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Preliminary FMEA for the MVDC shipboard power system distribution architecture

**Technical Report**

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**Mission Statement**

The Electric Ship Research and Development Consortium brings together in a single entity the combined programs and resources of leading electric power research institutions to advance near- to mid-term electric ship concepts. The consortium is supported through a grant from the United States Office of Naval Research.

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**Executive Summary**

This short report provides an overview of the failure mode and effects analysis (FMEA) studies undertaken to date for the MVDC shipboard power system (SPS) architecture. It is intended to highlight the approach, benefits and initial outcomes with respect to research approaches. The important benefits of the preliminary functional-FMEA (F-FMEA) to date are as follows:

* Indication of relative vulnerability of certain sections, components and subsystems to focus studies on their respective faults and failures
* An understanding of the need for detailed hardware information which would eventually lead to a more exhaustive hardware FMEA (H-FMEA). This would help to enhance the detail of the overall analysis.
* Help focus diagnostic efforts to manage identified risks using well established AI techniques or the need to develop novel ones.
* Aid efforts to enhance decision support by tapping into the data-rich FMEA resources.

The emphasis is laid on a F-FMEA which serves as the most appropriate method to start analysing failure cause and effects in a novel system such as the zonal shipboard power distribution architecture studied. The F-FMEA will be shown in a tabular format in the report.

To summarise, the contents of this preliminary report are:

* Introduction to the relevance and need to utilize FMEA as a starting point in this research.
* Example of a fundamental F-FMEA conducted on the MVDC system.
* Potential uses of FMEA data for benefiting future research.

This report explains the F-FMEA process applied to a notional MVDC ship system model already available on the Real-time Digital Simulator (RTDS) at CAPS. The relevant outputs are highlighted along with future directions for this particular research. Observing the merits of beginning at a more superficial F-FMEA are evident, mainly in the fact that the current research is centered around modeled representative systems with more generic than specific hardware information. F-FMEA is a logical start to understanding system and subsystem level risks and studying ways to mitigate their effects with accurate diagnostics.

Even though an F-FMEA is relatively less exhaustive than an H-FMEA, its outcomes form the driving force behind further research and eventually aid H-FMEA by narrowing down critical sections and devices. This in turn aids focusing and informing further research. While applying FMEA to a relatively detailed point design such as the notional MVDC ship system model represented on the RTDS explored and demonstrated the approach it will be of particular importance to incorporate FMEA into the ESRDC’s early stage design environment S3D as soon as possible.

The relevance of failure mode and effects analysis (FMEA) for this research

The aim of this research is to thoroughly understand the risks associated with a particular point design of a notional integrated SPS utilizing the MVDC zonal power distribution architecture. The anticipated use of large number of power electronic equipment onboard poses a challenge to de-risk the system owing to the fact that it is a relatively new and unproven technology for naval applications. The lack of benchmark systems further emphasizes the need to understand risks and study methods to mitigate their effects. The notional MVDC zonal architecture modeled on the RTDS at the Center for Advanced Power Systems (CAPS), Florida State University (FSU) is shown in Figure 1.

The model consists of a two zone system (Figure 1. shows more than two zones to illustrate a network with more number of segregations) with 4 primary power sources. The power is fed to longitudinal busses on the port and starboard sides with an option to connect them together to form a ring. A number or DC breakers are lined along the busses and form part of the protection system. More details on the modeled system’s constituents can be seen in Table 1 and Table 2. Figure 2 shows the zonal loads modeled on the RTDS. Each zone is fed by two dc-dc step-down converters (buck converters) which draw power from the main dc-busses on either side. The zones have AC loads which are fed via an AC-DC inverter.

In an effort to understand causes and effects of risks associated with the novel SPS architecture, FMEA is the most logical starting point. FMEA is an established reliability analysis process aimed at studying ways in which failure occurs in a system. A thorough FMEA provides a database of known failures, their known causes, effects and in the process can aid in assessing the severity of each thereby identifying the most pertinent disturbances. An FMEA could be used at any stage during system development and is an appropriate starting point to assess risks in a novel system with limited prior understanding regarding fault manifestations. It makes FMEA ideal to be used for the notional SPS architecture.

Previous research using this approach has been published in [1] with further applications of reliability analysis techniques explained in [2]. In both these papers, a robust research methodology beginning at FMEA is explained. FMEA helps outline pertinent issues, in turn helping focus further research into identifying and diagnosing disturbances. This methodology not only helps enhance the risk assessment process for the novel SPS, but also channels efforts into effective fault diagnostics capabilities.

## Two sub-parts of a detailed FMEA

FMEA as a detailed process can be divided into two parts of differing levels of technicality. These two parts are F-FMEA and H-FMEA and are elaborated in [3]. The fundamental differences between F-FMEA and H-FMEA are described in this section.

