TASK 2.6
SYSTEMS ENGINEERING BASED GUIDELINES AND RULES FOR DESIGNING A 100 MW/20 KV E-SHIP INCORPORATED INTO S3D

Year One – Deliverable(s)

Submitted to:
The Office of Naval Research

Contract: N00014-14-1-0198

Submitted by:
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1 Task Description

Building upon IEEE 1709 this task will develop a set of guidelines which can be used by design teams to systematically work through the design space of an electrical ship system. This task focuses on the electrical system design. In particular, a set of interface specifications for all major components of the 100 MW target system will be developed. Furthermore, these guidelines and rules will be integrated into the S3D environment to enable S3D to apply design rules based on system engineering principles to facilitate more automated design evaluations.

2 Year One Deliverables

- A basic system design rule base and FMEA framework ready to be implemented into S3D.

3 Appendix of Reports Submitted

A. Technical Report: Systems Engineering Based Guidelines and Rules for Designing a 100MW/20kV E-Ship incorporated into S3D

APPENDIX A

SYSTEMS ENGINEERING BASED GUIDELINES AND RULES FOR DESIGNING A 100MW/20KV E-SHIP INCORPORATED INTO S3D

Technical Report

Submitted to:
The Office of Naval Research

Contract: N00014-14-1-0198

Submitted by:
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December 2014

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Abbreviations used

CAPS	Center for Advanced Power Systems
CONOPS	Concept of Operations
ESRDC	Electric Ship Research and Development Consortium
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
FSU	Florida State University
FTA	Fault tree analysis
FY	Fiscal year
IEEE	Institute of Electrical and Electronics Engineers
MIL	Military
MVDC	Medium Voltage DC
MW	Mega Watt
NLP	Natural Language Processing
S3D	Smart Ships Systems Design
Std. or STD	Standard
tf-idf	Term Frequency Inverse Document Frequency
USC	University of South Carolina

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1 DEFINING ELECTRIC SHIP DESIGN RULES

1.1 Introduction

This report describes the on-going effort to define a process for developing a multi-level, rule-based design specification for naval ship electrical systems that can be implemented in the smart ship system design (S3D) enviroment. A generalized process for designing electric warships proposed by Doerry [1] consists of the following steps:

1. Analyze requirements,
2. Allocate requirements to mission systems,
3. Develop initial Concept of Operations (CONOPS),
4. Assign mission systems to ship zones,
5. Develop derived requirements for ship systems,
6. Develop distributed system architectures,
7. Calculate distributed system component ratings,
8. Synthesize the ship,
9. Evaluate total ship mission effectiveness, and
10. Iterate until total ship mission effectiveness requirements are met.

The principal focus of the study performed under this project was to provide the ship architect with information and tools for completing steps 1 and 5 for the design of the baseline MVDC ship electrical system. The section that follows describes the process of defining the "rules-base" for this ship system. This report details the preliminary work for extracting ship design guidelines and rules from well-known resources. Furthermore, the guidelines and rules extracted through this task will be integrated into the S3D environment to enable applying well-established engineering principles to the automation of design evaluation.

Figure 1 shows an envisioned ship design and analysis capability centered about S3D. The crucial aspect is the necessity of evaluating the user's designs, which could be accomplished by linking the environment to external specialized tools. This is anticipated to enable various types of individual analyses pertaining to the different systems and subsystem of an entire vessel. In Figure 1, the green boxes indicate existing functionalities within S3D available currently and being developed further. The specialized tools box is deliberately shown in a dotted-green border indicating a possible future application which adds an external functionality of linking S3D with well-known analysis tools. Further, the necessary data to be transported to an external tool as well as internally to the S3D databases is provided by the S3D "manager" or designer/user. At the current development stage, basic functionalities such as electrical power balancing is available within S3D.

