Root-Cause Analysis of Simultaneous Faults on an Offshore FPSO Vessel

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This paper was presented at the 59th Annual Petroleum and Chemical Industry Technical Conference, New Orleans, Louisiana, September 24–26, 2012, and can be accessed at: http://dx.doi.org/10.1109/PCICON.2012.6549654.

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Abstract—The paper "Simultaneous Faults on the 11 kV System of an Offshore FPSO Vessel" by Derrick Haas, Frederick D. Painter II, and Malcolm Wilkinson provides a case study of simultaneous faults that occurred December 5, 2009, on the 11 kV power system of a floating production, storage, and offloading vessel located in the Norwegian sector of the North Sea. The event resulted in severe damage to a 12,000-horsepower compressor motor, damage to the transformer feeding an adjustable speed drive, and interruption of many loads on the ship.

This paper shares analysis of the event, including initial responses and findings of the offshore technicians, event reports from two microprocessor-based protective relays, subsequent analytical work, and forensic work performed on the failed equipment. This paper includes additional analysis and forensic work that were not available at the time the previous paper on this event was published.

Modeling of simultaneous faults, zero-sequence sources, and a fault at the neutral point of an ungrounded-wye induction machine are also discussed. The paper shares the lessons learned as a result of the event, including proposed improvements to the protection system. The importance of root-cause analysis in identifying problems before they result in significant damage is also discussed.

Index Terms—Simultaneous faults, FPSO power, induction machine, event analysis, zero-sequence source, fault current limiter (FCL).

I. INTRODUCTION

The Alvheim floating production, storage, and offloading (FPSO) vessel is stationed in the Norwegian sector of the North Sea for the purpose of producing oil and natural gas. Prior to its conversion to FPSO service, the vessel was used as a shuttle tanker and was originally designed and constructed in 1999 with dynamic positioning Level 3 (DP3) capability. This history resulted in an unusually complex network of medium-voltage 11 kV switchboards that comprise the Alvheim FPSO power system. During its conversion to FPSO service, several significant changes to the electrical system were implemented, including the following:

- Addition of two 23.76 MW gas turbine generator packages.
- Addition of several 11 kV direct-on-line electric motor drives.
- Addition of variable frequency drives (VFDs) to provide speed control for two 4.7 MW water injection pumps.
- Addition of a fast-acting short-circuit fault current limiter (FCL).
- Philosophy change to primarily operate the 11 kV system as a single power system island.

An 11 kV neutral grounding system was configured as the resistance type, with ground fault current limited to no more than 112 A with all sources connected.

The requirement of the FCL was needed because the addition of the two turbine generator packages caused available short-circuit current to exceed the ratings of the installed 11 kV equipment. Upon detection of a fault, the FCL quickly divides the power system into two independent islands, in which available short-circuit current does not exceed equipment ratings. This is accomplished through rapid single-pole tripping in the FCL and a slower interlock that opens an associated three-pole circuit breaker. FCLs of this type have an electronically triggered bursting mechanism in parallel with a low-ampere fuse. The combination of the two provides for high-speed opening in times as fast as 0.6 milliseconds [1].

Protective relays in the power system are of the digital multifunction type, but capabilities vary widely. Most protective relays are from the original 1999 ship construction and are not equipped with advanced data logging or event recording capability. However, modern highly capable protective relays were in place for the two turbine generators and the two 9.2 MW export compressor drives.

II. THE INCIDENT

On the morning of December 5, 2009, a complex incident occurred within the FPSO 11 kV power system [2]. Just prior to the incident, production operations were stable, with no switching or other unusual activities underway. The total ship load was approximately 22 MW. A simplified one-line diagram showing relevant online equipment at the time of the incident is shown in Fig. 1 (online loads unrelated to this paper are not depicted).

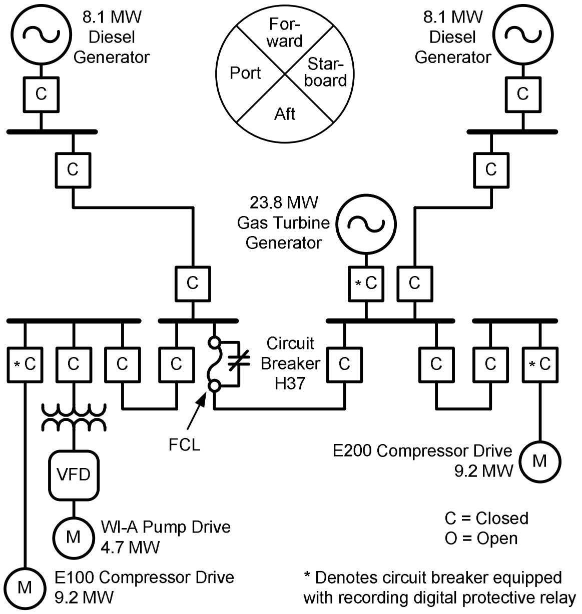

Fig. 1 Simplified Configuration Prior to Incident

As with most power system faults, the incident began and ended within a few milliseconds. When the incident concluded, 11 kV power remained in service on all 11 kV switchboards, but all production and process operations were offline. The active configuration following the incident is shown in Fig. 2.