### Functional FMEA

This type focuses on the functions that a system, process, or service is to perform rather than on the characteristics of the specific implementation. When developing a functional FMEA, a functional block diagram is used to identify the top-level failure modes for each functional block on the diagram. For example, a heater’s two potential failure modes would be: “Heater fails to heat” and “Heater always heats”. Another example of a functional FMEA would consider that a capacitor is intended to regulate voltage and then analyze the effects of the capacitor failing to regulate voltage. It would not analyze what would occur if the capacitor fails because of an open-circuit or shorted-circuit. As FMEAs are best begun during the conceptual design phase, long before specific hardware information is available, the functional approach is generally the most practical and feasible method by which to begin a FMEA, especially for large, complex systems that are more easily understood by function than by the details of their operation. When systems are very complex, the analysis for functional FMEAs generally begins at the highest system level and uses a top-down approach.

### Hardware FMEA

This type examines the characteristics of a specific implementation to ensure that the design complies with requirements for failures that can cause loss of end-item function, single-point failures, and fault detection and isolation. Once individual items of a system (piece-parts, software routines, or process steps) are identified in the later design and development phases, component FMEAs can assess the causes and effects of failure modes on the lowest-level system items. H-FMEA is also referred to as piece-part FMEAs, and are more common than F-FMEAs since usually in a system, the individual components are well known and altogether novel components as such are rare. H-FMEAs generally begin at the lowest piece-part level and use a bottom-up approach to check design verification, compliance, and validation.

For complex systems, a combination of (a) and (b) may be required which constitutes a “Detailed FMEA”. In the case of the novel SPS, the combination of F-FMEA and H-FMEA is necessary as it is a system still in the conceptual phase, without the presence of any hardware based benchmarks. Figure 4. illustrates the difference in scope between F-FMEA and H-FMEA showing that both together constitute a detailed FMEA. Also, FMEA is iterative in nature, needing regular exchange of and updating of data on failure causes and effects. This is shown by bi-directional arrows in both F-FMEA and H-FMEA in Figure 3.

F-FMEA applied on the notional zonal SPS provides information on critical sections and devices in the network. This output in turn guides the more intensive H-FMEA to focus on such critical devices for fault studies. Outputs of H-FMEA in turn narrow down vital components whose faults and failures may lead to disturbances in the sub-system or system that could be termed as catastrophic (or highly severe). This progressive filtering provides a list of pertinent faults on which further studies could be centered. The next logical progress would be into testing known diagnostic methods to differentiate faults or develop novel techniques. Another outcome could be the development of prognostics techniques to help predict failure times in order to prevent major faults if possible.

F-FMEA is a logical start to understanding subsystem and system level risks and studying ways to mitigate their effects with accurate diagnostics. Even though an F-FMEA is relatively less exhaustive than an H-FMEA, its outcomes form the driving force behind further research and eventually aid H-FMEA by narrowing down critical sections and devices. This aids in focusing and informing further research.

## F-FMEA process

F-FMEA is a relatively superficial analysis compared to the more detailed Hardware FMEA (H-FMEA). F-FMEA considers the fundamental capability of the system under scrutiny to perform its function. An inability to do its regular or required “job” is deemed a functional failure.

Such functional failures however could vary in severity which can be assessed during the analysis process. H-FMEA on the other hand considers individual component-level faults and failures for which detailed information on parts of a device that in turn make up a device/system are needed. Such level of detail can get cumbersome and exhaustive; hence F-FMEA forms a reasonable starting point to the study the novel SPS architecture from view of risk assessment.

Before breaking down a system to perform a failure analysis, it is useful to list out various sub-parts and constituents in a tabular format and highlight the function of each.

### F-FMEA applied to the overall MVDC zonal SPS architecture

Figure 1 shows the representative system. Two zones are modeled on the RTDS for analysis. The system can be segregated into progressively smaller parts on which F-FMEA can be conducted. Table 1 shows various subsections that the overall system can be broken down into, listing their respective functions and constituents.

Table 1: Subsections of the architecture with their constituents and functions

The subsections in turn can be segregated into constituent devices. The list of devices, their type and function is shown in table-2.

