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A more effective DP FMEA power system testing regime

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Abstract

Modern power systems aboard DP vessels have incorporated advanced technologies that make proving system operation more difficult than in the past.

While many DP FMEAs are trying to capture the advanced systems used today, key components specific to modern systems have been overlooked and in some cases, testing of particular functions has become over-emphasised to the detriment of overall system functionality.

The “Built to Test” requirements offer a new opportunity to build DP FMEA testing programs with a view to comprehensive and safe testing solutions. This paper offers a more complete FMEA set of testing that can be adapted and applied to modern DP2 and DP3 power systems, in conjunction with a robust commissioning, sea-trials and maintenance package.

This paper will include a logical power system document review process and provide a comprehensive, safe and efficient test regime.
Considerations which are vital to the health of the overall system include the order in which testing is performed and the overall test program, including DP FMEA testing.

Abbreviation / Definition

<table>
<tr><th>Term</th><th>Definition</th></tr>
<tr><td>ASOG</td><td>Activity Specific Operating Guideline</td></tr>
<tr><td>AVR</td><td>Automatic Voltage Regulator</td></tr>
<tr><td>BOB</td><td>Battery on Board</td></tr>
<tr><td>Complex systems</td><td>In this paper shall refer to systems with any of the following:
• Closed bus ties
• Dual fuel systems
• Energy Storage Systems (ESS), including fly-wheels, batteries, super-capacitors and any combination of these
• Advanced digital protection relays
• IEC61850 protection networks,
• Dedicated generator fault detection and protection systems
• Remote condition monitoring</td></tr>
<tr><td>DP</td><td>Dynamically Positioned</td></tr>
<tr><td>DP2</td><td>DP Class 2</td></tr>
<tr><td>DP3</td><td>DP Class 3</td></tr>
<tr><td>ESS</td><td>Energy Storage System</td></tr>
<tr><td>FMEA</td><td>Failure Modes & Effects Analysis</td></tr>
<tr><td>FMEA proving trials</td><td>Test program for verifying the FMEA</td></tr>
<tr><td>IGBT</td><td>Insulated Gate Bipolar Transistor</td></tr>
<tr><td>IGCT</td><td>Integrated Gate-Commutated Thyristor</td></tr>
<tr><td>OEM</td><td>Original Equipment Manufacturer</td></tr>
<tr><td>PMS</td><td>Power Management System</td></tr>
<tr><td>TTT</td><td>Time to Terminate</td></tr>
<tr><td>VFD</td><td>Variable Frequency Drive</td></tr>
<tr><td>WCFDI</td><td>Worst Case Failure Design Intent</td></tr>
<tr><td>WSOG</td><td>Well Specific Operating Guideline</td></tr>
</table>

Introduction

The Authors do not represent Classification Societies and highlight the need to comply with all Class Rules and Guidelines. This information is presented as a thought-piece to assist in asking questions and challenging the industry to best practice for improved reliability and incident free Dynamic Positioning (DP) Operations.

FMEAs and the proving trials programs in the past decade have focussed on a systems-approach to ensure a comprehensive Failure Modes & Effects Analysis (FMEA) has been developed and tested. This approach yielded very successful results in situations where the Worst Case Failure Design Intent (WCFDI) could easily be validated as a result of redundant systems. The failures of systems were generally isolated to a specific section of the facility, and cross-connections were managed primarily through elimination and secondarily by testing of specific system failures. Figure 1 below demonstrates the philosophy.

