Simultaneous Faults on the 11 kV System of an Offshore FPSO Vessel

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Abstract**—**This paper provides a case study of simultaneous faults that occurred December 5, 2009, within 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 9.2 MW compressor drive motor, damage to the transformer feeding an adjustable speed drive, and interruption of many loads on the ship. Background regarding the power system on the vessel and the state of the system at the time of the event is provided in Section I and Section II. This paper shares an exhaustive analysis of the event, including initial responses and findings of the offshore technicians, event reports from two microprocessor-based motor protection relays, subsequent analytical work, and forensic work performed on the failed equipment.

This paper highlights the importance of event analysis, including the value of time-aligned event reports from devices throughout a power system. Modeling of simultaneous faults, zero-sequence sources, and faults at the neutral point of an ungrounded-wye induction machine are also discussed. This paper shares the lessons learned as a result of the event, including proposed improvements to the protection system.

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 were implemented, including the following:

- Addition of two 23.76 MW gas turbine generator packages.
- Addition of several 11 kV direct-on-line (DOL) 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 earthing system was configured as the resistance type, with earth 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. The FCL installed is an electronically triggered device. 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. 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).

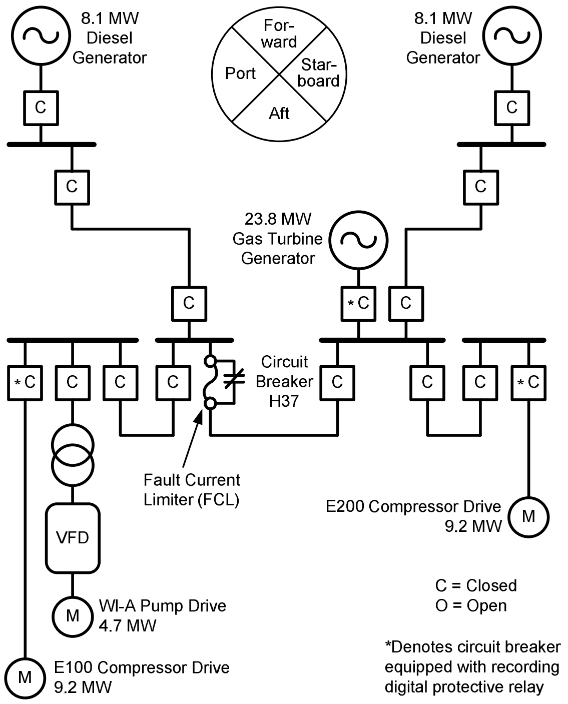

Fig. 1 Simplified Configuration Prior to Incident

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.

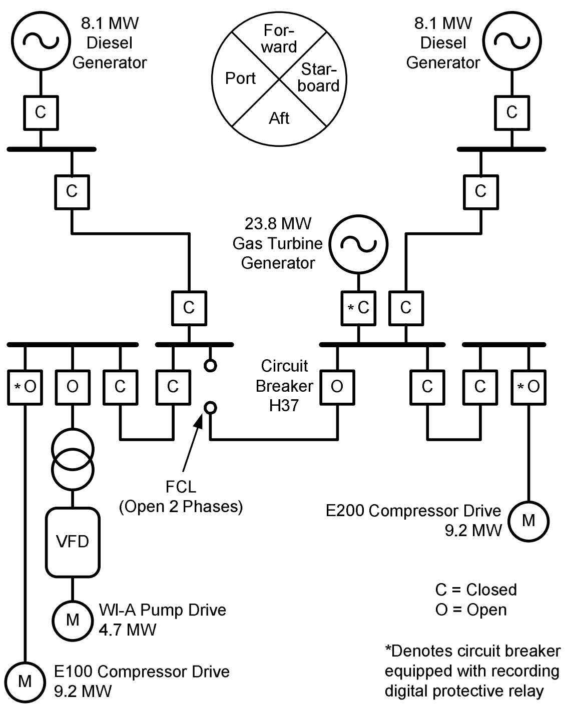

Fig. 2 Simplified Configuration Following Incident

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 earth fault trip. No other protective relays flagged any alarms whatsoever.