Table 2: List of devices in subsections and their respective functions

|  |  |  |  |
| --- | --- | --- | --- |
| **Device name** | **Special abbreviations** | **Type** | **Function** |
| Main turbine generator |  MTG1  | Primary power source | Provide continuous power at the specified rating and quality. |
| Main turbine generator |  MTG2  | Primary power source | Provide continuous power at the specified rating and quality. |
| Auxiliary turbine generator |  ATG1  | Primary power source | In case main generators fail, then to provide continuous power at specified rating and quality. Provide continuous power in case general power demand increases. |
| Auxiliary turbine generator |  ATG2  | Primary power source | In case main generators fail, then to provide continuous power at specified rating and quality. Provide continuous power in case general power demand increases. |
| AC-DC rectifier |  ACDC\_P\_MTG1  | PEC | Convert AC power from generator side input to DC power at output fed into the DC bus at specified rating and quality |
| AC-DC rectifier |  ACDC\_S\_MTG2  | PEC | Convert AC power from generator side input to DC power at output fed into the DC bus at specified rating and quality |
| AC-DC rectifier |  ACDC\_P\_ATG1  | PEC | Convert AC power from generator side input to DC power at output fed into the DC bus at specified rating and quality |
| AC-DC rectifier |  ACDC\_S\_ATG2  | PEC | Convert AC power from generator side input to DC power at output fed into the DC bus at specified rating and quality |
| DC-DC converter |  DCDC\_P\_ES  | PEC | Convert DC power from bus at input to DC power at specified values. Provide rated DC power in a continuous manner to zonal loads and other vital loads. |
| DC-DC converter |  DCDC\_S\_PL  | PEC | Convert DC power from bus at input to DC power at specified values. Provide rated DC power in a continuous manner to zonal loads and other vital loads. |
| DC-DC converter |  DCDC\_P\_RAD  | PEC | Convert DC power from bus at input to DC power at specified values. Provide rated DC power in a continuous manner to zonal loads and other vital loads. |
| DC-DC converter |  DCDC\_S\_RAD  | PEC | Convert DC power from bus at input to DC power at specified values. Provide rated DC power in a continuous manner to zonal loads and other vital loads. |
| DC-DC buck converter |  DCDC\_P\_Z1  | PEC | Convert DC power from bus at input to DC power at specified values. Provide rated DC power in a continuous manner to zonal loads and other vital loads. |
| DC-DC buck converter |  DCDC\_S\_Z1  | PEC | Convert DC power from bus at input to DC power at specified values. Provide rated DC power in a continuous manner to zonal loads and other vital loads. |
| DC-DC buck converter |  DCDC\_P\_Z2  | PEC | Convert DC power from bus at input to DC power at specified values. Provide rated DC power in a continuous manner to zonal loads and other vital loads. |
| DC-DC buck converter |  DCDC\_S\_Z2  | PEC | Convert DC power from bus at input to DC power at specified values. Provide rated DC power in a continuous manner to zonal loads and other vital loads. |
| DC-AC inverter |  DCAC\_P  | PEC | Invert DC to AC at required rating. Supply continuous power to AC motors. |
| DC-AC inverter |  DCAC\_S  | PEC | Invert DC to AC at required rating. Supply continuous power to AC motors. |
| DC-AC inverter |  DCAC\_Z1  | PEC | Invert DC to AC at required rating. Supply continuous power to AC loads. |
| DC-AC inverter |  DCAC\_Z2  | PEC | Invert DC to AC at required rating. Supply continuous power to AC loads. |
| High power radar |  RAD  | Load | To perform tasks related to navigation and tracking. |
| Capacitor banks |  ES  | Secondary power source | To act as back-up for providing additional power. |
| High power pulsed load |  PL  | Load | To provide high power weapons capability under special circumstances and mission-modes. |
| Propulsion motor |  PM\_S  | Load | Propel the vessel at required speed and in the required direction as needed. |
| Propulsion motor |  PM\_P  | Load | Propel the vessel at required speed and in the required direction as needed. |
| Zonal DC lumped load |  DCLL\_Z1  | Load | General ship loads. |
| Zonal DC lumped load |  DCLL\_Z2  | Load | General ship loads. |
| Zonal AC lumped load |  ACLL\_Z1  | Load | General ship loads. |
| Zonal AC lumped load |  ACLL\_Z2  | Load | General ship loads. |

Table 3 to Table 9 show F-FMEA for the various subsections of the overall systems considered.