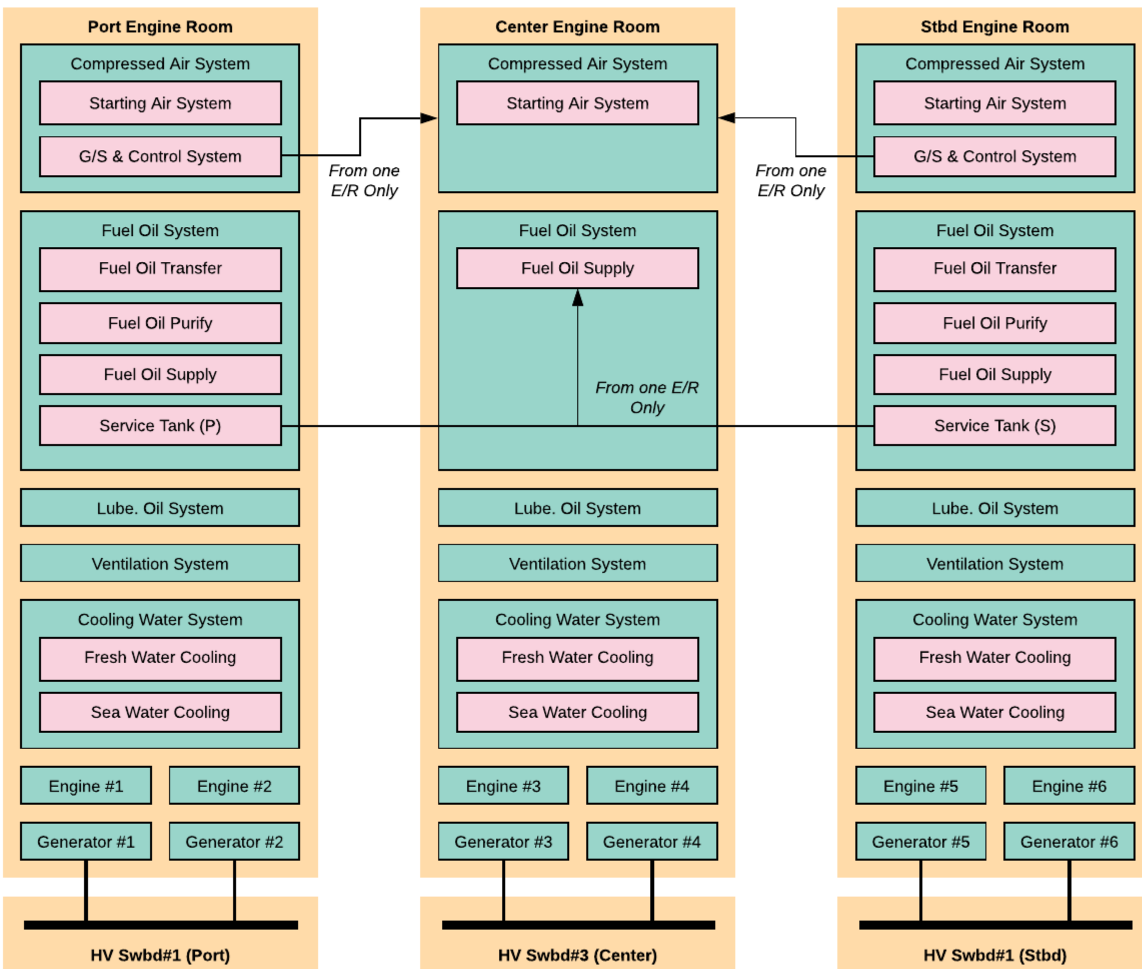

Figure 1 - Example of an open bus system with very limited and clearly identified cross-connections

As vessel complexity increased, industrial mission and digitalization requirements began to affect this redundancy concept. The addition of cross connections, closed bus ties, battery on board and remote condition monitoring has made the clear-cut redundancy concept harder and harder to deliver.

Failures which were contained to a section due to segregation (open bus ties) are not acceptable when cross connections provide the opportunity for these faults to propagate beyond section boundaries. As a result, more comprehensive control and protection systems are required to provide barriers to fault propagation. Battery hybrid and closed bus systems particularly require additional considerations as a result of the increased complexity and cross connections.

The addition of these complexities means that there is an increase in cost and time, during the design, installation and verification stages. It must be understood that the validation and verification process for complex systems must ensure correct operation of the system, and safe failures. This process will take a substantial period of time due to the integrated nature of the system and the multi-faceted nature of the verification now required.

In order to provide safe power systems to the maritime sector, vessel owners and DP stakeholders will need a new approach which can tackle these complexities, and future challenges. The safe introduction of technology that is required to make our industry cleaner, safer and more efficient lies in the introduction of new and innovative testing devices. With the introduction of complex systems; simply trying to induce a fault into a specific system in isolation from the rest of the system or with protections disabled not only gives a false sense of security but also leads to incidents in operation (IMCA, 2015 & 2016).

As in many other industries, there is a trend towards placing trust in equipment vendors with regard to verification of the power system. While Original Equipment Manufacturers (OEMs) are the experts at generation and distribution technology, they are generally not experts on the requirements for DP systems and what can go wrong. Recently, the aviation industry has encountered issues with design changes not being correctly validated or verified, resulting in incidents that led to the loss of human life. A validation process needs to be adopted by the industry to prevent incidents, including robust FMEAs focussed on vessel-specific threats associated with the installation of ESS and closed bus systems.

The industry cannot afford to learn from incidents with these systems. We must be proactive in identifying and mitigating possible failures in advance of operations. As the saying goes, prevention is better than cure.

Power System Document Review

A major portion of a vessel's Failure Modes Effects Analysis (FMEA) is document review. The FMEA should start at the point of the initial concept of design. The entire system should be designed with the methods of protection and control set out at the start to ensure a compliant and safe system is delivered.

The power system cannot be reviewed in isolation. The aim of documentation review during the FMEA development should be:

- understanding of the integrated vessel operation intent, including industrial mission
- understanding of the integration to achieve the operational intent
- understanding of the barriers used to achieve safe operations
- understanding of the failure modes and effects
- understanding of the limitations of the system
- identify any shortcomings in the barriers used
- identify any shortcomings in the design with regards to the design intent
- built to test requirements and testing methods
- demonstration of class compliance, including novel class notations

The full intent of the vessel directly impacts the operation of the vessel's power management system and protections. Not only is a full and complete understanding of the power generation and distribution system required but also the anticipated load profile of the industrial mission as this will have an impact on how the system protection is set up. It must also be recognised that there are instances where the industrial mission can have a significant impact on the power system.