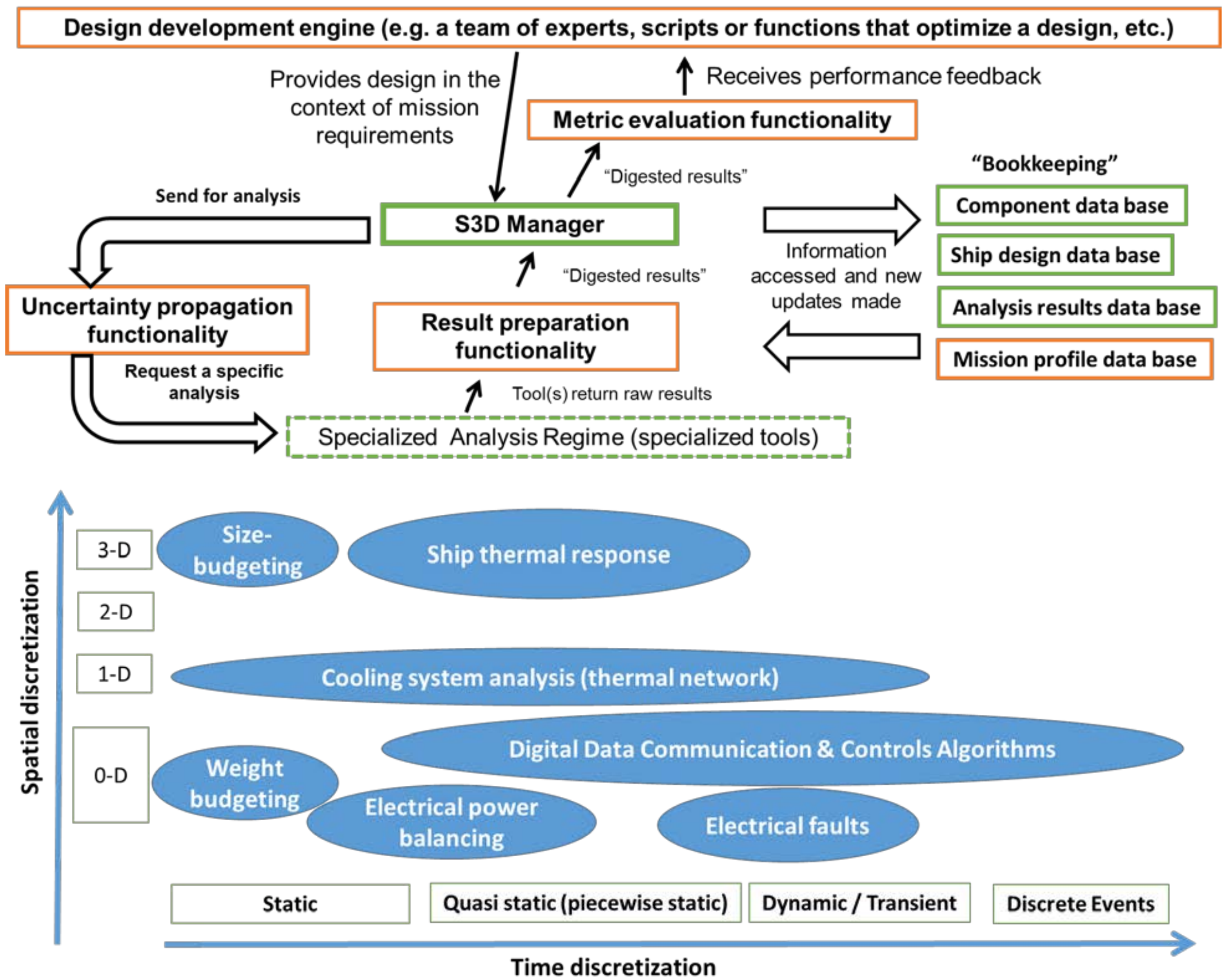

Figure 1 Complete design-analysis capability by linking S3D with specialized tools

The major body of this report lies in sections 1 to 3. Section 4 is an overall summary of work done and near term goals for FY2015. Appendix-A provides a detailed example of the natural language processing (NLP) based tools used to assist with this work and Appendix-B demonstrates the use of NLP results to extract design related information for selected devices.