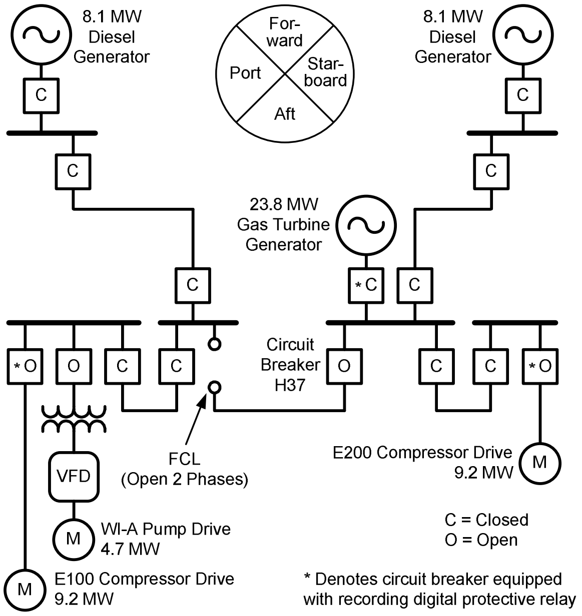

Fig. 2 Simplified Configuration Following Incident

With circuit breaker H37 open, the power system had separated into two independent islands (i.e., port and starboard island separation). Within a short time, offshore operating and maintenance staff determined that two poles in the FCL had activated (opened) and the E200 export compressor had experienced a motor ground fault trip. No other protective relays flagged any alarms whatsoever.

Initial efforts following the incident were aimed at gaining understanding of the event. Activities included further testing of the E200 motor, gathering data from the three protective relays with event capture capability, and attempting to understand why the FCL had activated on two phases. Insulation resistance testing results from the E200 motor revealed an internal failure and were as follows:

- Winding to winding: all winding combinations > 6 GΩ.
- Winding A to ground: > 4 GΩ.
- Winding B to ground: short circuit.
- Winding C to ground: > 4 GΩ.

No event data were captured by the turbine generator protective relay, but oscillography records and sequence of events data were gathered from the E100 and E200 protective relays.

III. EARLY ENGINEERING OBSERVATIONS

Early engineering observations were crucial to further understanding. First, the ground fault current recorded by the E200 protective relay was over 17,000 A, which is well in excess of the system design maximum of 112 ground fault amperes. Hence, it was quickly concluded that this was not an incident involving a single zero-sequence current source. Second, high fault current had flowed through the FCL, causing it to activate on Phases A and B. This supported a conjecture that a second zero-sequence current source had existed on the port side of the power system (i.e., on the opposite side of the FCL from the E200 motor). Event profiles from the E100 and E200 protective relays can be seen in Fig. 3 and Fig. 4, respectively. Note that the currents and voltages displayed in these figures are divided by a factor of √2.

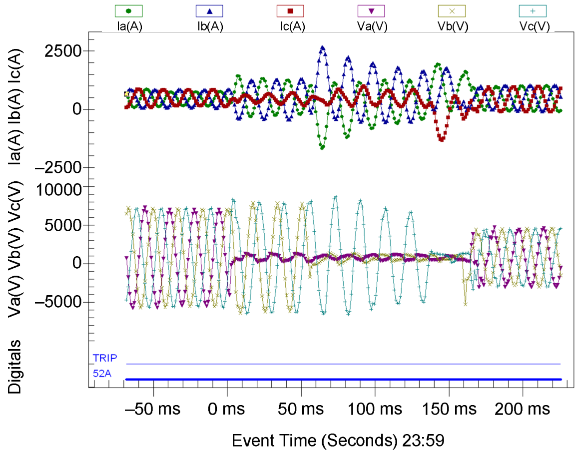

Fig. 3 Event Profile From E100 Protective Relay

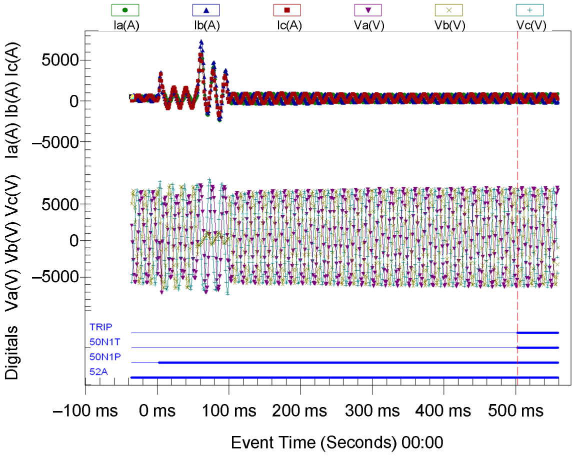

Fig. 4 Event Profile From E200 Protective Relay

Another puzzling early observation was seen in the current profile associated with the E200 event record. While the ground fault current exceeded 17,000 A for a few cycles, the measured current from the 50:1 core-balance current transformer appeared to indicate that the fault had cleared itself and the E200 motor was returning to normal operation. In fact, ground fault current as detected at the protective relay was returning to near zero, and the relay barely timed out, causing the motor trip, as shown in Fig. 5. The motor nearly rode through this event, yet it tested with a solid ground fault on one phase.