At this time, management efforts 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 were the following:

- Winding to winding: all winding combinations > 6 GΩ.
- Winding U to earth: > 4 GΩ.
- Winding V to earth: short circuit.
- Winding W to earth: > 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. With one spare set of elements with which to rearm the FCL, management was especially careful to ensure reasonable understanding before restoring the FCL to service. Hence, engineering support was sought almost immediately.

III. EARLY ENGINEERING OBSERVATIONS

Early engineering observations were crucial to further understanding. First, the earth 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 earth 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 U and V. 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). Offshore efforts were then focused on searching for this phantom second earth connection. In particular, the search was focused on confirming that neutral earthing systems and associated connections were properly configured and functional. One possible theory was that this second earth connection had unknowingly existed for some time and its existence was highlighted when the E200 motor fault occurred. 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.

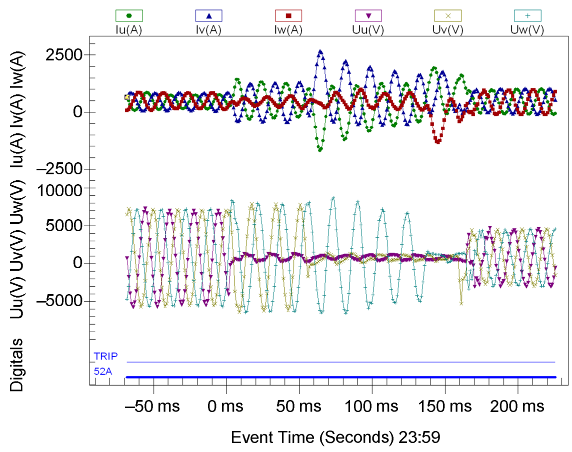

Fig. 3 Event Profile From E100 Protective Relay

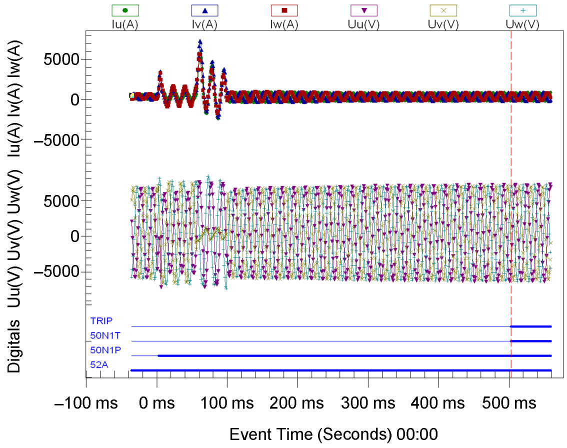

Fig. 4 Event Profile From E200 Protective Relay

Another puzzling early observation was seen in the current profile associated with the E200 event record. While the earth 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, earth 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 earth fault on one phase. This was particularly puzzling.

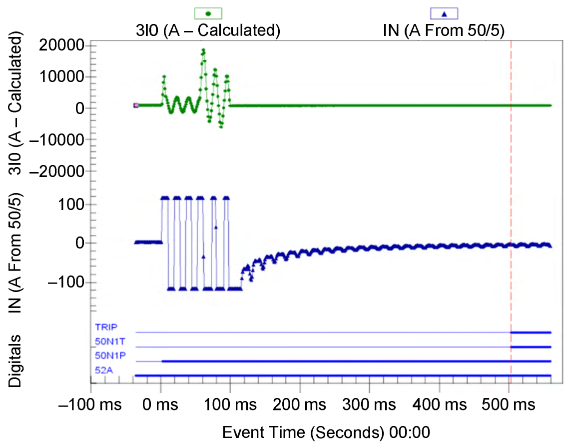

Fig. 5 Event Profile From E200 Protective Relay Showing Neutral and Ground Current

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, which corresponds to a time of 60.0 seconds in Fig. 3, Fig. 4, and Fig. 5. Fig. 6 through Fig. 8 show the phase-by-phase voltage profiles across both sides of the FCL.