1.2 The electric ship design process

Figure 2, displays the classical system engineering process. It illustrates a highly iterative design process in which a set of "direct-", or operational/strategic requirements for a desired system design, i.e. the "System Need", spawn additional "derived" requirements as they undergo functional allocation analysis, and design synthesis operations. Taken together, these direct- and derived requirements form the engineering rules-base for the intended system design.

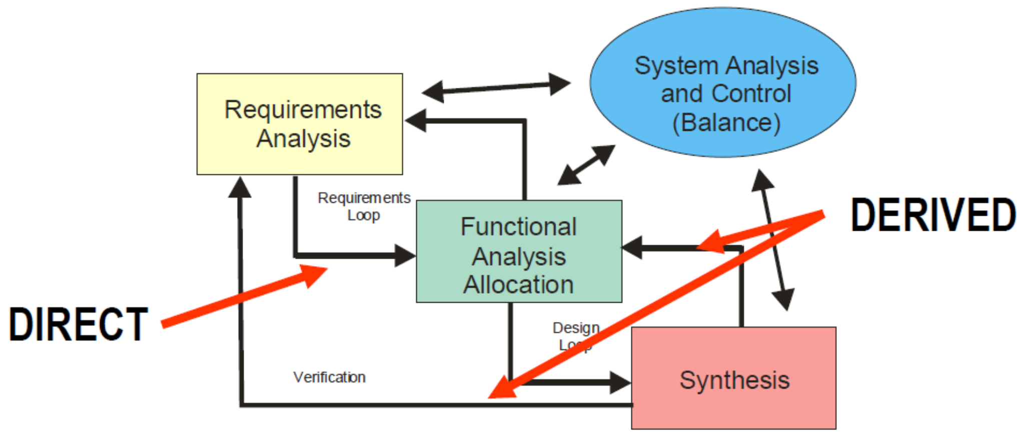

Figure 2 The Classical System Engineering Process [3]

Step 8 of the design process yields a synthesized ship design with only limited consideration given to the interdependencies between the designs of the electrical-, thermal-, and mechanical systems. S3D provides a capability for evaluating total ship mission effectiveness (step 9) when all three of these ship systems are considered together in the same system simulation. Planned enhancements to S3D will give it the capability to perform these assessments over the entire duration of a mission, with pre-programmed changes in the designs of the electrical, thermal, and mechanical ship systems capable of being made at the start of sequential portions of a mission, i.e. Mission Segments. This will enable the final step of the design process (step 10) to be performed as well.

1.3 Direct- and derived requirements for shipboard MVDC power systems

The direct- (i.e. operational/strategic) requirements for the performance of a shipboard MVDC power system are defined by performing a requirements analysis of the intended ship system (Figure 2). This involves searching pertinent Navy/IEEE policies, practices, customs, statutes, standards, specifications, handbooks, and engineering guideline documents for definitive declarations of the operational/mission-related capabilities the electric power system must demonstrate. Linkages between power system capabilities and tasks that a naval vessel must perform during specific missions are highlighted.

As part of a Universal Navy Task List (UNTL) [2], the US Navy publishes a list of tasks essential to the accomplishment of missions, i.e. the Mission Essential Task List (METL). The UNTL is a comprehensive hierarchical listing of the tasks that can be performed by a naval force. It describes the variables in the environment that can affect a ship system's performance with respect to a given task, and provides measures of performance (i.e. metrics) that can be applied by a commander to establish a standard, and its associated criterion of expected performance.

The functional analysis allocation operation in the classical system engineering process (Figure 2) allocates specific design requirements to mission components that fulfill specific functions in the overall process of providing electric power to the ship's loads. The direct-requirements for any new ship design are determined during Requirements Analysis. This operation involves careful review of all potentially applicable IEEE/Military ship power system design standards, guidelines, and handbooks to identify all technical design requirements/rules associated with the set of operational- and strategic tasks that define the performance requirements of any new ship design effort.