Of particular note in relation to the power systems verification is the protection coordination study. This document is vital in ensuring that all protection functions have been implemented in a way that is suitable for the operational configurations the vessel is designed to operate in.
The introduction of complex systems such as ESS and the impact they have on the power system as a whole needs to be considered in great detail.

When applicable, fault capabilities and fault reactions of ESS need to be taken into consideration, including:

- does the unit keep supplying during a fault at its full current limit?
- does the unit keep supplying at an increased current rating?
- does the unit detect the fault and stop supplying?
- does the unit have communications such as an IEC61850 network?

These questions must be considered and reflected upon during review of the protective relay coordination study. This is to ensure that all fault scenarios will result in no failure worse than WCFDI.

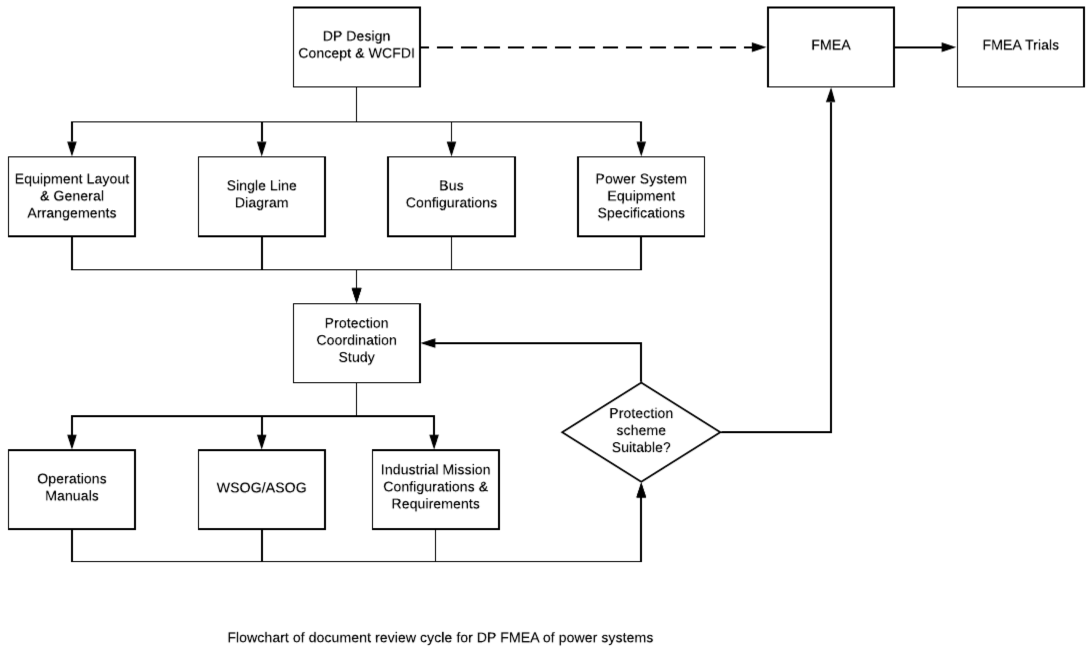

Figure 2 - Flowchart of document review cycle for DP FMEA of power systems

It must be recognised that traditional testing methodologies are not sufficiently comprehensive to effectively verify system responses to failure modes on modern complex power systems. Previously, FMEA trials relied upon "does not exceed WCFDI" as the acceptance criteria. These newer systems require well-defined methodologies and acceptance criteria which should be reviewed and accepted by all stakeholders. This should be identified during the document review stage with a view to making the required changes prior to commencement of trials.

At this point it is important to note DNV's requirements regarding retrofits:

> *"1.1.3 In order to be valid, the FMEA, the test program, and the test report must at all times during the operational phase be maintained and updated in case of alterations of the system. In case of alterations it must be evaluated if:*
> *— additional FMEA is required*
> *— test program need to be updated*
> *— functional testing and/or failure testing is required*
> *— other parts of the documentation needs to be updated." (DNV AS, 2012)*

Integrated Testing Methods

> *"Testing is useful and very important. These testing should incorporate tests reflecting the changed pre-failure load conditions (e.g. generator sets being heavily loads before failure, as opposite to the traditional situation with low load before failure occurs)" (Eriksen & Karlsen, 2018)*

> *"It is common practice to individually test the components of a protective relay scheme (e.g., instrument transformer tests, relay tests, wiring checks, trip checks, and end-to-end tests). Complexity is added when companies opt to hire different contractors to perform these tests. Each contractor will focus on its scope of work and most likely not spend time considering the big picture of how the equipment being tested interacts with all the other components of the protective relay scheme." (Peterson, Scharlach & Baltazar 2009)*

> *"Periodic maintenance tests*
> *The objective is to detect in-service failures of components, wiring, interfaces, communications, or unwanted changes of setting or configuration.*
> *a) Assume the design requires no additional verification.*
> *b) Test for correctness of wiring or switching configuration that could conceivably have been changed by maintenance elsewhere in the substation, including polarity or phase rotation, and instrument transformer or other interface grounding/earthing.*
> *Periodic testing should focus on carrying out steps that detect most in-service hardware failures and avoid additional testing that tends to reverify the design, software behavior, or the fundamental installation correctness that were already confirmed. Excessive testing risks accidental introduction of problems and work errors that leave the system unable to protect after the test is complete and the technicians have left the site. This is especially true for invasive testing that calls for taking systems out of service, disconnecting circuits, changing settings, or opening unit cases." (IEEE, 2009)*

Integrated testing methods which demonstrate how a fully functioning system performs are required. The industry will need to develop comprehensive, less invasive, methods of verification and validation. The industry will need to adopt and adapt external testing technologies. Additionally, the DP community will need to develop new and improved testing technologies specifically for the challenges of DP.