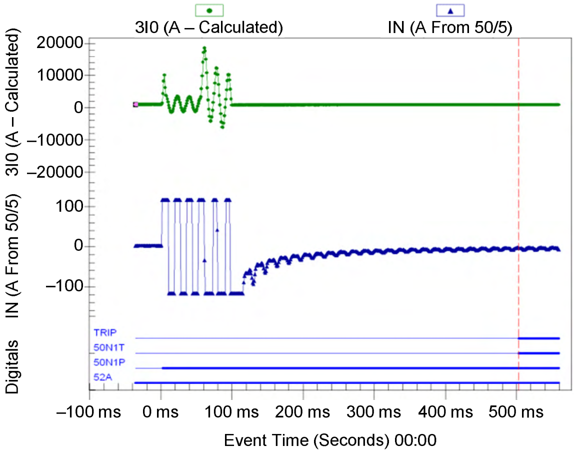

Fig. 5 Event Profile From E200 Protective Relay Showing Neutral and Ground Current

Further engineering analysis of voltage profiles produced valuable insight into event understanding. Being careful to properly synchronize the time scales from each of the independent relays, voltage profiles from the E100 relay and the E200 relays were overlaid on a phase-by-phase basis. This time-alignment process involved importing both event files into a mathematical software tool and manipulating the time stamps on the two event records so that they matched. In an ideal installation, all relays are time-synchronized by distributing a common time signal, such as IRIG-B. Having relays time-synchronized would have avoided the extensive effort of time-aligning the event reports manually. For the time scale in Fig. 6, Fig. 7, and Fig. 8, $t = 0$ was set to be the beginning of the event. Fig. 6 through Fig. 8 show the phase-by-phase voltage profiles across both sides of the FCL.

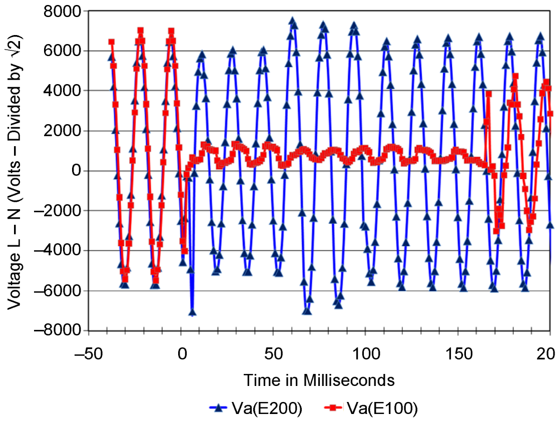

Fig. 6 Comparison of Phase A Voltages After Time Alignment

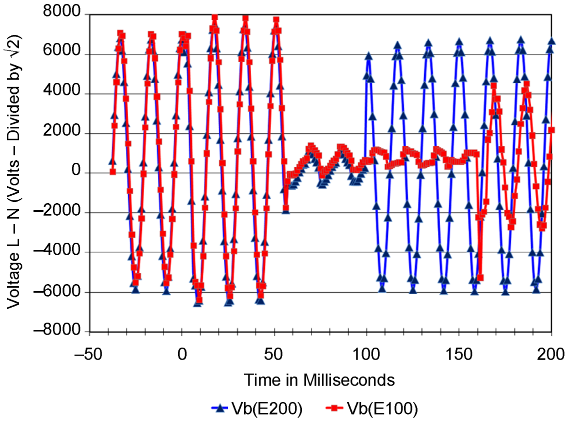

Fig. 7 Comparison of Phase B Voltages After Time Alignment

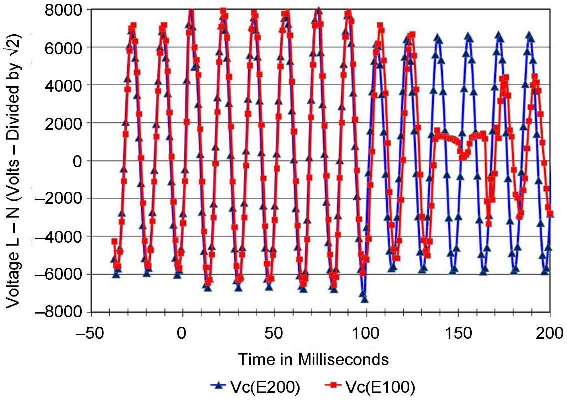

Fig. 8 Comparison of Phase C Voltages After Time Alignment

From the plots in Fig. 6, Fig. 7, and Fig. 8, the following points are clear:

- The Phase A element of the FCL cleared first at *t* = 5 milliseconds.
- After the Phase A element opened, Phase A voltage collapsed on the port side of the power system until *t* = 165 milliseconds, when voltage restoration began and the fault cleared.
- The Phase B element of the FCL cleared second at *t* = 95 milliseconds.
- Phase B voltage collapsed system-wide at *t* = 55 milliseconds. When the FCL opened Phase B at *t* = 95 milliseconds, voltage was instantly restored on the starboard power system. After the Phase B element opened, Phase B voltage collapsed on the port side of the power system until *t* = 165 milliseconds, when voltage restoration began.
- Phase C appears to have separated between the port and starboard power systems at *t* = 135 milliseconds and was the last phase to separate. Once Phase C was the only connection between the port and starboard power systems, it appears that a torque angle was developing between the two power systems. The torque angle is evident in the slight separation between the Phase C voltage on the port side and the Phase C voltage on the starboard side between 95 milliseconds and 135 milliseconds. Because FCL controls are interlocked so that FCL activation opens circuit breaker H37, it is asserted that this Phase C separation was due to the three-pole opening of breaker H37.
- After Phase C opened, Phase C voltage collapsed on the port side of the power system until *t* = 165 milliseconds, when voltage restoration began and the fault cleared.