Analyzing a ship power system design on the basis of the *functions* it must perform in order to satisfy all direct requirements, is one method of identifying the functionally-related, derived requirements of the system design. The process involves conducting a top-down, functional decomposition of the power system. Doerry illustrates the methodology employed by performing a functional decomposition of a MVDC integrated power system (IPS). The principal function of this power system is to, *"Safely generate, transport, and deliver electrical power of the proper quality and continuity needed by the served loads."* [4].

A list of common sub-level, functions that must be performed in order for the IPS to perform its principal function includes the following:

1. Power Management – Normal Conditions,
2. Power Management – Quality of Service,
3. Power Management – Survivability,
4. System Stability,
5. Fault Response,
6. Power Quality,
7. Maintenance Support, and
8. System Grounding.

The following are some of the system requirements/design rules derived from the definition of these functions:

1. *Under normal operating conditions, the IPS shall be capable of being configured such that:
    a) All loads receive sufficient electrical power,
    b) Sufficient rolling reserve is provided to supply load steps due to pulse loads, large motors starting and large radars changing modes of operation (e.g. cruise to battle),
    c) Balance between the average power generated and consumed/dissipated is maintained. (e.g. total power generated = total power consumed + total power dissipated as heat),
    d) Dedicated energy storage can be used to level load spikes,
    e) Expected system dynamics do not cause any of the energy storage mechanisms to either "overfill" (i.e. attempt to store more energy than its rated storage capacity), or "run dry" (i.e. attempt to output more energy than is available based on its current state-of-charge).
    f) The use of energy disposal is minimized,
    g) Generators operating in parallel share load power without requiring dedicated communication lines,
    h) System stability is maintained during system disturbances,
    i) During the initial five minutes following an imbalance between electrical power generated and power consumed and dissipated, the IPS shall be capable of ensuring that the Quality of Service (QOS) standards [5] for all loads are maintained.

2. *Under conditions where the power system cannot serve all loads, due to either battle damage or equipment failure, the IPS shall

a) Exhibit a proper survivability response, e.g. appropriate loads are shed in the order of their mission priority,
b) Determine the health of loads and power system equipment,
c) Restore power to shed loads if sufficient capacity and connectivity is present, and the load is safe to re-energize,
d) Isolate unsafe loads,
e) Achieve optimal reconfiguration following a system disturbance.

3. *IPS power management controls shall ensure that
   a) Stable system operation is maintained in the presence of negative incremental resistance on the DC bus,
   b) Generator speed is not directly observable on the DC bus,
   c) The kinetic energy of each prime mover neither drops so low as to cause prime mover stall/shutdown, or output voltage collapse, nor rises so high as to trigger a prime mover over-speed induced shutdown or failure.

1.4 Requirements and rules search using NLP

For the ship designer, the difficult task of identifying the sets of direct- and derived requirements for a desired ship design described in Section 1.3 is tedious at best. In order to make it easier, a natural language processing (NLP) tool was developed and used during the literature search phase of the work. NLP algorithms are capable of performing exhaustive searches of IEEE/MIL standards and handbooks for rules-related terminology.

Two examples are described in this section of using NLP to identify component-level design rules that have the potential of impacting the design of the ship electric power plant at the system-level (e.g. power transformer design in [6] and motor design in [7]). The design equations for both components are analyzed and shown to generate new (i.e. derived) requirements for inclusion in Step 5 of the ship design process. A detailed description of the actual NLP-based tools used in the study is provided in Appendix A.

As mentioned in the proposed approach of investigating IEEE-Std. and MIL-handbooks, natural language processing (NLP) based ideas were used in the initial stages. NLP is an exhaustively researched wing of artificial intelligence mainly dealing with creating "intelligent" human-machine interfaces focusing on increasing the levels of automation related to computational tasks. In this case, NLP principles were used to heavily reduce the man-hours that would have gone into investigating technical resources.