These tools will need to be a combination of hardware, software, and testing methods specifically designed to verify the system as a whole. This will require all sectors of the industry working together: owners, vendors, chartering companies, classification societies and legislative bodies will need to agree on what level of verification and validation is needed to ensure the safe and efficient operation of DP vessels.

While this paper is dedicated to the requirements of DP vessels it must also be noted that the DP market is not the only maritime industry currently increasing the efficiencies by the application of technology and much of the technology developed for the DP market could be applied to other maritime sectors and high value assets.

The aim of FMEA testing for any power system failure should be to:

- Validate the control and protection system has been designed and set to isolate the fault correctly i.e. to the smallest possible section of the system.
- Verify vessel behaviour through introduction of non-destructive, repeatable faults. Due to the integrated nature of these systems, introduction of these faults should be such that a system-wide fault response can be observed, and repeated in the same fashion at every FMEA trials.

Unless stated otherwise, the authors recommend performing the testing described herein during each FMEA 5 year survey cycle.

While there are many failure modes, each power-system failure will fall into one of five broad categories:

1. Prime Mover Failures
2. Excitation Control Failures
3. Ground Faults
4. Short Circuits
5. Overload

Failure Mode 1 - Prime Mover Failures

A simple way to express a prime mover failure in a multiple generator system is:

$$Power_{Output} \neq Power_{Requested}$$

While prime mover failures can be initiated in countless ways, the symptoms will be:

- Over-power
- Under-power
- Engine shutdown

Over-power faults are caused by over-fuel events. Over-fuelling events will result in kW imbalance, driving other generators into reverse power, system instability, and over-speed/ over-frequency.

Under-power will generally be caused by under-fuelling. Under-fuelling events will result in kW imbalance, reverse power on faulty generator(s), system instability and under speed/under frequency.

With the introduction of fuel injection and electronic servo-motor fuelling systems, adjusting the governor manually is no longer an option. Thus, governor and governor control manufacturers need to be engaged during design to ensure a method for reliably inducing a fuelling fault is included in the equipment package (Built to Test). New tools will need to be developed for systems undergoing upgrade.

In open bus systems, engine shutdown, initiated as a result of myriad mechanical and control system failures, should result in the generator circuit breaker opening. Engine shutdown testing and load step testing should be performed for all configurations. There are a number of ways to perform engine-shutdown testing repeatably, and these are understood by the industry, so will not be discussed here. (Clarke, Cargill & Coggin, 2014)

Effect of closed bus ties:

> *"3.2.8 Sudden load changes resulting from single faults or equipment failures should not create a blackout." (IMO, 2017)*

Traditionally, prime-mover faults were mitigated by open bus. In closed bus systems, without the correct protection, load steps associated with prime mover faults may cause the system to black out.

A suitable system for engine & generator monitoring and protection is required for systems with closed bus ties. Systems operating with less than 3 engines online have even greater need of these advanced protections.

Modern monitoring and control systems need to be able to identify and mitigate large load steps rapidly in advance of the system experiencing mechanical responses. When developing this system it is vital to consider industrial mission equipment which may be affected by the load-step protections. The integrated system should be tested with full loads, including industrial mission, with engine configurations per operational guidelines (ASOG/WSOG/DP Operations Manuals)

Effect of ESS:
Multiple generators w/ ESS as spinning reserve

- Per the closed bus discussion above.

Single Generator w/ESS as spinning reserve

- A detailed study into the effects of engine fuelling and load step faults will need to be conducted to assess the response of the grid-tie inverter.

Questions to ask include:

- If on one diesel generator w/ ESS, if system over-fuels and bus frequency increases does the inverter follow the frequency or does it shut down.
- How does the system respond to kW sharing failures? Does the governor control system for the diesel generators communicate with the ESS control system, or is there some other method of integration for kW?
- ESS control must also be considered: does it get a signal from the PMS saying go into charge or discharge and if so, what is the effect when a failure on that system happens? Does it have redundant lines, etc?

Failure Mode 2 - Excitation Control Failures

Excitation control failure in a multiple generator system may be simplified as:

$$\text{Reactive Power}_{\text{Output}} \neq \text{Reactive Power}_{\text{Request}}$$

While there are many failure modes which will result in excitation control anomalies, there are only two possible mechanisms:

- Over-excitation events can result in either a VAr imbalance, or system over-voltage.
- Under-excitation events can result in either a VAr imbalance or system under-voltage.