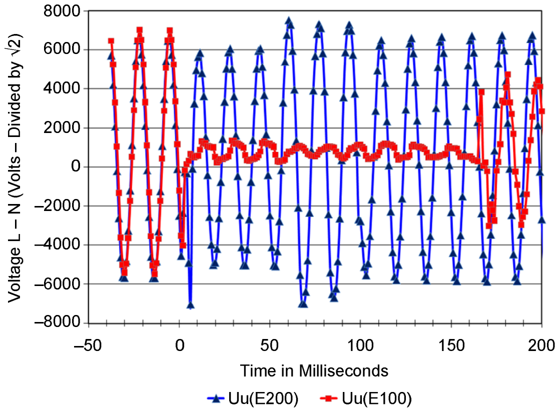

Fig. 6 Comparison of Phase U Voltages After Time Alignment

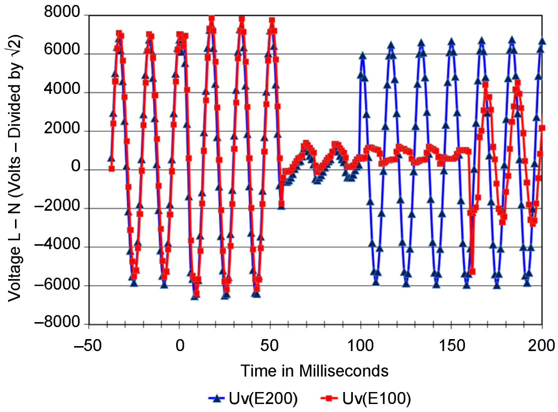

Fig. 7 Comparison of Phase V Voltages After Time Alignment

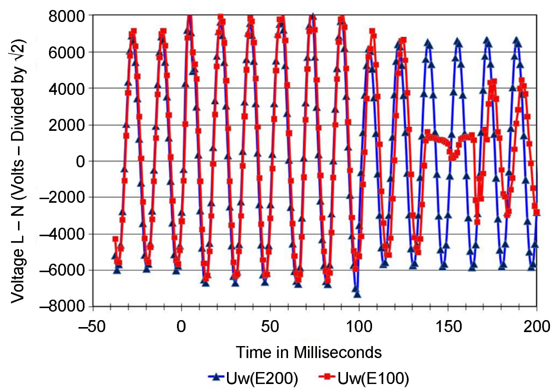

Fig. 8 Comparison of Phase W Voltages After Time Alignment

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

- The Phase U element of the FCL cleared first at *t* = 5 milliseconds.
- After the Phase U element opened, Phase U voltage collapsed on the port side of the power system until *t* = 165 milliseconds, when voltage restoration began and the fault cleared.
- The Phase V element of the FCL cleared second at *t* = 95 milliseconds.

- Phase V voltage collapsed system-wide at t = 55 milliseconds. When the FCL opened Phase V at t = 95 milliseconds, voltage was instantly restored on the starboard power system. After the Phase V element opened, Phase V voltage collapsed on the port side of the power system until t = 165 milliseconds, when voltage restoration began.
- Phase W appears to have separated between the port and starboard power systems at t = 135 milliseconds, which was the last phase to separate. Once Phase W was the only connection between the port and starboard power systems, it appears a torque angle was developing between the two power systems. Because FCL controls are interlocked such that FCL activation opens circuit breaker H37, it is asserted that this Phase W separation was due to the three-pole opening of breaker H37.
- After Phase W opened, Phase W 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. AUTHORIZATION TO RESTART

On December 6, 2009, the day after the initial incident, all neutral earthing systems were found to be healthy and a second fault site had not been located. However, with both starboard and port power systems independently energized and in service continuously since the original incident, a plan for restoring normal system configuration and safely restoring production was agreed upon. In this plan, all FCL elements were replaced to restore the unit, and the starboard and port power systems were reconnected into a single island. This was important because the reactive power requirement for DOL starting of the large motor drives necessary for production required the FCL to be in service and breaker H37 to be closed. Further, it was agreed that each 11 kV feeder circuit that was open would be adequately tested for electrical integrity prior to closing.