Table 1 shows a summarized snapshot of NLP results for the various IEEE standards and MIL handbooks accessed for this research. Important features underpinning the advantage of using an NLP inclusive approach could be listed as follows:

- **General effort reduction:** As can be seen in Table 1, some source texts have as low as 20 pages, while the largest is IEEE Std.1100 with 603 pages. Directly corresponding to page counts is the number of words. Utilizing NLP enables the identification of keywords which reduces the workload of reading by anything between 13-200 times.
- **Pinpoint information:** In addition to reducing workload, another vital aspect of using NLP is the ranking of pages based on their importance. This in turn is based off the term

frequency inverse document frequency $(tf - idf)$ metric which produces the most relevant pages the researcher can readily turn to.

- **Generic search for mathematical equations:** Another important part is the search for standard equations, limits and tolerances used in industry. This is facilitated by the common search terms across all sources shown in Table 1. The nature of these common terms selected could help readily identify standard representations for engineering tolerances/limits and formulae.

SOURCE NAME	TOTAL PAGES	TOTAL WORDS (T)	NLP OUTPUT: Keywords (K)	TOP 10 pages (as per tf-idf metric)	Reduction factor (T/K)
IEEE STD.45.2-2011	91	36986	1294	70,71,72,73,74,75,76,81,82,83	28
IEEE STD.45.7-2012	34	11542	633	24,25,26,28,29,30,31,32,33,34	18
IEEE STD.45	273	118569	2282	213,216,223,224,225,228,229,231,233,249	51
IEEE STD.142	225	73870	1918	110,112,113,114,166,191,200,201,208,210	38
IEEE STD.1100	603	254689	3859	371,377,386,387,392,398,401,403,408,456	65
IEEE STD.1313.1	22	6979	507	5,14,15,16,17,18,19,20,21,22	13
IEEE STD.1313.2	65	24194	821	25,36,38,48,50,54,58,59,61,62	29
IEEE STD.1580	104	24582	762	51,52,53,54,55,56,57,58,59,103	32
IEEE STD.1584	20	7027	526	5,12,13,14,15,16,17,18,19,20	13
IEEE STD.1597.1	41	16722	937	30,33,34,35,36,37,38,39,40,41	17
IEEE STD.1597.2	124	42950	1618	95,96,97,98,99,100,101,102,103,104	26
IEEE STD.1628	59	21971	967	42,43,45,46,47,48,49,52,53,54	22
IEEE STD.1662	72	23862	1137	44,50,51,52,57,59,61,62,65,72	20
IEEE STD.1676	47	12724	674	31,32,33,34,35,36,37,38,40,46	18
IEEE STD.1709	54	20571	1041	36,37,38,39,40,41,42,48,51,53	19
IEEE STD.1826-2012	46	13812	642	33,34,35,36,37,38,39,40,43,45	21
IEEE STD.C.37.100	96	32597	1561	77,79,80,81,82,83,84,85,89,95	20
IEEE STD.C.57.18.10	68	22911	746	53,57,58,61,62,63,64,65,66,67	30
IEEE STD.C.57.91-2011	120	44151	1458	84,85,86,87,88,89,90,108,110,113	30
MIL 1025-10	180	47260	236	3,4,7,12,18,19,23,24,26,30	200
MIL 1399-390	47	21651	253	3,9,10,11,12,13,14,15,16,18	85
MIL 1399-680	31	8674	333	17,18,19,20,21,22,23,24,25,26	26
Common terms searched across all sources	< , > , % , + , ± , ac , dc , acdc , dcdc , dcac , acac , ac-dc , dc-dc , dc-ac , ac-ac				

Table 1 NLP statistics for sources of reference considered

Two examples are shown where NLP was used to extract design rules from IEEE and MIL standards. Appendix-A shows detailed codes used for applying NLP and data mining tools and the results obtained relevant to the context of examples of the transformer and motor. Appendix-B utilizes information from Appendix-A to demonstrate setting up a design evaluation methodology using well established equations. The active use of equations while designing is encouraging to include fault tree analysis (FTA) during the early design as it relies on tested failure probability values which could be directly applied. This line of thought is reflected in Table 17 of Appendix-B in the "Design recommendation" row, where the estimated time-to-failure dictates suggestions to the designer. Figure 3 shows the tie-up between using NLP and failure analyses (FMEA, FTA) to ultimately produce design evaluations. The overall aim is a set of robust design guidelines that help evaluate the ship design as a whole and particularly for the electrical system.