Examples of faults include:

- Loss of sensing
- Loss of field
- Loss of Automatic Voltage Regulator (AVR) control

Faults such as loss of sensing and loss of field on a single unit are induced by interrupting the circuits. Modern AVR systems increase the complexity of inducing other styles of faults such as over voltage, under voltage and kvar imbalance. With the correct protection equipment and settings it is possible to detect these style of fault before a major system disturbance is experienced.

In a system with only two generators online it is difficult for the system to identify which generator is actually in fault. The detection of these faults can be difficult if the correct systems are not installed and it is not uncommon for a system that has been designed to operate with open bus ties for generators on the affected bus to trip. Some modern AVRs have protections to ensure that the output matches what is required however these protections need to be validated onboard.

Effect of closed bus ties:
Loss of the section in an open bus scenario was an acceptable result within the WCFDI. With the closure of the bus ties, faults must be highlighted and assessed with a far stricter discrimination requirement (each generator). AVR tuning and protection settings are vital to the correct detection of faults at an early stage. Protection equipment must be able to identify which generator is in fault and must remove it from the system prior to introducing a significant disturbance (kVAr or voltage) onto the bus.

Modern systems do not allow for manual manipulation of AVRs without affecting protection settings. An alternative method for manipulating excitation and inducing excitation-based faults include utilising technologies such as OneStep Power’s Generator Voltage Response Tester.

Effect of ESS:
Multiple generators with ESS as spinning reserve:

- System should be able to isolate the faulty generator in similar fashion to the scenario mentioned in closed bus above.

Single Generator with ESS as spinning reserve:

- A detailed study into the effects of engine excitation faults will need to be conducted to assess the response of the grid-tie inverter.

Questions to ask for any ESS:

- Does the drive follow the bus voltage from the generator? How far will it follow, and what is the outcome?
- How does the system respond to kVAr sharing failures? Does the AVR system for the diesel generators communicate with the ESS control system, or is there some other method of integration for kVAr? What happens if kVAr sharing fails?

Failure Mode 3 - Ground Faults

Ground faults are the most common type of short circuit fault experienced by power systems, with industry experience agreeing that between 70 and 80 percent of faults are of this type (Csanyi, 2016). A ground fault occurs when a live conductor connects to the ground of the system. A simplistic description of a ground fault can be given as:

$$\text{Current}_{\text{ground}} > 0$$

The detection and isolation of ground faults is a very complex subject and is not the topic of this paper. It must however be understood that the style of protection system used will directly impact the required verification and validation. While there are numerous ways to implement the earthing system it will either have the generator and/or transformer neutral points tied to ground or isolated from ground. There are a number of standards that give full descriptions of what each grounding system is and how it should be implemented.

In a system where the power system is grounded, be it directly or through a current limiting device, the power system should be designed to isolate any faults detected as close as possible to the fault location.

When the power system is fully isolated from ground, the distribution network will generally only provide indication of a ground fault.

Testing for ground faults on open bus systems with grounded neutrals may be limited to primary injection testing at commissioning. This testing shall verify the current transformers have been installed correctly and the protection system operates correctly to isolate the fault and protect the power generation system.

Effect of closed bus ties:
Closed bus ties increase the complexity of the protection system requirements for ground fault detection. Ground fault testing to confirm correct setting of zones and pickup currents should be completed after commissioning but prior to sea trials. This testing should include the introduction of live ground faults on systems that have current limiting devices in the earth return path, such as earthing transformers or resistors. On systems with grounded neutrals that do not have current limiting devices installed, primary injection should be employed at commissioning to verify correct operation.

Without an automated protection system, there is an increased chance of multiple ground faults concurrently. A second ground fault before the first one is cleared may allow the situation to develop into a phase to phase fault, with significantly greater impacts to the overall health of the power system. Therefore, It needs to be identified in the DP FMEA of vessels with closed bus ties and a non-grounded system: when a ground fault is indicated, the operator should open the bus ties to remove the threat of a ground fault developing into a short circuit condition and propagating across the system.

Effect of ESS:
The complexities which were added with the closure of the bus ties have not been eliminated with the addition of ESS. Further to the concerns above, Vessel owners considering ESS should also ask:

- How is the VFD connected to the system?
- What are the effects of ground faults on this specific system layout?

Some of these questions have already been asked and are being addressed in the onshore energy sector, resources from these industries should not discounted (Advanced Energy, 2013).

Failure Mode 4 - Short Circuits

In this paper a short circuit is considered as any low impedance connection between two or three phases i.e phase to phase or phase to phase to phase faults. Phase to ground faults are discussed in the Ground Fault section above. The simple definition of a short circuit for the purpose of this paper is:

$$\text{Current}_{\text{System}} \gg \text{Current}_{\text{Nominal}}$$

Short circuit faults range from failure of a silicon device such as an insulated gate bipolar transistor (IGBT) or integrated gate-commutated thyristor (IGCT) to a bolted fault at the main bus bars and anything in between.

With an open bus configuration, the aim is to ensure the protection of the generators by opening the generator circuit breaker on overcurrent, with minimal delay. This should be validated using primary and secondary injection test methodologies during commissioning and at IEEE recommended intervals (IEEE, 2009).