Approximately two days later, after partial production had been restored, the electrical integrity testing process reached the A water injection pump (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 faulted. Both Phases U and V were found shorted to earth. Upon disassembly and physical inspection, several signs of damage and flashover were observed.

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

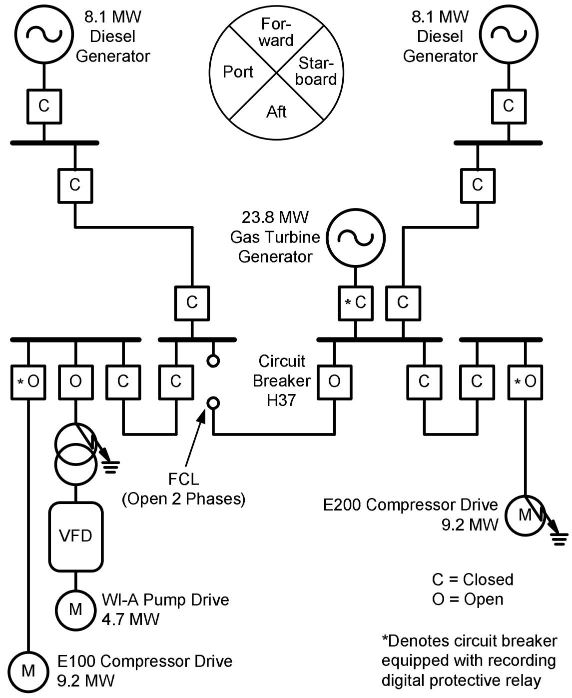

Fig. 9 Simplified Configuration Following Incident With Fault Sites Identified

At this point in the timeline, early theories about a second fault site were confirmed, but several questions remained. 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. THEORIES OF EXPLANATION

Several theories of explanation were asserted by various investigators to explain one or both failures. Some of these theories are included in the following sections.

A. Theory I: Voltage Spike

The only common connection between the two failed electrical components is the power system itself. Could a system voltage spike have caused multiple simultaneous failures across the system? While this could serve as an explanation for simultaneous failure, there was no evidence in any event record that a voltage spike occurred.

B. Theory II: Fault Escalation Due to Voltage Shift

If the motor earth fault occurred first, it would have caused phase-to-earth voltages on the unfaulted phases to approach typical phase-to-phase voltage. If the earth fault was an arcing fault, voltages may have been even greater [2]. This increased voltage could have caused a second fault site, which then caused the event to escalate into a high-current, phase-to-phase-to-earth fault. Unfortunately, the event recordings did not support this explanation because fault currents were high from the very beginning of the event. Escalation from an event of 112 A or less to an event of several thousand amperes was not observed.

C. Theory III: Motor Insulation Failure Due to High Number of DOL Starts

The E100 export compressor package was placed into service in June 2008. From December 2008 to the moment of failure in December 2009, the E200 motor was started 129 times. The sister machine, E100, had been started 217 times in the same time period (see Fig. 10 for monthly data). Some asserted that this high number of starts contributed to premature motor failure. The digital relays for both E100 and E200 had thermal overload protection enabled. Analysis of this protection is provided in Section VI. Unfortunately, this theory does not explain the simultaneous transformer failure nor the apparent recovery of the motor to normal operation, as depicted in Fig. 5.

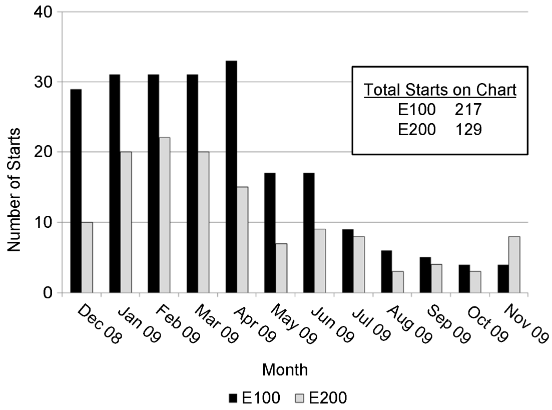

Fig. 10 Comparison of Number of Starts for E200 and E100 Motors by Month

D. Theory IV: Pre-Existing Fault Near Neutral of Motor Stator and Subsequent Fault on Transformer

This theory was based on the assertion that the motor earth fault was near the star point connection, it had existed for some time prior to the fault of December 5, 2009, and it was undetected by protection equipment. When a second earth fault occurred elsewhere in the power system at the VFD transformer, high fault currents flowed immediately in the system. Strong evidence in support of this theory is the apparent restoration of the motor to normal operation, as observed in Fig. 5, which occurred after the FCL had separated the power system and isolated the two failure sites. However, this does not explain why a motor earth fault would occur at the star point, which is the point of least voltage stress.