An event recorder measuring currents and voltages at the FCL would have been extremely valuable. Much time and effort were spent during this engineering review attempting to indirectly understand the FCL current flow and behavior. However, from all known indications, the FCL functioned exactly as designed.

IV. DISCOVERY OF SECOND FAULT SITE

Approximately three days following the original incident and after partial production had been restored, electrical integrity testing efforts discovered damage at Water Injection Pump A (WI-A). Offshore electrical technicians discovered that the complex 11 kV phase-shifting dry-type transformer that serves as the input to the VFD for WI-A was damaged. Upon disassembly and physical inspection, several signs of failure and flashover were observed.

Fault sites are labeled on the post-incident simplified diagram in Fig. 9.

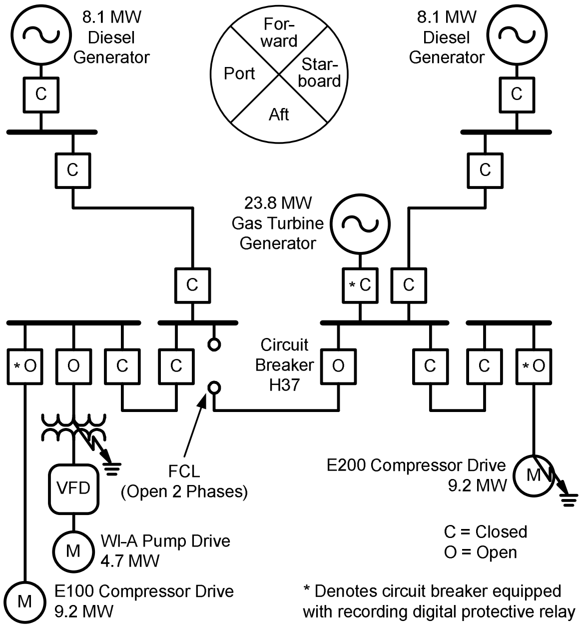

Fig. 9 Simplified Configuration Following Incident With Fault Sites Identified

Scarce, but significant, evidentiary information was gathered in the first few days following the failure. Early theories of a second ground fault site were confirmed. However, significant questions remained, which required further analytical work. Why did the incident occur? Did one fault cause the other? What could have caused two simultaneous faults? Which fault occurred first? Why did the E200 motor fault seem to clear itself such that the motor appeared to be returning to normal operation when it tripped?

V. ANALYTICAL WORK

After initial observations and data gathering and while equipment was being removed for forensic work, analysis of recorded data from the two available event records commenced. With only two event reports, the level and amount of analysis were limited; however, the following sections include some of the more interesting analytical aspects.

A. Zero-Sequence Equivalent for an Induction Motor

One interesting note from the E200 motor event is that, looking at the phase currents shown in Fig. 5, Phases A, B, and C are all nearly in phase.

This observation leads to the question, “Why would an ungrounded machine ever see nearly pure zero-sequence current?” Even if the fault were in the machine, such as a ground fault on one of the windings, we would expect the system to supply positive-, negative-, and zero-sequence currents to the faulted motor. It seems just from the current plots that the motor acted as a zero-sequence source to a fault elsewhere in the system, similar to the way a grounding transformer is a source of zero-sequence current.

We can recall that for a motor whose windings are connected in a star configuration with the neutral point ungrounded, no zero-sequence current can flow in the windings. However, if for some reason the machine became a grounded machine, then the zero-sequence equivalent circuit for the motor would be as shown in Fig. 10 [3].

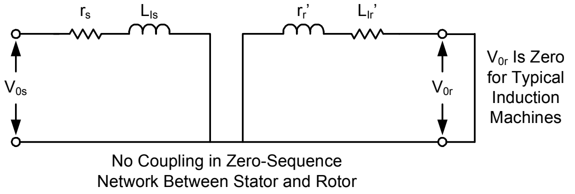

Fig. 10 Zero-Sequence Network for an Induction Machine Whose Windings Are Connected in a Grounded Star Configuration

Because the machine is intended to be an ungrounded motor, one possible explanation is that a fault occurred at or near the neutral point of the machine. To help illustrate how a grounded induction machine can supply zero-sequence current to a second fault elsewhere in the power system, consider the simplified one-line diagram shown in Fig. 11.

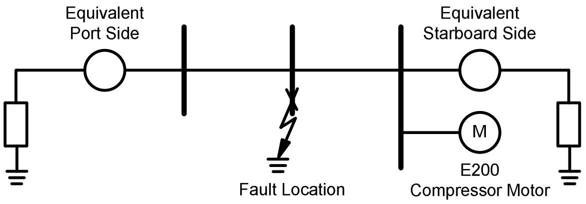

Fig. 11 Simplified One-Line Diagram With Thévenin Equivalent Circuits for Port- and Starboard-Side Power Systems

If we consider only the zero-sequence network, use Thévenin equivalent circuits for the port- and starboard-side power systems, and include the equivalent circuit for the induction machine shown in Fig. 10, we arrive at the zero-sequence network shown in Fig. 12. Because the motor impedance $Z0_{motor}$ is much less than the port or the starboard equivalent impedances (because of the grounding resistors), the motor provides a low-impedance path for the zero-sequence current to flow. Again, this path is only present when the machine is either a grounded star machine or there is a ground fault near or at the neutral point of the machine.