Effect of closed bus ties:
With a closed bus system it is important that the generator circuit breakers are delayed to the point that the downstream breakers, i.e. the feeder breakers and bus tie breakers, open and limit the loss of power to the smallest section of the distribution network possible, while still not allowing damage to the generators.
Unlike the previously discussed faults, short circuits cannot be isolated prior to the network being severely disturbed. Therefore, in addition to correct detection and isolation the systems must be proven to ride through the network disturbance.

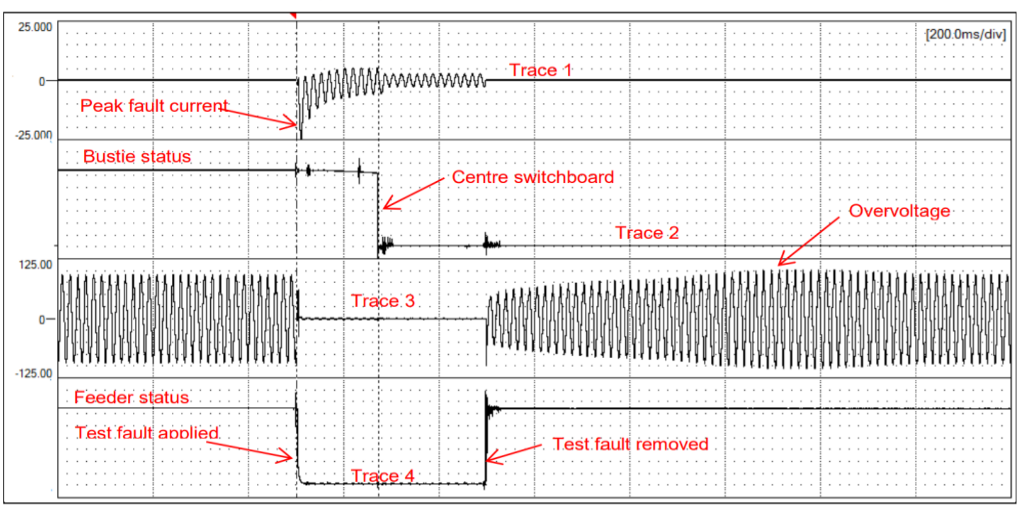

Figure 8-9 Fault Current, Bus Voltage and Status for Bustie Circuit Breaker and Feeder Circuit Breaker

Figure 3 - Fault current, bus voltage and status for bus tie circuit breaker and feeder circuit breaker (MTS, 2015)

Full verification and validation of the power system will require a multi layered approach to ensure that all possible failures are accounted for. MTS TECHOP-ODP-09 (2015) provides details of one method for vessels with “Built to Test” HV switchgear.

However, TECHOP-ODP-09 highlights the need for a different solution for vessels with LV systems:

> *"A very significant part of the DP fleet have low voltage power systems such as 690V or 480V power generation and this is particularly true of the platform supply and light construction vessel fleet. There is a consensus amongst power system manufacturers contacted as part of this study that it is impractical to prove the fault ride-through capability of low voltage power systems in exactly the same way as their high voltage counterparts." (MTS, 2015)*

Solutions are available to prove fault ride through capability for all vessels. A comprehensive solution should include:

- Secondary injection testing to ensure that the circuit breakers operate at the correct time and level.
- Primary injection, currently not in wide use in the DP industry, should be undertaken after completion of the secondary injection testing.
- Fault Ride Through

Primary & Secondary Injection

Primary and secondary injection testing can only prove the detection and descrimination systems have been wired, set and are operating correctly. Csanyi (2017) states:

> *"Primary injection testing is, however, the only way to prove correct installation and operation of the whole of a protection scheme. Primary injection tests are always carried out after secondary injection tests, to ensure that problems are limited to the VTs and CTs involved, plus associated wiring, all other equipment in the protection scheme having been proven satisfactory from the secondary injection tests."*

These tests are possible with equipment such as the Omnichrom CPC-100 and Doble M7100. These devices are designed to conduct testing in generation and distribution networks, and should be employed aboard DP2 and DP3 class vessels during commissioning and after major upgrades.

Fault Ride Through

Fault ride through testing proves the ride through capability of the downstream equipment. There are three main components to validation of fault ride through:

1. Voltage dip, possibly to zero for the time it takes the bus ties to open.
2. Transient overvoltage, generated by the generators once the fault is cleared.
3. Power supply from the AVR, during a short circuit the AVR should be capable of delivering the higher excitation current required.

The voltage disturbances are validated using excitation control to confirm the system's capability to ride through. An example technology for producing this disturbance is OneStep Power's Generator Voltage Response Tester.

Effect of ESS:

It is important that the reduced fault current capability of the ESS does not prevent a short circuit fault from being isolated with maximum discrimination. Additionally it is vitally important in instances where ESS is being used in lieu of conventional generators, that the system continues to provide power after a fault has been cleared.