Analytical work and forensic investigation of failed equipment followed and is further described in subsequent sections.

VI. 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 analysis aspects.

A. Zero-Sequence Equivalent for an Induction Motor

One interesting note from the E200 motor event is that when we look at the phase currents shown in Fig. 5, Phases U, V, and W are all nearly in phase. To further illustrate this point, the U, V, and W currents from the E200 event report are plotted on a phasor diagram in Fig. 11.

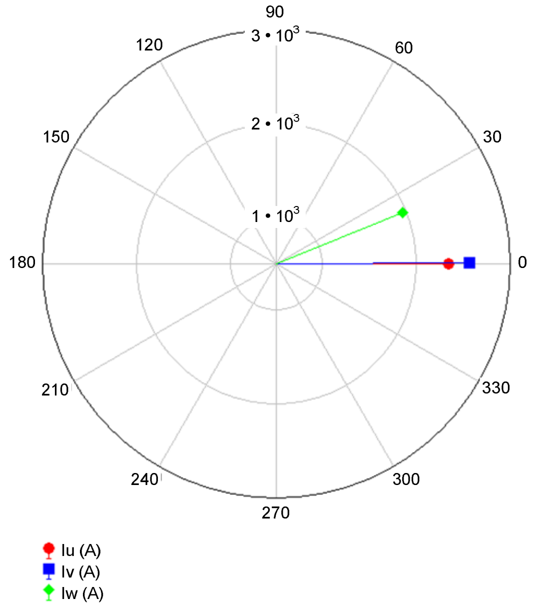

Fig. 11 Polar Plot of Phase Currents From E200 Event

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 is acting 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 star 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. 12 [3].

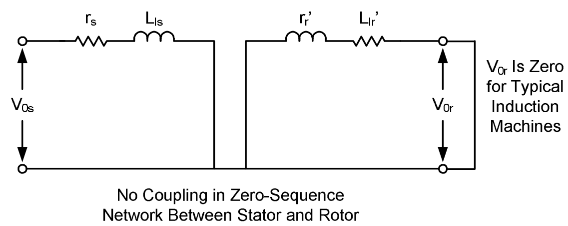

Fig. 12 Zero-Sequence Network for an Induction Machine Whose Windings Are Connected in a Grounded Star Configuration

Because the machine is intended to be an ungrounded motor, one possible explanation of this is Theory IV (outlined in Section V): 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. 13.

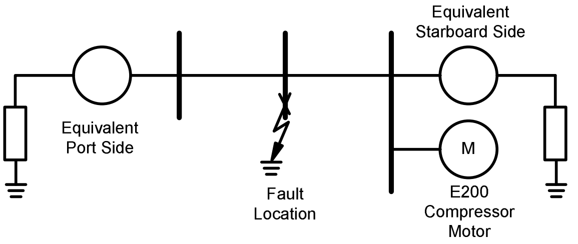

Fig. 13 Simplified One-Line Diagram With Thévenin Equivalent Circuits for Port- and Starboard-Side Power Systems

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. 12, we arrive at the zero-sequence network shown in Fig. 14. 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, as Theory IV asserts, there is a ground fault near or at the neutral point of the machine.