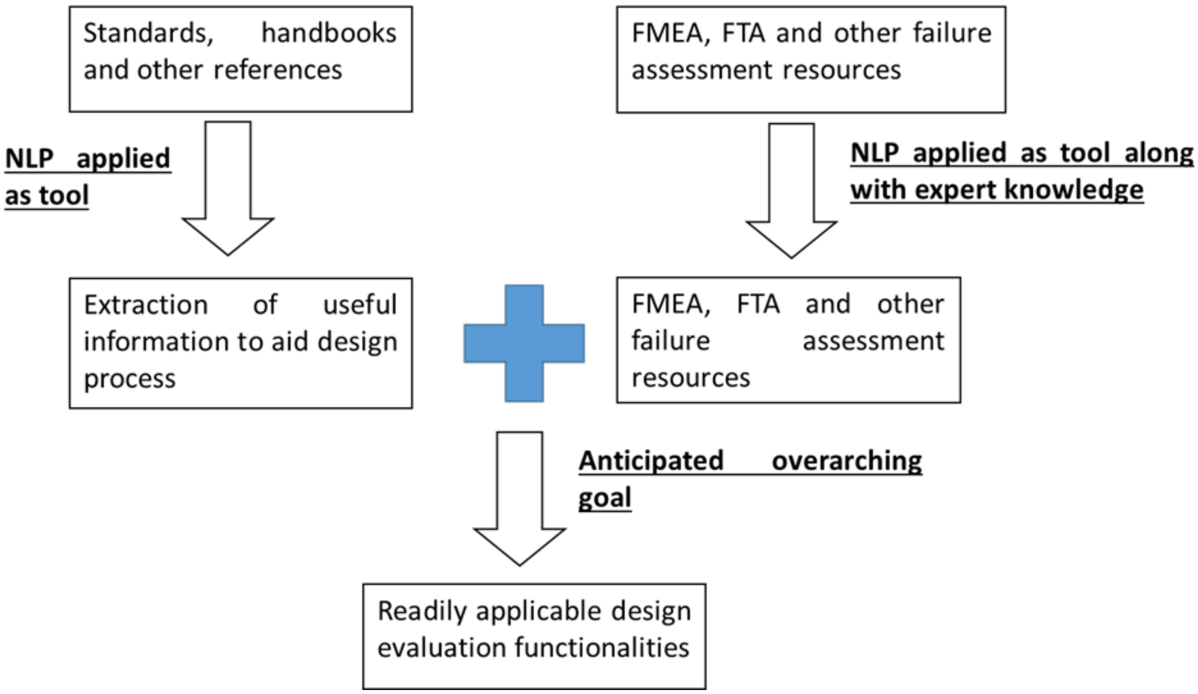

Figure 3 Combination of NLP and failure analysis to yield design related functionalities

1.5 Review of data mining tools used to narrow search

The following standard NLP practices were used for this task:

1. **Latent semantic analysis** – Stop word removal was performed to obtain only the most important words. Stemming was not performed in this case is normal because the main goal here is not from the point of view of automatic grading or building a search engine. The ultimate step is wherein the expert assesses the outcome and selects relevant equations that can be applied as design stage rules (at initial, intermediate and advanced design levels).
2. **Logarithmic weighting** – The words obtained from the previous step were weight using a logarithmic scale called term frequency inverse document frequency ($tf - idf$) which further helped identify the most vital keywords and which page they appear on.
3. **Page ranking** – Based on the frequency of most important words from the previous stage, pages were ranked and the complete document presented to experts, who would then assess these important pages to obtain information.