> *"When the batteries are used as one of the main sources of power it is important that the electrical circuits are arranged with discrimination between the circuit breakers such that a downstream fault (e.g. short circuit) do not lead to black out of the whole electrical power plant. To achieve this, it is important to consider that a battery power converter (DC/DC or AC/DC converter) typically will limit the maximum short circuit power (typical 1.2 – 1.5 times nominal power), and by that will add some*

additional challenges in the relay coordination which also need to be managed." (Eriksen & Karlsen, 2018)

Full details of the currents and directions of currents developed by ESS need consideration and fault path propagation is going to require a greater analysis than the fault calculations that have historically been accepted in the industry.

Questions to ask for any ESS include:

- How does the ESS communicate with the power system?
- How does the ESS address a fault that is directly coupled/in the same node?
- How does the ESS address a fault that is on the other side of a circuit breaker?
- Fault currents across bus ties and through breakers must be considered.

An example of a possible critical failure is shown in the diagram below. If the ESS is not capable of reaching the required fault current to operate the bus tie, the voltage on the main bus will be dragged down due to the current limit of the output on the ESS. Either the ESS will trip offline or it will stay low to the point that all the equipment falls offline due to under voltage. Either way, the system will suffer a total loss of DP capability. There are a number of readily available solutions for this style of fault, however, as the challenge of ESS is only relatively new, these solutions have not been required in the past.

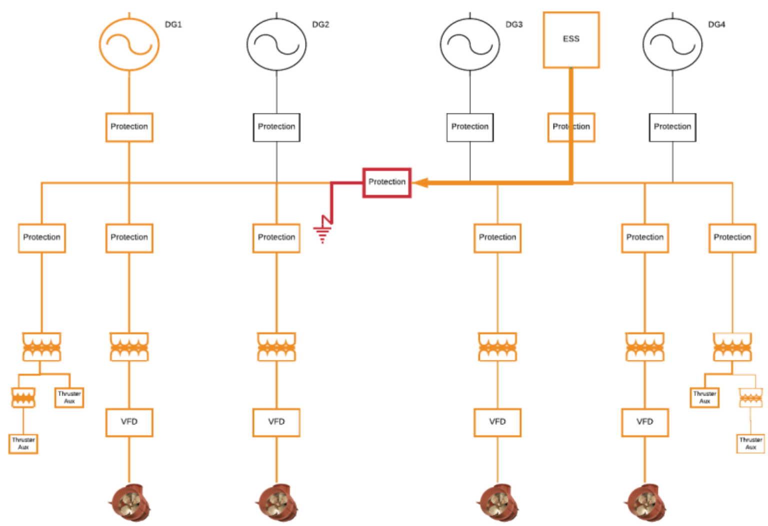

Figure 4 - Fault path with ESS

This fault is only one scenario which must be engineered. The industry must rapidly develop knowledge and experience in identifying these types of fault scenarios and solutions. An independent third party power specialist is recommended to confirm that the impact of ESS on relevant fault scenarios has been considered and mitigated.

Failure Mode 5 - Overload

An electrical overload occurs when a device or system consumes or produces more power than it has been designed for:

$$Power_{Used} > Power_{Rated}$$

For the purposes of this paper, only overload of power system will be discussed. Individual consumers are assumed to be sufficiently protected by the use of individual protection and control systems.

Overload protection should be implemented to prevent blackout. This is generally accomplished by a number of layered methods:

1. Use of power management systems to limit the consumption of "controllable load". Examples of this equipment include variable frequency drives, fixed pitch propellers etc.
2. Load shedding of non critical equipment.
3. Correct selection of curves in the power system protection devices in order to isolate individual feeders before disconnecting generators.

Testing for overload protections on open bus systems is generally performed by inducing load variations, and by turning off overload protections to run the system at high load to validate secondary protections.

> *"8.4.4 Overload, e.g. caused by the stopping of one or more generators subject to common mode failures, shall not create a black-out.*
>
> *Guidance note: Reduction in thruster load, i.e. pitch or speed reductions, should be introduced to prevent blackout and enable standby generators to come online. If this function is taken care of by the positioning control system, the function should be co-ordinated with the power management system. Load reductions should preferably be achieved through the tripping of unimportant consumers, and the requirement does not exempt such means. But, it is common that the relative load proportions will require thruster load reduction, in order to effectively reduce overload situations. When the system is running with open bus-ties, partial black-out contained within one redundancy group (i.e. one main switchboard section), may occur in case a failure causes stop of the last connected generator set in that same redundancy group (main switchboard section). ---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---" (DNVGL, 2018)*

Effect of closed bus ties:
Closed bus ties have the potential to both decrease and increase the number of overload events experienced by a DP system. If correctly implemented, the loss of an engine or engine room, will result in less DP system disturbance as all thrusters may remain online. A small drop in available power while the extra engines come online may be experienced, however the overall thrust available to the vessel will be greater than that of the scenario where the engine room loss results in thrusters in that section being lost.

Modern protections which must be considered for closed bus ties include rapid load response and the associated high speed protection network. It is very important to ensure the settings and systems used to control overloads are correctly designed, tested **and understood by the crew**.

Testing of the rapid load response system will require application of high load steps. For example, as a minimum, shutting down of an entire engine-room. If there is the potential for an industrial mission load to rapidly draw power (e.g. drawworks), the system response to this requirement should also be validated.