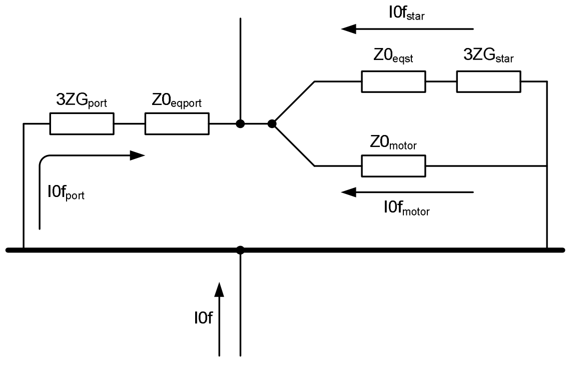

Fig. 14 Equivalent Zero-Sequence Network

B. Directional Element

To continue to investigate the theory that there were two earth 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. Because few overcurrent relays had the opportunity to time out (owing to the short duration of the fault and the fast operation of the FCL), no good data were available to support which direction the fault occurred with respect to the two relays. 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 our 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).

$$z2 = \frac{\text{Re}\left\{V_2 \cdot \left(I_2 \cdot 1\angle \text{MTA}\right)^*\right\}}{\left|I_2\right|^2} \quad (1)$$

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. 15 shows a plot of z2 and the thresholds for this protection algorithm.

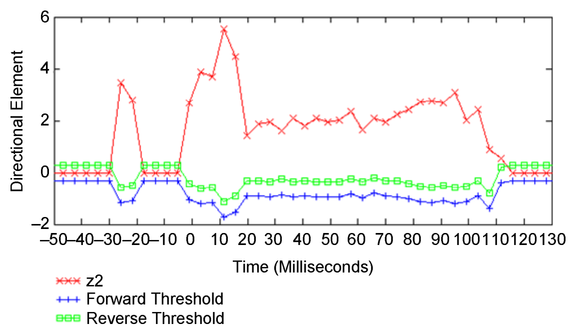

Fig. 15 Plot of z2 and Thresholds Versus Time for Simulation of Negative-Sequence Voltage-Polarized Directional Element

It is clear from Fig. 15 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. 16. The zero-sequence voltage-polarized directional element also determined a reverse direction.

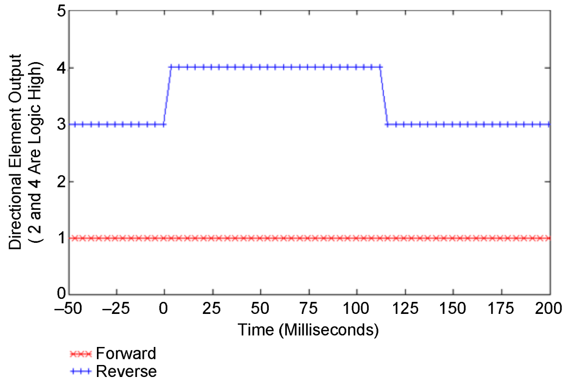

Fig. 16 Response of the Zero-Sequence Voltage-Polarized Directional Element

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. While this analysis does not prove a fault location, it does highlight 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.

C. Evaluation of Thermal Element

Theory III (described in Section V) was that a fault occurred in the E200 motor because of thermal overload. This prompted a thorough analysis of how well the motor protection relays were protecting both the E100 and E200 machines against stator and rotor overloads. The thermal element estimates a thermal capacity used for the rotor and stator based on measured relay current. Enhanced thermal models can help optimize motor protection against damage from both locked rotor conditions and overloading [6] [7]. In addition, the motor data available for these particular motors are extensive and include all of the required parameters necessary to set the motor protection without having to estimate any of the settings.

In Fig. 17, the stator thermal damage curve from the motor manufacturer is plotted, as well as the relay thermal element response for both "hot" stator and rotor conditions. While this is not a complete dynamic simulation, the curves provide some verification that the relay thermal overload element is protecting the machine adequately.

In addition to verifying the relay response again, the motor manufacturer thermal damage curve, motor start reports, and trending data were reviewed. The data gathered showed no evidence of overloading, despite the large number of starts. This particular motor protection relay was also available with an algorithm to limit the number of starts per hour and number of consecutive starts based on simple timers and counters, without any dependence on the calculated thermal capacity. Enabling these elements could address the concerns about the large number of starts and provide an additional assurance that the machine is not being subjected to any thermal overloads.