Table 3: Energy storage F-FMEA

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| **Energy storage subsection** |
| **Function:** | To enable efficient charging of ES such that it can be operated and utilised as desired. |
| **Constituents:** |  DCDC\_P\_ES, ES |
| **No.** | **Constituent devices (general)** | **Quantity** | **Type** |
| 1 | DCDC | 1 | Power delivery device (specific PEC) |
| 2 | ES | 1 | Secondary power source |
| **No.** | **Failure mode** | **Cause** | **Effect** | **Severity and remarks** |
| 1 | Faulty or inadequate charging of ES. | Faulty power output from DCDC device due to internal fault. | Cannot charge and operate ES as desired. | Medium – The ES is generally for back-up during highly specific scenarios whose occurrence could be relatively rarer than general mission-modes. |
| Faulty power output from ACDC devices due to internal fault. |
| Faulty power output from primary power source(s) due to internal fault. |
| Power quality issues in DC busses due to cabling fault. |
| Internal fault in ES device. |
| 2 | No charging of ES. | No power output from DCDC device due to internal failure. | Cannot operate ES as desired. | High – This failure mode may be traced back to serious issues as stated in the causes unless the ES itself has a failure in it. |
| No power output from ACDC devices due to internal failure. |
| No power output from primary power source(s) due to internal failure. |
| No power flow in DC busses due to cabling failure or burnout. |
| Internal failure in ES device. |

Table 4: Radar F-FMEA

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| **Radar subsection** |
| **Function:** | To provide continuous power to RAD enabling it to be operated within acceptable parameters. |
| **Constituents:** |  DCDC\_P\_RAD, DCDC\_S\_RAD, RAD |
| **No.** | **Constituent devices (general)** | **Quantity** | **Type** |
| 1 | DCDC | 2 | Power delivery device (specific PEC) |
| 2 | RAD | 1 | Load |
| **No.** | **Failure mode** | **Cause** | **Effect** | **Severity and remarks** |
| 1 | Faulty or inadequate operation of RAD. | Faulty power output from DCDC device due to internal fault. | Cannot operate RAD as desired. | High – RAD is a vital load and must be in available at all times. |
| Faulty power output from ACDC devices due to internal fault. |
| Faulty power output from primary power source(s) due to internal fault. |
| Power quality issues in DC busses due to cabling fault. |
| Internal fault in RAD device. |
| 2 | No operatin of RAD. | No power output from DCDC device due to internal failure. | Cannot operate RAD at all. | High – RAD is a vital load and must be in available at all times. |
| No power output from ACDC devices due to internal failure. |
| No power output from primary power source(s) due to internal failure. |
| No power flow in DC busses due to cabling failure or burnout. |
| Internal failure in RAD device. |

Table 5: Propulsion motors F-FMEA

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| **Propulsion motors subsection** |
| **Function:** | To provide required power to propulsion motors to enable their acceptable operation as desired. |
| **Constituents:** |  DCAC\_S, DCAC\_P, PM\_S, PM\_P |
| **No.** | **Constituent devices (general)** | **Quantity** | **Type** |
| 1 | DCAC | 2 | Power delivery device (specific PEC) |
| 2 | PM | 2 | Load |
| **No.** | **Failure mode** | **Cause** | **Effect** | **Severity and remarks** |
| 1 | Faulty or inadequate operation of PM. | Faulty power output from DCAC device due to internal fault. | Cannot operate PM as desired. | High – PM is a vital load and must be in available at all times. |
| Faulty power output from ACDC devices due to internal fault. |
| Faulty power output from primary power source(s) due to internal fault. |
| Power quality issues in DC busses due to cabling fault. |
| Internal fault in PM device. |
| 2 | No operatin of PM. | No power output from DCAC device due to internal failure. | Cannot operate PM at all. | High – PM is a vital load and must be in available at all times. |
| No power output from ACDC devices due to internal failure. |
| No power output from primary power source(s) due to internal failure. |
| No power flow in DC busses due to cabling failure or burnout. |
| Internal failure in PM device. |

Table 6: Pulsed load F-FMEA

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| **Pulsed load subsection** |
| **Function:** | To provide desired power enabling charging of the pulsed load allowing it to be used as desired. |
| **Constituents:** |  DCDC\_S\_PL, PL |
| **No.** | **Constituent devices (general)** | **Quantity** | **Type** |
| 1 | DCDC | 1 | Power delivery device (specific PEC) |
| 2 | PL | 1 | Load |
| **No.** | **Failure mode** | **Cause** | **Effect** | **Severity and remarks** |
| 1 |

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| Faulty or inadequate operation of PL. |
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 | Faulty power output from DCDC device due to internal fault. | Cannot operate PL as desired. | Medium – Though PL is a vital load, it's availability is required less frequently across mission-modes. |
| Faulty power output from ACDC devices due to internal fault. |
| Faulty power output from primary power source(s) due to internal fault. |
| Power quality issues in DC busses due to cabling fault. |
| Internal fault in PL device. |
| Internal fault in charging circuit. |
| 2 | No operation of PL. | No power output from DCDC device due to internal failure. | Cannot operate PL at all. | High – This failure mode may indicate more serious issues towards power generation side. |
| No power output from ACDC devices due to internal failure. |
| No power output from primary power source(s) due to internal failure. |
| No power flow in DC busses due to cabling failure or burnout. |
| Internal failure in PL device. |
| Internal failure in charging circuit. |