There were two major benefits of using the mentioned NLP steps:

- **Reduction in time spent** – The other way of investigating standards for design rules would be to read every page. NLP provided pages with information such as equations, practices, tables, tolerances and similar useful information which reduced the time spent per standard significantly. An average estimate was that a 150 page standard would take close to 2 hours (in one sitting) to be well assessed, but with NLP that time was reduced to 30min as only the most relevant page numbers were highlighted to which the expert directly referred to.

- **Further application** – This NLP based technique to extract design rules is being iteratively improved upon such that it could be made more sophisticated. Potentially, it could be used by the designer in real-time to check whether his/her design meets engineering recommendations by "drag-and-drop" of the relevant standard in the NLP tool.

The design example shown through in Appendix-B for assessing transformer life and motor failure, use the following individual aspects which have been integrated to produce the final design recommendation:

- **Referring experts to standards** – IEEE Std.1709 [8] formed the base from which other relevant resources were investigated.
- **NLP to highlight important pages of standards** – Once a set of IEEE standards was obtained, NLP techniques mentioned earlier were used to further focus on the most important parts.
- **Extracting design rules** – Information obtained in the form of equations, tolerances and operational limits were utilized.
- **Deriving design recommendations** – After using design rules, based on results obtained and iteratively referring back to standards for operational limits, recommendations were made as shown in Table 17 and Table 19.

2 SYSTEM-LEVEL DESIGN GUIDELINES

The crux of S3D as an environment is the ability of designers across different domains to simultaneously access and assess each other's analyses. This touches the well-known engineering realm of concurrent engineering. Set-based design (SBD) falls into such a category with a specific application to large team-based complex design spaces [9]. The similarities between SBD and the envisioned S3D functionalities could be summarized as follows:

- Large number of design alternatives are considered by exploring the design space.
- Separate teams of specialists (designers) are able to evaluate outputs and provide preferences and solutions on their own perspectives.
- Intersection between sets are used to establish feasibility before an optimal solution is finalized.
- Fidelity of analysis is increased as the design progresses.

Figure 4 shows the SBD design stages involving a concurrent approach from an initial "separate solution" stage to a final "optimal solution" stage.