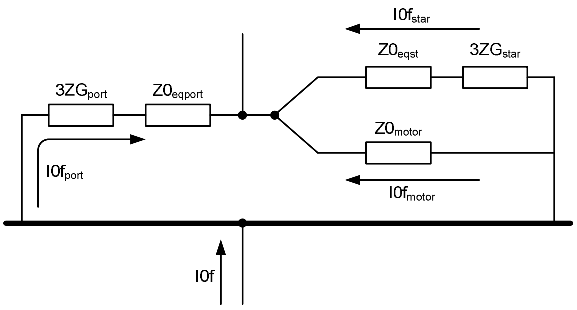

Fig. 12 Equivalent Zero-Sequence Network

B. Directional Element

If we consider the possibility that there were two ground faults in the system, with one occurring at the neutral point of the E200 motor, we could consider the operation of any directional relays in the system. The relays that did capture event data were motor protection relays where directional overcurrent protection is not typically applied.

One advantage of event report data is that the data can be replayed to other relays or the event analyzed using a mathematical software tool. If there had been a directional overcurrent relay installed at E200, would the relay have declared the fault as forward or reverse? A forward fault would indicate a fault in the motor itself, whereas a reverse fault would indicate a fault elsewhere in the system. Because several of the theories considered two faults on the system occurring at the same time, a directional decision becomes even more interesting. A reverse directional decision would support the theory that the fault in the E200 motor was near the neutral point and, hence, it was acting as a source of zero-sequence current.

To answer this question, two common methods of ground directional element polarization are considered: the negative-sequence voltage-polarized directional element and the zero-sequence voltage-polarized directional element [4] [5]. It is interesting to note that even though the currents for this particular event consisted of almost pure zero-sequence current, there was enough negative-sequence current measured at the E200 motor relay for both directional analysis tools to make a directional decision.

For the negative-sequence voltage-polarized directional element, the algorithm for the directional decision is given in (1).

$$z2 = \frac{\mathrm{Re}\{V_2 \bullet (I_2 \bullet 1\angle \mathrm{MTA})^*\}}{|I_2|^2} \quad (1)$$

where:

V_2 is the negative-sequence voltage measured by the relay in secondary volts.

I_2 is the negative-sequence current measured by the relay in secondary amperes.

MTA is the maximum torque angle (a relay setting).

The value of z2 is then compared against forward and reverse thresholds. If the calculated z2 is less than the forward threshold, the fault is declared forward, and if the calculated z2 is greater than the reverse threshold, the fault is declared a reverse fault. To determine the expected response of a directional relay, we simulate the response of a negative-sequence voltage-polarized directional relay to the event report data, with typical maximum torque angle and forward and reverse threshold settings. Fig. 13 shows a plot of z2 and the thresholds for this protection algorithm.

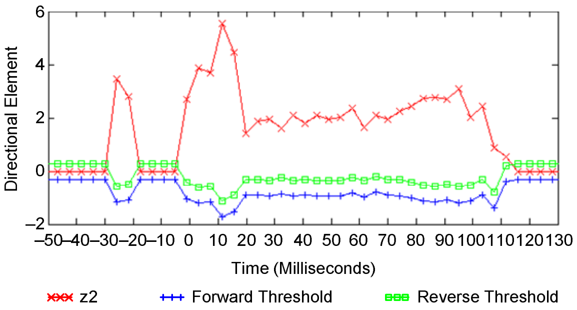

Fig. 13 Plot of z2 and Thresholds Versus Time for Simulation of Negative-Sequence Voltage-Polarized Directional Element

It is clear from Fig. 13 that the calculated z2 is above the reverse threshold, indicative of a reverse fault.

The simulation was performed again for the zero-sequence voltage-polarized directional element. For the sake of brevity, only the results are given in Fig. 14. The zero-sequence voltage-polarized directional element also determined a reverse direction.

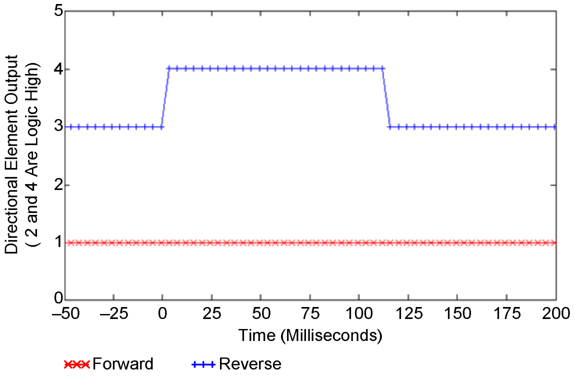

Fig. 14 Response of the Zero-Sequence Voltage-Polarized Directional Element

Having a reverse decision from both algorithms offers some support to the theory that the fault in the E200 motor occurred at the neutral point, making the second ground fault elsewhere in the system a reverse fault. This analysis highlights two important points. First, installation of multiple digital relays capable of recording events can aid in troubleshooting. Second, event reports can be replayed into relays or analyzed in mathematical tools to help analyze how different protection elements would have responded to a particular event.