Table 7: Zone 1 and 2 F-FMEA

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| **Zones 1 and 2** |
| **Function:** | To provide continuous power to DCLL and ACLL. |
| **Constituents:** |  DCDC\_S\_Z1, DCDC\_S\_Z2, DCDC\_P\_Z1, DCDC\_P\_Z2, DCLL\_Z1, DCLL\_Z2, DCAC\_Z1, DCAC\_Z2, ACLL\_Z1, ACLL\_Z2 |
| **No.** | **Constituent devices (general)** | **Quantity** | **Type** |
| 1 | DCDC | 4 | Power delivery device (specific PEC) |
| 2 | DCAC | 2 | Power delivery device (specific PEC) |
| 3 | DCLL | 2 | Load |
| 4 | ACLL | 2 | Load |
| **No.** | **Failure mode** | **Cause** | **Effect** | **Severity and remarks** |
| 1 | Faulty or inadequate power input to DCLL. | Faulty power output from at least one DCDC device. | Cannot operate DCLL as desired and may affect achieving mission objective. | Medium – Depending on every mission, the priority of loads may vary, making it vital to be able to operate the DCLLs which are needed at the time. Further, faults in the PEC (in this case DCDC) of zones may cause disturbances in the DC bus leading to issues for other zones owing to factors such as switching harmonics and current surges. |
| Power quality issues in DC busses. |
| Internal fault with DCDC device. |
| Faulty power output from ACDC devices. |
| Faulty power output from primary power source(s). |
| Internal fault in DCLL. |
| 2 | No power input to DCLL | No power output from at least one DCDC device. | Possible system-wide power outage and inability to operate DCLL in turn hampering mission goal(s). | High – This failure mode may point towards system-wide disturbances apart from the obvious hindrance in achieving the mission goal in case a particular DCLL is off-line. |
| No power flow in DC busses. |
| Internal fault with DCDC device. |
| No power output from ACDC devices. |
| No power output from primary power source(s). |
| Internal failure in DCLL. |
| 3 | Faulty or inadequate power input to ACLL. | Faulty power output from at least one DCDC device. | Cannot operate ACLL and may affect achieving mission objective. | High – Similar reasoning to case-1. Further, faults in the PEC (in this case DC-AC converter device) of zones may cause disturbances within its zone (propagation of fault to busses and in turn other zones is evaded owing to isolation provided by the DCDC devices) owing to factors such as switching harmonics because of the added DC-AC inversion. |
| Power quality issues in DC busses. |
| Internal fault with DCDC device. |
| Faulty power output from ACDC devices. |
| Faulty power output from primary power source(s). |
| Faulty power output from DCAC device. |
| Internal fault in ACLL. |
| 4 | No power input to ACLL | No power output from at least one DCDC device. | Cannot operate ACLL and very likely that entire zone is without power. | High – Similar reasoning to case-2 with respect to inability of being able to operate ACLL for a particular mission. |
| No power flow in DC busses. |
| Internal fault with DCDC devices. |
| No power output from ACDC devices. |
| No power output from primary power source(s). |
| No power output from DCAC device. |
| Internal failure in ACLL. |

Table 8: DC power ring F-FMEA

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| **DC ring subsection** |
| **Function:** | To provide continuous power at required rating and quality to DC busses. |
| **Constituents:** |  MTG1, MTG2, ATG1, ATG2, ACDC\_P\_MTG1, ACDC\_S\_MTG2, ACDC\_P\_ATG1, ACDC\_S\_ATG2, DCD |
| **No.** | **Constituent devices (general)** | **Quantity** | **Type** |
| 1 | MTG | 2 | Primary power source |
| 2 | ATG | 2 | Primary power source |
| 3 | ACDC | 4 | Power delivery device (specific PEC) |
| **No.** | **Failure mode** | **Cause** | **Effect** | **Severity and remarks** |
| 1 | Faulty or inadequate input to DC bus. | Faulty power output from ACDC device due to internal fault. | Faulty and degraded quality power flow in DC busses. | High – System wide issue which would have impacts on all devices and loads. |
| Faulty power output from primary power source(s) due to internal fault. |
| Power quality issues in DC busses due to cabling fault. |
| Internal fault in DC bus. |
| 2 | No power input to DC bus. | No power output from ACDC devices due to internal failure. | System wide power outage. | High – System wide issue which would have impacts on all devices and loads making it unable to fulfill mission goal(s). |
| No power output from primary power source(s) due to internal failure. |
| No power flow in DC busses due to cabling failure or burnout. |