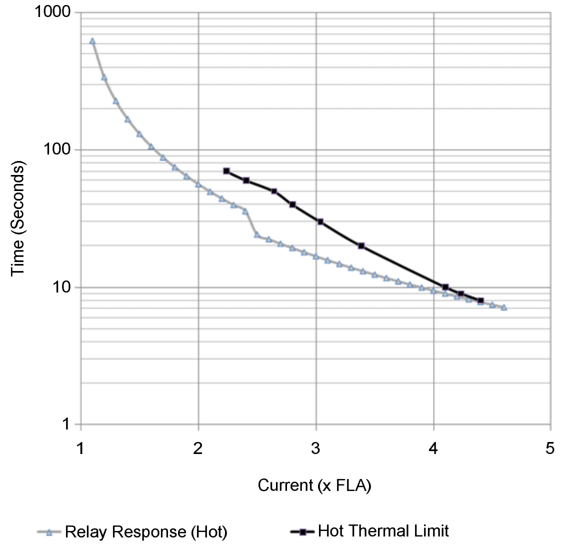

Fig. 17 Hot Thermal Limit Curve and Thermal Overload Element Response

VII. 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 V was shorted to earth. Other phases were not shorted to earth.
- 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. 18.
- Detailed examination of stator winding connections confirmed that the winding puncture described in Fig. 18 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. 19.
- 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. 18).
- It was theorized that the remnant of the missing steel support that was wedged into the stator winding was melted and destroyed during the fault event and that the molten steel, described in Bullet 5 above, originated from the missing steel support.

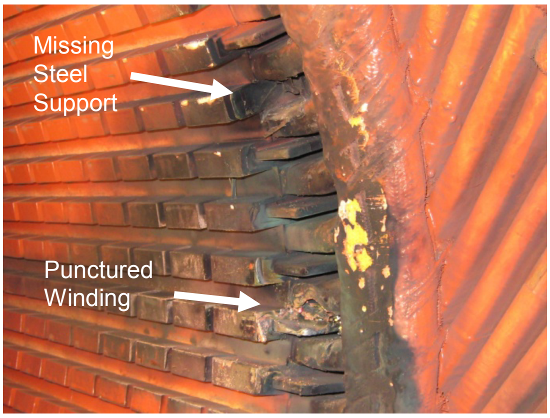

Fig. 18 Photo of E200 Stator Point of Failure

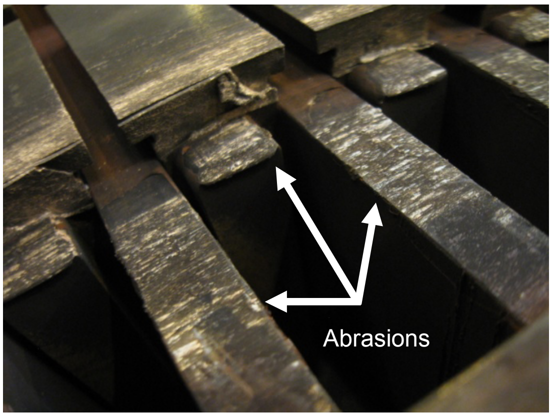

Fig. 19 Photo of E200 Rotor Opposite Stator Damage

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 a short circuit was found. However, significant evidence of flashover was found 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 U terminal. Investigators were not able to pinpoint the cause of this fault, but a couple of theories have been asserted. First, it is possible 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. Second, it is possible that a change in the dielectric properties of the air gap occurred at the time of the flashover. Potential explanations include airborne contamination (dust and moisture) or a rodent that accidentally bridged the air gap to trigger the short. Methods to further define root cause of the transformer failure have been exhausted.

VIII. BEST AVAILABLE EXPLANATION

Investigators 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 earth. By coincidence, the puncture occurred on the first turn nearest the star point of the Phase V winding. This failure created a low-impedance earth fault near the star point, which was undetectable by electrical protection equipment in place. Earth 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 earthing impedance, which was designed to limit earth fault current should a fault occur. The power system apparently operated with this point of low-impedance earthing at the E200 motor neutral for an unknown period of time.