VI. FAILED EQUIPMENT FORENSIC WORK

The failed E200 motor was returned to a repair facility for failure investigation and repair. Key findings from the failure investigation were as follows:

- Initial testing confirmed that Phase B was shorted to ground. Other phases were not shorted to ground.
- A clear burn mark was observed inside the stator once the rotor was removed. At the center of the burned area, a stator winding was found to be mechanically punctured, as shown in Fig. 15.
- Detailed examination of stator winding connections confirmed that the winding puncture described in Fig. 15 was electrically in the first turn nearest the star point.
- Clear mechanical abrasions were observed on the rotor opposite the burned area on the stator, as shown in Fig. 16.
- Several small hardened droplets of what was previously molten steel were found on the inside of the stator rotationally following the fault site.
- One of the steel supports for the stator core pack was missing, and there were signs of a fatigue failure at the point of separation. Dimensions of this missing component were approximately 6 mm x 30 mm x 147 mm. This missing steel support was situated just a few degrees rotationally ahead of the burn mark (see Fig. 15).
- At least one other steel support for the stator core pack was found with a developing crack at the same position where the missing support failed.

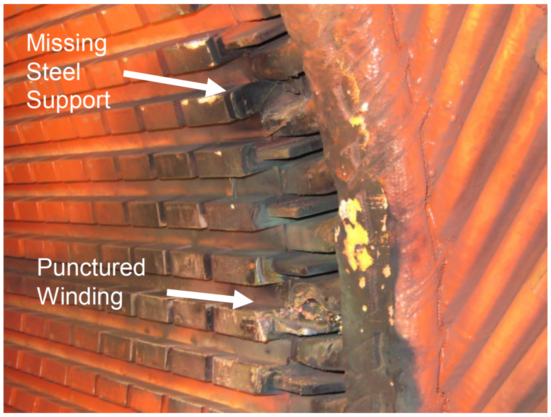

Fig. 15 Photo of E200 Stator Point of Failure

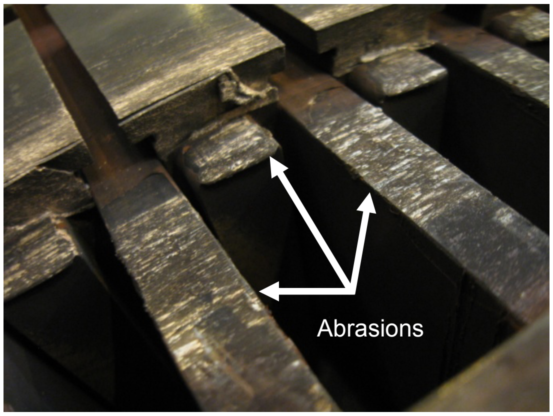

Fig. 16 Photo of E200 Rotor Opposite Stator Damage

Forensic investigation of the failed WI-A dry-type transformer revealed that a failure had not occurred within a transformer winding. Each of the three coils was fully tested and unwound, and no evidence of an internal short circuit was found. However, significant evidence of flashover was found externally between the sharp corners at the uninsulated high-voltage winding terminals and the transformer enclosure. The largest metal loss due to fault current was on the Phase A terminal. It was discovered during forensic examination that the bare copper bars being used for cable termination not only were coated with a thin transparent insulating film, but also exhibited signs of heating. This clear thin insulating film was apparently applied during past reconditioning of the transformer.

We were not able to pinpoint with certainty the cause of the fault in the transformer, but a few theories were asserted. First, it was theorized that the thin coating of insulation applied to the busbar at the point of cable connection could have developed a high-resistance connection, causing undetected open-air flashovers. With time, these local flashovers could have caused air ionization, which could create a dielectric environment that permitted a phase-to-ground flashover. Second, it is theorized that a high-frequency, high-voltage transient that was not detected by an export compressor protective relay (which gathers 16 samples per cycle) triggered the flashover. Third, it was theorized that airborne contamination (dust and moisture) or a rodent that accidentally bridged the air gap could have contributed to the initiating ground fault event. Methods to further define root cause of the transformer failure have been exhausted.

VII. BEST AVAILABLE EXPLANATION

We concluded that the most likely explanation of the event is as described in this section.

A. Prefault

Some time before the moment of the large fault event on December 5, 2009, a steel component inside the E200 electric motor became dislodged, wedged between the stator and rotor, punctured a stator winding, and shorted the winding to ground. By coincidence, the puncture occurred on the first turn nearest the star point of the Phase B winding. This failure created a low-impedance ground fault near the star point, which was undetectable by the electrical protection equipment in place. Ground fault current was approximately 0.2 A, which was well under the protection pickup setting of 2.0 A. Unknown to system operators, this failure effectively shunted the power system neutral grounding impedance, which was designed to limit ground fault current should a fault occur. The power system apparently operated with this point of low-impedance grounding at the E200 motor neutral for an unknown period of time.