Table 9: DC busses F-FMEA

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| **DC busses subsection** |
| **Function:** | To provide continuous DC power flow to connected parts. |
| **Constituents:** |  ACDC\_P\_MTG1, ACDC\_P\_ATG1, ACDC\_S\_MTG2, ACDC\_S\_ATG2, DCDC\_P\_ES, DCDC\_P\_RAD, DCDC\_S\_RAD, DCDC\_S\_PL, DCDC\_S\_Z1, DCDC\_S\_Z2, DCDC\_P\_Z2, DCDC\_S\_Z2, DCAC\_P, DCAC\_S, DCBUS  |
| **No.** | **Constituent devices (general)** | **Quantity** | **Type** |
| 1 | ACDC | 4 | Power delivery device (specific PEC) |
| 2 | DCDC | 8 | Power delivery device (specific PEC) |
| 3 | DCAC | 2 | Power delivery device (specific PEC) |
| **No.** | **Failure mode** | **Cause** | **Effect** | **Severity and remarks** |
| 1 | Faulty power flow. | Faulty power output from ACDC device due to internal fault. | Unable for zone to fulfil its function. | High – An assessment is needed to determine whether the fault is limited to a zone or has origins nearer the generation side. |
| Faulty power output from primary power source(s) due to internal fault. |
| Power quality issues in DC busses due to cabling fault. |
| Faulty power output from zonal DCDC due to internal fault. |
| 2 | No power flow. | No power output from ACDC devices due to internal failure. | System wide power outage. | High – System wide issue which would have impacts on all devices and loads making it unable to fulfil mission goal(s). |
| No power output from zonal DCDC due to internal failure. |
| No power output from primary power source(s) due to internal failure. |
| No power flow in DC busses due to cabling failure or burnout. |

# Application of F-FMEA data for further research

F-FMEA helps identify various disturbances that could occur in the system by analyzing known failures, their causes and effects. This helps understand dependencies of parts of the system on each other from the risk assessment point of view. The information is used for considering techniques to diagnose the disturbances that could occur. These techniques need to be intelligent to provide accurate diagnosis of faults and failures with decision support to onboard crew.

## Automating F-FMEA for different modes of the SPS

The F-FMEA Table 1through Table 9 show a generalized outcome with standard connectivity information, where the particular mode of the naval vessel is not considered. It is understood that the SPS will have varying network configuration to cater to different scenarios. During these modes, the connectivity between devices and subsystems will vary, leading to differences between dependencies that would eventually change the cause-effect deductions of a general F-FMEA.

Such information about network connections during each operational mode, if utilized for an automated computation of F-FMEA, could provide real-time information about known risks, causes and effects. Knowing mode-specific F-FMEA information can further be utilized for aiding the AI based diagnosis performed by the FACS as well as decision support during different scenarios. An example of different operational modes of the ship is;

1. Ring battle mode (RBM) shown in Figure 4(a)
2. Split –plant battle mode (SPBM) shown in Figure 4(b)

In the RBM, a bus connection at either end makes a continuous path between all generators (power sources). This ensures redundancy in the supply for vital subsections such as radar, pulsed power load, propulsion motors etc.

The SPBM as the name suggests, divides the power network. In this case, an equal division is made and each of the two busses (starboard and port) receives the same amount of power from connected power sources. The vital loads on either bus can be fed only through their respective sources. The zonal loads however in both modes mentioned, receive supply from either bus, as seen from the connectivity diagram in Figure 4.

In both modes, there are fundamental differences to the network architecture, yet there are some commonalities. These variations change the nature of dependencies that determine functional failure cause-effect relations in turn modifying the F-FMEA data. Each new mode means the F-FMEA information needs to be appropriately altered. While this can be done for a finite number of modes using a relatively small number of devices and subsections (like on the RTDS model with 2 zones), it becomes a cumbersome task to produce F-FMEA tables for a real ship system with its full complement of subsections, devices and over 6 zones typically. In such a case, it may be prudent to study ways in automating F-FMEA at a more fundamental level such that network connectivity information could be optimally utilized to produce a real-time F-FMEA.

### Multi agent systems technology research

The use of a decentralized multi-agent system (MAS) for reconfiguring the shipboard power architecture is reported in [4]. The agents are developed in MATLAB while the system is simulated on a virtual test bed. MATLAB-SIMULINK is extensively used to simulate power systems in part or whole using the various toolboxes available within the software. The use of MATLAB to build agents as presented in this paper makes this software in general promising to be utilized for analyzing and experimenting within this research field.

Feliachi et al propose a distributed scheme with MAS based control agents in [5]. This is to aid the notion of automated reconfiguration and self-healing in the event of battle damage and other fault scenarios. With a system utilizing agents, the crucial aspect is the information fed into individual software agents and its accuracy. Here, the authors aim to implement a graph theoretic self-stabilizing maximum flow algorithm as the agents’ strategy to ensure efficient power management which would include considering constraints and load priorities.

