults, respectively.

Reactive-power protection continuously measures the drive input reactive power with respect to the transformer primary side to determine whether a fault has occurred on the secondary side of the transformer. For example, a short circuit in one of the secondary windings will result in poor power factor on the HV side of the transformer. This technique is far more effective than conventional apparent-current-based schemes since the ASD normally operates close to unity power factor.

Differential real-power protection measures the differential real power between the ASD input and output and is therefore suitable to effectively detect high-impedance/arcing faults (associated with additional losses).

The overall sensing and tripping time depends on the fault severity, factory default settings, and any additional time-delay settings.

The input protection was however set to alarm mode during the initial idle mode of operation (at the time of the ASD failure in October 2005).

These input-protection functions are plotted in terms of current (referred to 11 kV) in Fig. 6 for analysis associated with the incident. The reactive-power-protection curve shows that the ASD input protection would have taken 300 ms to send a trip signal had the input protection been activated. On this basis, the overall trip time would have been 360 ms, which includes 60 ms for the breaker and associated control. This is less than the 460 ms that it actually took the backup breaker to operate during the incident in October 2005. The ASD damage could have been reduced had the breaker operated in 360 ms instead of 460 ms.

B. Protection Coordination

It is often overlooked but is critical to ensure availability of the ASD and to minimize process upsets. A summary of main points of the coordination curves of Fig. 6 is as follows.

1) The new power cables installed between the transformer secondary windings and the cells are adequately protected by the ASD internal protection.
2) Adequate margins are shown between the ASD input protection (curves 3 and 4), feeder backup protection (curve 2, 52-2), and the main switchgear incomer (curve 1, 52-1).
3) The feeder backup protection is set to ensure operation before the transformer thermal damage curve limits are reached. This backup protection adequately functioned to protect the transformer during the event that took place during commissioning in October 2005.
4) A short-circuit fault (e.g., "maximum fault level transformer secondary," as shown in Fig. 6) in a power cell is sensed by both the input-protection reactive-power scheme (curve 3) and the cell-fuse protection (curve 5). Proper coordination between them is vital. When a power-cell fuse operates, the intent is that a faulty power cell is automatically bypassed without causing process interruption. In the event that the reactive-power scheme is activated before the cell fuse, it would initiate an ASD trip. Likewise, the input-protection differential real-power (curve 4) scheme must coordinate with the fuse curve to avoid an unwarranted ASD trip. Fig. 6 shows miscoordination (as found) in certain zones between the input protection and the fuse protection. In addition, it can be seen that the ASD input protection may create nuisance tripping when energizing the ASD transformer due to inrush current. The inrush problem was addressed by

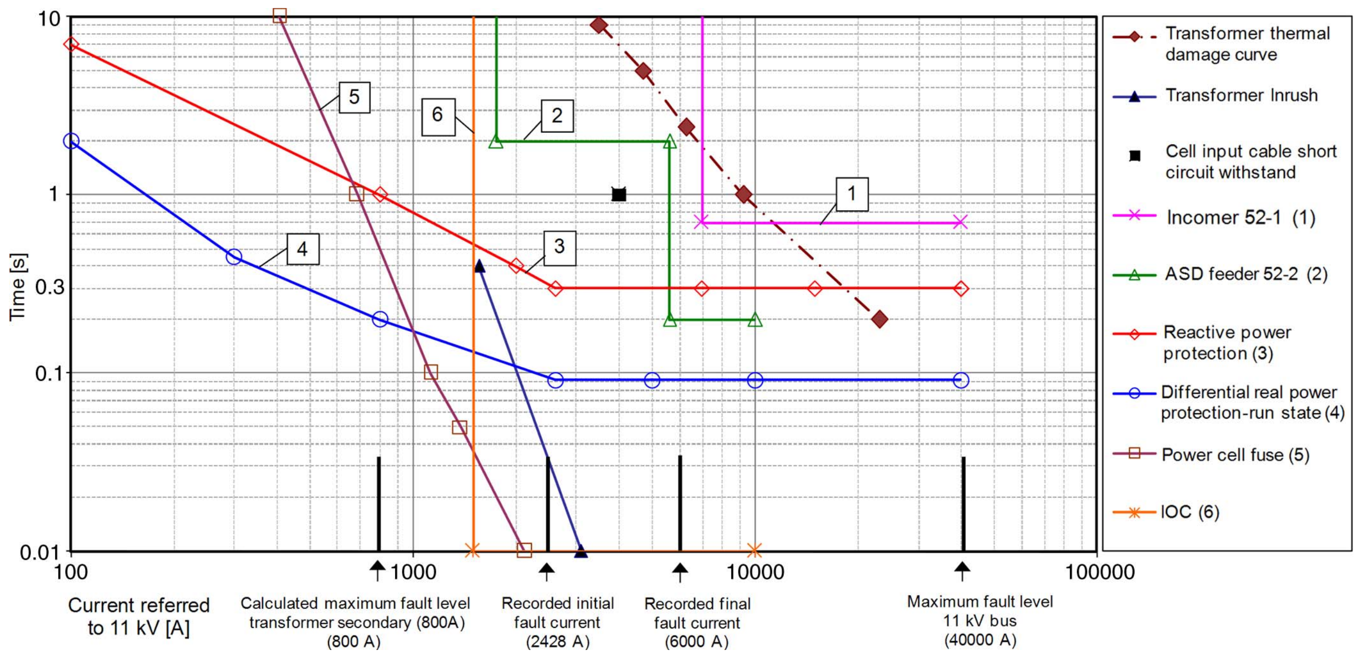

Fig. 6. Protection coordination curves for ASD—all currents shown are referred to 11 kV.

disabling the input protection for 0.5 s when energizing the ASD transformer.