B. Fault Event

It is believed that on December 5, 2009, a new earth fault developed in the WI-A transformer (at time *t* = 0 in Fig. 6 through Fig. 8), most likely in the Phase U primary winding as indicated by the data. With two earthed 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 U in 5 milliseconds, thereby breaking fault current flow and dividing Phase U into a starboard island and a port island. Phase U 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 V of the transformer, creating a phase-to-phase-to-earth fault. Generator excitation systems were unable to maintain voltage on Phase V with this increased fault current, and Phase V voltage collapsed. Shortly thereafter at *t* = 95 milliseconds, the FCL opened its Phase V element because of the increased Phase V flow of current. Once the Phase V pole of the FCL was opened, Phase V voltage recovered on the starboard system where the majority of power generation capacity was connected; port-side voltage on Phase V remained collapsed due to the active fault that was present. With only Phase W 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 earth fault current began decaying back to normal levels. This subsidence current resulted from residual magnetism in the 50:1 core-balance current transformer [8], 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 earth 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 protective 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.

IX. PROTECTION PERFORMANCE

Evaluation of a protection system should always be a multistep procedure. One such procedure is outlined in [9]. 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 for the fault. 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 is prior to the fault. In Fig. 20, we see there is 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.

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 sensitivity 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.

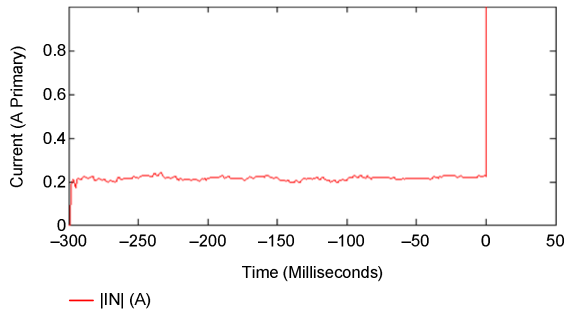

Fig. 20 Neutral Current Magnitude at E200 Motor Relay

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.

In addition, after reviewing the thermal overload settings, as described in Section VI, 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 protective relay at E100, which captured the event record shown in Fig. 3, 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, if the best theory of what happened is accepted, 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.

X. CONCLUSIONS

While it may be theoretically possible to detect an earth fault near the star point of an ungrounded motor in an impedance-earthed power system, it is impractical to implement because the likelihood of this failure mode is very low. In this case, the undetected motor fault effectively shorted out the benefits available through an impedance-earthed 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 invaluable. 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.

While the thermal overload element was proven to be adequately protecting the motor against thermal overloads, enabling additional elements to limit the number of starts per hour and the number of consecutive starts enhanced the overall protection.

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XII. VITAE

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Frederick D. Painter II graduated from West Virginia University in 1982 with a BSEE. Upon university graduation, he began a career as a power systems engineer with Marathon Oil Company, where he remains presently employed. During his nearly 29-year career, Frederick has performed a variety of engineering duties associated with onshore and offshore oil and gas production/processing operations throughout the world. Since January 2007, he has been assigned to Marathon Oil Company’s Upstream Reliability Organization, where he serves as a subject-matter expert on power systems reliability. Frederick is a licensed professional engineer in the State of Texas and a member of IEEE.

Malcolm Wilkinson graduated in 1979 with a Bachelor of Science Honours degree in Electrical Engineering from the University of Salford, United Kingdom (UK). He initially worked as a power engineer with NORWEB UK power utility, where he undertook HV operational duties up to 33 kV, before transferring to the utility headquarters section responsible for determining utility policy on cable and overhead line systems up to 132 kV. Malcolm then joined 3M UK in the electrical products division, rising to technical manger with responsibility for technical service support and new product developments for cable accessories up to 66 kV worldwide. Petrochemical industry experience followed as lead electrical engineer at the BP Oil Coryton refinery before joining AREVA Inc., where he worked in conjunction with Eskom to develop the dry keep transformer moisture management system. 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 that vessel. Malcolm has extensive experience with electrical distribution systems worldwide. He is a Chartered Electrical Engineer registered with the UK Engineering Council and a full member of the Institution of Engineering and Technology (formally IEE), and Energy Institute.

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