A MAS with two layers (shown in Figure 5) for power system reconfiguration is proposed by Cartes et al in [6]. One layer is the power system layer with a network of devices and the other layer is the one with software agents. Every device has its agent with whom information can be exchanged. The communication constraints on every agent are placed such that information exchange is possible only with a neighboring agent. This paper is one of the first to introduce a layered MAS where the electrical devices in the hardware layer is mapped onto its respective agent in the MAS software layer. Simulations are carried out by the authors using a RTDS model. Cartes et al systematically propose a structured methodology making use of state-of-the-art technology to provide a potentially promising intelligent system that may be adopted for the SPS not only for reconfiguration (as suggested in [6]) but for other tasks such as condition monitoring, fault diagnosis and perhaps prognosis as well.

A SPS power system restoration scheme using a MAS is proposed by Momoh in [7]. The rationale given by the author to use a MAS is its decentralized network and local data processing capability which greatly reduce the computation time and network bandwidth. Another advantage is the ease of scalability in case newer loads/devices are added to the network and the subsequent ease of extensibility to carry out required tasks.

Figure 5 – Each device mapped onto an agent in supervisory control architecture [6]

Cartes and Srivastava et al have published research related to use of MAS for onboard modes of the ship [6, 9 – 10]. The work outlines how a MAS can be deployed and configured to handle a mesh-structured topology [6] as well as a ring topology [9, 10]. A general overview of agents being used in large numbers for supervisory control, such that each device is represented by its own agent is presented in [6, 11].

The idea of using agents which hold operational and functional information of the device it is mapped onto, for supervisory control decisions, could be exploited further for the purpose of a real-time F-FMEA. This process taps into a wealth of known information of fault/failure cause-effect relationships and in a real-time manner computes dependencies based on given network topology. Such real-time updating could potentially also aid the diagnosis system by providing it up-to-date information on the network’s connections. Also, the F-FMEA information could come in handy for explaining briefly the cause and effect of a diagnosed fault/failure.

Agent based technology could be harnessed for a real-time F-FMEA during different modes of the ship. Research listed in the previous paragraphs mention advantages of a MAS being mainly;

* Extensibility to add modules
* Flexibility to cater to different scenarios
* Effective use of information

These three benefits could be utilized in an information rich supervisory control environment tapping data from FMEA documentation. The mode of a ship is a standard baseline for connected devices and subsections, but during a mission, it is possible some of these constituents become unavailable because of various reasons. In such an event, a real-time F-FMEA would need to be performed that comprises the existing connected parts. This incorporates the extensibility and flexibility features of using agents. Further research into language processing capabilities (highlighted in section 3.2 onwards) may potentially solidify the choice of using MAS.

## Natural language processing (NLP)

NLP forms an important wing of AI with rigorous research prevalent in mainly user-interaction based systems employing text and/or speech and their combinations. Statistical data mining and analysis methods are used to process large volumes of linguistic data in documents to find meaningful means of reproducing the information for human use. A popular technique to pre-process large volumes of data from a corpus to derive meaningful links between words is latent semantic analysis (LSA).

LSA could be employed on F-FMEA data as a corpus, to build a system capable of answering fundamental queries. This can potentially form the primary part of a decision support system which aids onboard crew to react during various situations. The F-FMEA documentation contains precise information on failure/fault cause and effects, which makes it a resourceful corpus to run LSA on.

The same LSA process that is used to streamline F-FMEA data is used on queries put forth by crew. This ensures consistency between the word-processing analyses such that a basic level of accuracy is always achieved. Modifications to conventional LSA could then be experimented with to seek improvements to accuracy of the decision support capability.

This report demonstrates use of conventional LSA on the F-FMEA generated corpus. The results of streamlining the data are shown. A sample of general queries that could be asked by onboard crew is then tested to check if the system answers them correctly. This NLP based system for decision support arising out of information derived from F-FMEA is a novel approach in the field of SPS fault management. Combined with automated control decisions based on measured quantities of the power network, the overall intelligent system could potentially have a very high accuracy not only to diagnose faults but also to provide credible decision support.

### LSA applied to extract useful information from the F-FMEA database

The first step to conduct LSA is to use a set of stop words (SW). These are words that are used commonly in communication and as such can be omitted from the corpus. An example of SW are words like “the, a, is, it, and, or” etc. There exists a list of common SW used extensively for LSA involving news reports on the web. At the moment, as a primary threshold, this common list of SW is used to perform the first step of LSA on the given data. However, it may be useful and could enhance accuracy if a dedicated list of SW is created for specific applications such as SPS in this case.