C. Ground-Fault Protection

The 11-kV supply system is a low-resistance grounding system having a neutral grounding compensator and resistor to limit the ground-fault current to 400 A. The stator-winding insulation of the synchronous motors has been designed for this grounding system with conventional trip schemes when directly operated on the 50-Hz bus supply. The ASD transformer delta-based secondary windings and the ASD output are both ungrounded. A ground fault on the ASD output is normally detected by a voltage displacement and is only alarmed. For this ASD application, a trip command was selected because the motor phase-to-ground insulation is not rated for continuous operation at line-to-line voltages which will be experienced during a ground fault.

Due to the critical nature of this application, the motor insulation system should have been designed to continuously withstand line-to-line voltage until the ground fault is addressed.

The low-voltage 525-V motor control center (MCC) supply to the ASD is of high-resistance grounding (HRG) system at 5 A. The ASD distributes the power to auxiliary loads, including the motors for the cooling-water pumps and air-cooled heat exchanger fans.

The HRG system is normally selected to limit damage associated with ground faults as well as to maintain process continuity. For this specific application, it was decided to trip on an HRG fault because of the redundancy in the system (normal and emergency 525-V supply feeders). However, for this application, low-voltage ground faults in the ASD has resulted in the 525-V feeder circuit to trip, initiating transfer to the emergency power which also tripped on ground fault resulting in an ASD trip. A review of the ground protection showed that the ASD low-voltage supply scheme is incompatible with the HRG system (no dedicated HRG fault detection on individual internal ASD auxiliary feeders). To address this problem, isolation transformers (delta–star, with the star winding solidly grounded) in the normal and emergency feeders were installed to ensure that internal ASD feeders to auxiliary circuits clear ground faults effectively (i.e., avoiding the 525-V normal feeder, emergency feeder, and ASD trip).

This is similar to a retrofit application for an uninterruptible power supply system that was not designed for HRG, as discussed in detail in [11]. For future ASD applications, it is recommended that the internal ASD low-voltage circuits be designed to be compatible with HRG system for increased reliability and to avoid adding an isolating transformer.

VI. Success of Modification and Operating Experience

Since January 2006 when the ASD system was fully placed in service, the overall performance has been very good, in spite of some problems. The gathered field data and measurements show that the ASD input and output waveform are near sinusoidal with very high input power factor [12], [13].

The drive is designed so that upon loss of one power cell, the ASD will successfully bypass the faulty cell without causing it to shutdown. If the ASD suffers a second power-cell failure, the ASD, under this condition, would not be capable of producing the required output voltage to achieve motor synchronization. Therefore, the operating procedure for this ASD is such that following the loss of the first power cell, the operator immediately initiates a motor transfer to 50-Hz bypass mode and shutdown the ASD to replace the faulty power cell.

The ASD has experienced two failures since it has been placed in service.

In the first instance, the ASD suffered a cell malfunction (IGBT fault). The ASD performed as designed, and the cell was successfully bypassed. The cell-bypass condition was alarmed. The operator then manually issued a command for the ASD to accelerate the motor, synchronize it with the supply bus frequency, and to transfer it to the 50-Hz supply. The ASD was then deenergized (52-2 opened), and the faulty power cell was replaced with a spare. The ASD was reenergized and placed in service. The ASD resynchronized its output with the running synchronous motor and retransferred it to ASD mode. This event did not cause any process interruption.

In the second event, a cell was damaged, but the fault/arcing was contained within the cell owing to the ASD design-modification improvement introduced in October 2005. However, the differential real-power protection did trip the drive since the power-cell fuse was not coordinated with the input protection, as explained in the previous section. The subsequent investigation revealed that all remaining 14 power cells were intact.

VII. Conclusion

This paper has described the challenges faced during commissioning of the first-of-its-kind 11-kV ASD using VSI topology for synchronous motors. This ASD system offers considerable advantages over the widely used LCI drive, including almost sinusoidal input/output waveforms and direct connection to the 11-kV synchronous motor without an output transformer.

The new ASD system suffered a failure during commissioning in October 2005. The investigation revealed that the problem was caused by a minute cooling-water leak that caused a power-cell failure and escalated to bus fault and ASD shutdown. Several improvements were implemented to the ASD design to avoid recurrence. The bare bus connection between the 15 power cells was replaced with cables, and additional barriers were added to avoid arcing between cells or between a power cell and the associated busbar. A propagating arcing fault is therefore unlikely. No other water-leak incident has taken place since the ASD was placed in service in January 2006.

The ASD input-protection scheme underwent a thorough review to ensure proper coordination between various devices and increase drive availability. It should be noted that information related to ASD internal-protection coordination is typically not readily available unless specifically asked for from the manufacturer. The findings of the project resulted in increased collaboration between the end user and the ASD manufacturer in enhancing the ASD protection.

Following the improvements that were introduced in late 2005, the ASD has suffered two failures that were associated with power cells. In the first case, the ASD functioned as designed and bypassed the faulty cell, and the ASD remained in service with no process interruption. In the second case, a cell failure occurred causing the ASD to trip but the damage was contained within the cell. It is believed that the design modification and protection enhancements carried out following the incident of October 2005 have considerably helped to mitigate the impact of the subsequent two events. An ASD trip in the second event could have been avoided if proper coordination between the cell fuse and ASD input protection was possible.

It is important to ensure that the plant HV and low-voltage grounding system is compatible with the ASD grounding. In this case, the plant has HRG and was incompatible with low-voltage ASD supply that resulted in tripping on ground fault. A delta/star with solidly grounded neutral was installed to address this problem.

The IEEE 2006-1566 standard [14], [15], when revised, should include a section covering ASD internal-protection coordination with upstream devices and ASD grounding-system compatibility with existing plant HV and low-voltage grounding.

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