Effect of ESS:

> *"The philosophy is to consider a battery as a "generator with a limited fuel tank"" (Eriksen & Karlsen, 2018).*

If ESS is used to reduce the level of spinning reserve on a system, overload protection becomes even more important as the load increase required to instigate an overload event is much smaller.

Questions to ask include:

- Does the ESS provide 110% overcurrent capability?
- What happens to the output voltage if the load demand is greater than the ESS is capable of providing? Does the ESS shut down which increases the overload to any other power supplies that are online?
- What are the duty cycle limits of the ESS with respect to an overload?
- Are there temperature rise concerns during an overload event?

Further considerations - Industrial Mission Interference

With the introduction of the complexities detailed in this paper, DP FMEAs can no longer isolate the DP systems from the industrial mission. Faults from one system are transferrable to the other, often with significant consequences.

Effect of closed bus ties:
Situations which must be considered include:
Closed DC bus ties present an opportunity for fault propagation.
Automated fire and gas logic which may cause engine rooms to be removed from service automatically.
Industrial mission major consumers and the load steps associated with their use, which may cause system disturbances, for example an under-frequency event.

Effect of ESS:
Has the "Time to Terminate (TTT)" calculation taken into account the industrial mission, hotel load and other parasitic consumers? Testing of the TTT must be an integrated test and include the aforementioned equipment. In this discussion, parasitic loads refers to things such as tubing or wireline or other third party equipment not installed at the shipyard.

> *"Battery energy may also be needed to support other functions during the termination process." (Eriksen & Karlsen, 2018).*

Further considerations - Obsolescence

It should be noted that direct replacement of controllers may be increasingly difficult as systems are upgraded by OEMs and old versions are removed from circulation.
It has been witnessed by the Authors that upgrades to newer versions of controller equipment have resulted in unforeseen outcomes due to "smarter" systems not reacting as expected. These newer systems require greater design oversight and tuning during installation.

After installation of a new controller series, the FMEA should be reviewed for applicability and testing performed as appropriate.

Further considerations - Field observations to reduce testing requirements

Many modern vessels are equipped with both protection relays and data recorders. Could implementation of a data capture policy be used as evidence of correct operation of the system?

Consider the situation: A vessel is on location and a short circuit on the crane slip ring is experienced. The vessel's protections react correctly and the fault is isolated appropriately. Six months later, the vessel is asked to demonstrate the ride through and fault discrimination capabilities of the complex power system. The testing will take days out of the vessel schedule, and there have been no system changes since the incident.

Data captured from the above example should provide reasonable assurance to the DP FMEA provider and stakeholders of the capability of the vessel to operate safely after a significant network disturbance. In order to use this data as evidence, as a minimum the following must be recorded:

- Fault current & duration
- System voltage levels
- Other information required by stakeholders

While additional testing to further solidify the evidence, and ensure the situation translates to other fault types may still be required, this data package should provide a sound validation basis. Class notations are being developed to take advantage of continuous condition monitoring, providing opportunities for this style of validation.

Further considerations - Cybersecurity

Vessel complexity in the form of remote monitoring/diagnostics and condition monitoring should be considered with respect to the opportunity these systems present to external threats. No longer are vessels isolated from digital threats by “air-gapped” systems. The advent of remote monitoring and digital twins provide a window for unauthorised access. Ransomware, direct hacks and other invasive digital activities may cause a complete disruption of the DP power system. System integrators need to consider implementation of mechanisms to prevent these types of events propagating throughout a system during design, and with a view to the continued upgrades which will be required over the life of a vessel.

> *“Additionally, if the protection scheme includes application of cyber security communication links (i.e., routable protocols), it is important to verify the performance of the scheme, as well as test data communications channel integrity on a continuous basis. Refer to IEEE Std 1686TM for cyber security standards associated with devices used at substations.” (IEEE, 2009)*

> *“There's no doubt the IoT digital twin can transform products and services, as well as reduce development costs and operating and capital expenses. However, some of the cost savings and profits they generate have to be put back into ensuring they are properly secured. If they're not, then organizations will experience data breaches and attacks that can compromise proprietary technologies and affect critical infrastructure assets and services.” (Cobb, 2019)*

Conclusion

The goal of power system testing in FMEAs is not actually to test the power system. FMEA testing is to verify and validate that the integrated system continues to operate in the event of a single point failure and does not exceed WCFDI. FMEAs and their testing programs in the next decade will face a number of challenges:

- Closed bus ties and battery hybridisation
- Networked control systems
- Centralised condition monitoring
- Rapid obsolescence
- Digital and cyber threats

New technologies provide opportunities for safe and more reliable DP operations. These technologies must be considered in the wider context of the aims and applications of DP fundamentals. Many technologies are still underutilised and a systematic restructure in testing procedures could in fact gain significant safety and efficiency benefits when compared to current methodologies.

To increase efficiencies, energy storage such as batteries have been added to reduce the amount of emissions generated by vessels in operation. The addition of these batteries adds even greater complexities to the overall power system that will require a new set of testing tools in both the form of hardware and procedures.

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