The initial experiments are carried out to test whether basic and general questions about the system’s state are answered.

These questions are in text form and using NLP processes, the appropriate answer is found from the F-FMEA documentation. Rather than just answering a simplistic “Yes” or “No”, using F-FMEA documentation, a more detailed explanation or description to a question could be obtained. The question is processed as per LSA guidelines and the remaining keywords form the basis for searching the F-FMEA corpus.

Owing to the highly specific nature of the corpus in this case, it may be needed to adopt a slightly different or novel approach using LSA to process data in order to derive the required information. This possibility needs to be explored in detail to ensure accuracy of decision support. A proposed approach to begin experimental studies on an F-FMEA informed automated decision support system is shown here. The approach is illustrated in Figure 6.

Figure 6- Proposed approach using FMEA information with NLP and AI-based diagnostics for decision risk mitigation and decision support.

Figure 6 shows a proposed approach utilizing information from the onboard intelligent diagnostics and supervisory control system. Combined with information from FMEA databases, one can enhance the diagnostic capability by adding descriptive elements to it by utilizing NLP. This may not necessarily improve diagnostic accuracy, but is anticipated to aid in decision support for the onboard crew by enabling word-queries to be answered satisfactorily.

The following process steps describe the working of an NLP based decision support system deriving information from both the diagnostic engine and FMEA corpus.

1. Initial fault diagnosis – This action is performed by the onboard diagnosis system most probably utilizing a sophisticated AI based methodology. Information from this system is combined with the already existing FMEA database.
2. NLP process runs – The combined information from the previous steps is passed through the selected NLP processes which analyze the input, to produce a relevant output.
3. Response to user query – In case onboard crew requires information about the current state of operation, the system harnesses the NLP engine’s output to respond to this query. A sophisticated NLP capability is able to analyze the question asked and produce a relevant and correct answer.
4. Decision support – The ability of the onboard supervisory system to utilize data from the diagnosis system, combine it with FMEA database and be processed by the NLP system, bode well for providing enhanced decision support to onboard personnel.

# Discussion and Conclusions

This report showed the importance and rationale behind starting off with F-FMEA for understanding risks within the notional MVDC SPS. A generalized F-FMEA was demonstrated through the standard tabular format taking into account functional attributes at the subs-system and system levels. This activity helps understand fundamental risks associated with the network from a basic functionality point of view without dwelling on the specifics of hardware related data. From this stage on, the next research could be in the more detailed H-FMEA which derives severity and criticality information from the aforementioned F-FMEA. This however is a matter for further research especially when there is more clarity on the type and nature of hardware devices used. It would also make it imperative in future research to set up hardware test beds for conducting failure analysis to enhance understanding gained from RTDS models. By doing this, research done through simulations can be backed up using actual experimental data.

It was discussed that a useful application would be the capability to perform an automated F-FMEA that feeds off the prevalent network topology data per mission. This ability could supply information to the diagnostic engine to enhance its accuracy. Further, an automated F-FMEA could aid in the decision making process as it contains information of well known causes and effects of faults/failures.

A detailed FMEA database with an NLP capability onboard the SPS could provide the following advantages to the overall fault accommodating control syste

1. Enhance fault diagnosis – A fault accommodating system is anticipated to have a robust diagnostic engine, capable of providing accurate fault detection and identification. This action has sufficient information regarding the particular subsection/device/component that has caused the disturbance. A feasible remedial action is expected to be taken by the automated control system. In addition, a detailed description could be provided tapping the FMEA database to enhance understanding of the failure for the onboard crew.
2. Improve decision support – Specific information regarding failure modes, causes and effects contained in the FMEA database(s) could be accessed to enhance the process of decision making and taking remedial action when necessary manually. Combined with the ability to perform an automated real-time F-FMEA, the system remains up to date with network topologies and dependencies, thereby having the potential to improve upon aiding onboard crew to assess the scenario in event of a disturbance.

Current research focuses on developing techniques for performing an automated F-FMEA given a topology information and general F-FMEA information. Future research could be centered on developing NLP based algorithms to automate information retrieval at a user-query from the F-FMEA database shown. This part of the work is guided by the methodology shown in Figure 6, wherein the NLP components will be used to combine effectively with diagnostic components of the system.

Finally, we conclude that incorporating FMEA functionality into an early stage naval vessel design tool such as the Smart Ship System Design (S3D) environment developed at University of South Carolina, is an important next step to consider. It is envisioned that utilizing failure and risk data obtained from a thorough FMEA would prove to be vital in providing a systematic methodology based off established techniques which yield system reliability metrics.

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