B. Fault Event

It is believed that on December 5, 2009, a new ground fault developed in the WI-A transformer (at time $t = 0$ in Fig. 6 through Fig. 8), most likely in the Phase A primary winding, as indicated by the data. With two grounded points in the power system, high levels of short-circuit current instantly resulted and caused significant damage. The FCL was the first protective device to act by opening Phase A in 5 milliseconds, thereby breaking fault current flow and dividing Phase A into a starboard island and a port island. Phase A voltage on the port side of the power system subsequently collapsed, while starboard voltage remained reasonably healthy. At $t = 55$ milliseconds, a large increase in fault current is evident; this is believed to have occurred as the fault escalated to Phase B of the transformer, creating a phase-to-phase-to-ground fault. Generator excitation systems were unable to maintain voltage on Phase B with this increased fault current, and Phase B voltage collapsed. Shortly thereafter at $t = 95$ milliseconds, the FCL opened its Phase B element because of the increased Phase B flow of current. Once the Phase B pole of the FCL was opened, Phase B voltage recovered on the starboard system where the majority of power generation capacity was connected; port-side voltage on Phase B remained collapsed due to the active fault that was present. With only Phase C connecting the port and starboard systems, a torque angle began developing between the two systems (between $t = 95$ milliseconds and $t = 135$ milliseconds, as shown in Fig. 8). Next, it is believed that the interlock between the FCL and its adjacent three-pole circuit breaker, H37, caused breaker H37 to open at $t = 135$ milliseconds, which fully separated the port and starboard power systems. At this point, the port and starboard power systems are discussed separately in the following paragraphs.

In the port power system, all three-phase voltages fully collapsed as of $t = 135$ milliseconds. At $t = 165$ milliseconds, it is believed that WI-A VFD built-in protection opened its feeder breaker, isolating the faulted equipment. This allowed the lone diesel generator excitation system to begin restoration of voltage. However, voltage remained severely depressed throughout the duration of the E100 event record because load significantly exceeded generation capacity. Shortly following the event recording, most loads dropped offline because of insufficient system voltage or process control shutdowns. Overall, the port system experienced a few milliseconds of total voltage collapse and a significant loss of load, but did not experience a total blackout.

The starboard power system was particularly interesting. As soon as the FCL and breaker H37 had fully separated the failed transformer from the starboard system (as of $t = 135$ milliseconds), high levels of fault current ceased and measured ground fault current began decaying back to normal levels. This subsidence current resulted from residual magnetism in the 50:1 core-balance current transformer [6], which rapidly changed from thousands of primary amperes (fully saturated) to nearly zero primary amperes. This phenomenon can be seen in Fig. 5. In fact, protective relay-sensed ground fault current was approaching the relay 2 A pickup just when the protective relay element (50N1T) timed out and tripped the motor offline. The motor protection relay nearly did not trip on this event! If the trip had not occurred, the motor would likely have continued in operation for some further period of time, though it is believed that the motor damage from the fault event would have caused an imminent failure. Like the port-side power system, the starboard island also did not experience a blackout event.

VIII. PROTECTION PERFORMANCE

Evaluation of a protection system should always be a multistep procedure. One such procedure is outlined in [7]. The preceding sections have provided the background, information, data, and analysis to evaluate the performance of the protection system. We will focus on the individual components and then make conclusions about how the overall system operated as a whole, drawing lessons learned and identifying areas where the protection system can be improved.

We begin by looking at the protective relay for the E200 motor. It did trip on a neutral time-overcurrent element with a definite-time delay, as indicated in Fig. 4. The pickup setting for the neutral time-overcurrent element (50N1P) is 2 A primary. The measured current exceeded this value. In addition, the definite-time-delay setting (50N1D) is set to 0.5 seconds. As was pointed out previously and shown in Fig. 5, the fault current cleared well before 0.5 seconds. However, the neutral current did not go to zero immediately but exhibited a unipolar decay, or subsidence current, as described earlier. It is this decay that allowed the neutral overcurrent element to time out and trip the breaker. Had the current dropped instantly to zero when the fault was cleared by operation of the FCL, the motor relay would not have operated. The relay operated as it was set and was consistent with the published literature. Was it a correct operation of the protection system?

If we assume that the best theory of what happened is correct and there was an existing fault on or very near the neutral of the motor that went unnoticed for some time before a second ground fault occurred, the ideal operation would have been to detect that fault and alarm or trip the machine before a second ground fault occurred. A fault exactly at the neutral point of an ungrounded motor in an impedance-grounded system would draw very little, if any, measurable current during normal operating conditions. Because the digital event records contain prefault data, we can look at what the measured neutral current was prior to the fault. In Fig. 17, we see approximately 0.2 A primary of neutral current measured by the relay before the event. This could certainly be indicative of a fault at or near the neutral.

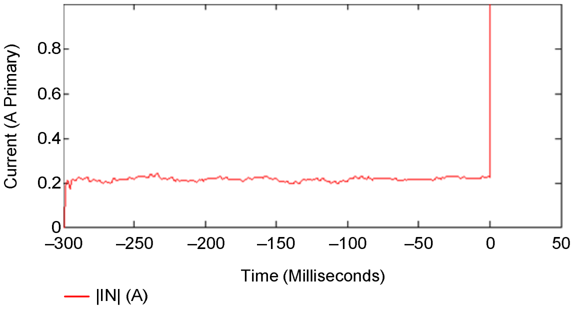

Fig. 17 Neutral Current Magnitude at E200 Motor Relay

A very sensitive time-delayed neutral overcurrent element could have been enabled to detect this. The minimum pickup setting for the neutral overcurrent element in this particular digital relay is 0.01 A primary. Protection is a balance between different principles and, in this particular case, a balance between sensitivity and security. Saturation and false residual currents are generally not a problem when using a ground fault current transformer; however, setting a neutral overcurrent element derived from a ground current transformer too low could present a security concern. It is also important to note that even the most sensitive neutral overcurrent setting will not detect a fault exactly at the neutral point.

There are other methods of detecting ground faults at the neutral of a stator winding that are often employed in the protection systems of large synchronous machines, such as third-harmonic undervoltage, third-harmonic voltage differential protection, and so on. However, these methods would involve changing the grounding connections of the machine itself and adding additional equipment. The existing settings were left as is. This particular fault was deemed to be a rare occurrence. Risking the security of the relay ahead of a critical motor to be able to detect such a rare fault was not deemed necessary.

To address concerns about the thermal overload protection, the thermal overload settings were extensively reviewed. The existing overload protection was considered adequate; however, additional elements were also enabled to limit the number of starts per hour and the number of consecutive starts. These elements, combined with the thermal element, provide more complete protection of the machine and assurance that the motor will not be overloaded.

Moving on to other components of the system, the FCL also functioned as expected. It limited the fault duty of the fault and effectively isolated the two systems. The motor protection relay at E100 did not trip, although it had an event report triggered from various protection elements picking up but not timing out. The other protective relays within the system, most of which did not operate and did not have event reporting capability, all performed as expected.

While the individual components of the protection system did their job and worked as designed, the system as a whole failed to detect the initial ground fault within the E200 motor. However, detecting this particular fault with today's technology would require setting a neutral overcurrent element with a very low pickup setting, which could compromise the security of the system, or drastically altering the design of the grounding system. Given that the likelihood of this fault occurring is extremely low, making changes to detect this type of fault is impractical.

IX. FOLLOW-UP ACTIONS

With regard to the failed E200 induction motor, the design was augmented in a way to best ensure that harmonic resonance could not excite the steel supports exhibiting cracking or breakage. Once the E200 compressor was returned to service, the twin E100 induction motor was proactively removed from service to receive the same upgrade. During teardown, a developing crack was discovered at the base of one of the steel supports. In this case, the defect was detected prior to failure and an unplanned failure was avoided. It is believed the augmented stator design will prevent further occurrence of this failure.

With regard to the failed dry-type transformer, several actions have been taken to prevent recurrence. First, busbars used as connection points were checked to ensure that no insulating coating was present. Second, sharp corners on energized bars, bolts, and nuts were rounded to restrain electrical stress points. Third, exposed busbars and connections were wrapped with a fit-for-purpose insulating tape. It is believed that these actions will prevent recurrence of the transformer failure.

X. CONCLUSIONS

While it may be theoretically possible to detect a ground fault near the star point of an ungrounded motor in an impedance-grounded power system, it is impractical to implement because the likelihood of this failure mode is very low and present technologies to detect this type of fault add extensive cost and complexity. In this case, the undetected motor fault effectively shorted out the benefits available through an impedance-grounded power system. The export compressor protection system and FCL functioned as designed and were designed consistent with applicable standards.

Event recording devices, such as protective relays, are exceptional tools for understanding power system events of only a few milliseconds in duration. Control systems for process control are too slow to capture information meaningful to event understanding.

With only two relays providing data from the Alvheim FPSO power system event on December 5, 2009, significant understanding of the complex fault was possible. With more event recording devices in strategic locations in the power system, faster and more thorough event understanding would be possible.

Having time-aligned event report data is valuable. Getting accurate time in all protective relays by distributing a time source to all devices, such as IRIG-B, avoids having to align the data manually, which can be difficult and time-consuming.

This incident underscores the value of root-cause failure analysis. Without intentional efforts to identify root-cause failure modes, the motor and transformer would have simply been repaired and returned to service, which could have led to future failures. Further, because of the failure analysis work, the equipment owner chose to proactively remove the nonfailing E100 motor from service before it exhibited any signs of trouble. Time proved this to be a wise decision because its teardown discovered similar failure mechanisms at work. Because of the root-cause failure analysis, an unplanned and perhaps costly failure was averted.

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XII. VITAE

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Malcolm Wilkinson graduated in 1979 with a Bachelor of Science Honours degree in Electrical Engineering from the University of Salford, United Kingdom (UK). For the past 4 years, Malcolm has been working with FPSO systems, initially with SBM and then with the Maersk Group/Marathon Petroleum Company, where he is now the electrical engineer responsible for the electrical generation and distribution systems onboard the Alvheim FPSO vessel. He is a Chartered Electrical Engineer registered with the UK Engineering Council and a full member of the Institution of Engineering and Technology (formerly IEE) and the Energy Institute.

Previously presented at the 59th Annual Petroleum and Chemical Industry
Technical Conference, New Orleans, LA, September 2012.

20120406 • TP6530