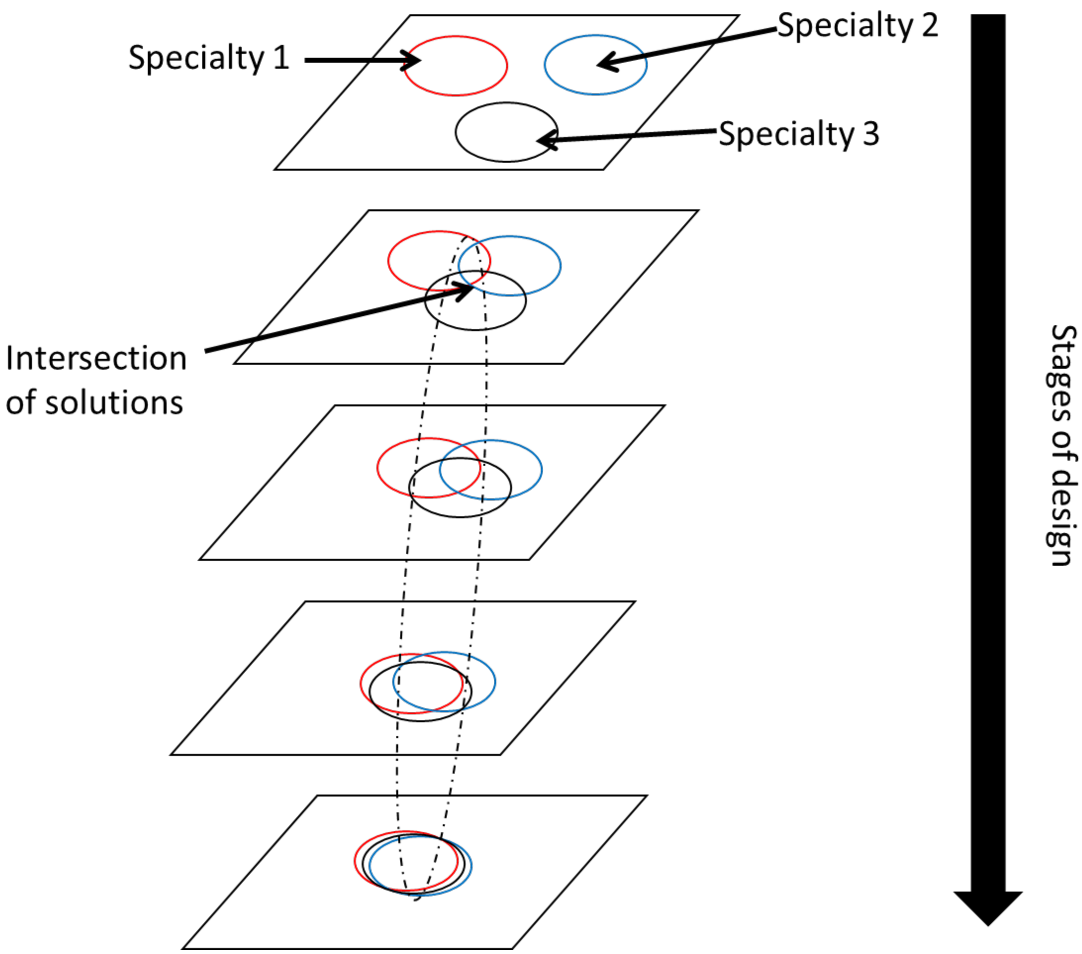

Figure 4 SBD design stages culminating in final solution [9]

Such an SBD based approach was used for the first time in a ship design and acquisition program for the US Navy under the ship to shore connector program in 2007. [9] elaborates in detail about using such an SBD approach for ship design with perceived issues and probable solutions.

This section discusses the methodology used to form design guidelines at the system-level. Owing to the fundamental difference between making a system and sub-system level decision laying in user-choices and iterative calculations respectively, the same NLP-led data-intensive technique may not be the appropriate choice at this stage. It might be argued that a simplistic yes/no choice could also be made for sub-system/devices, but eventually, the choice needs to be evaluated using mathematical understanding i.e. design rules/equations. This paradigm does not strictly apply to merely choosing a mission type, or hull type or the range etc. as these choices are high-level decisions which progressively lead the user/designer to specific sub-systems and eventually individual devices and components. Figure 5 shows a simplistic view of system level design aspects.

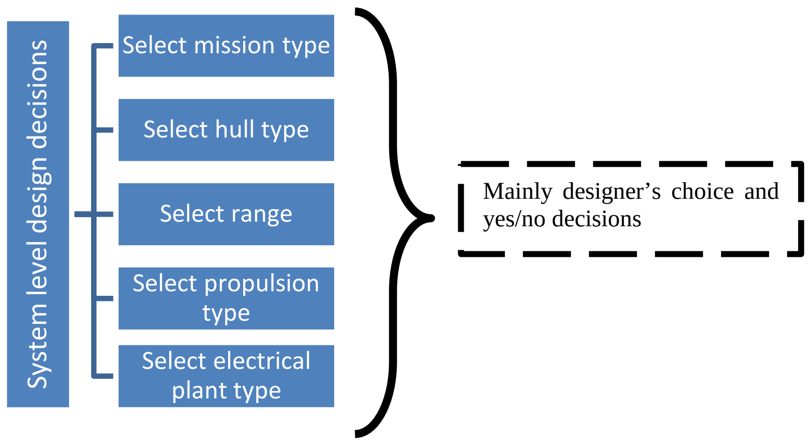

Figure 5 System-level design aspects

Figure 6 shows the entire design space for a generic ship with numbered stages and arrows showing movement of data and information.

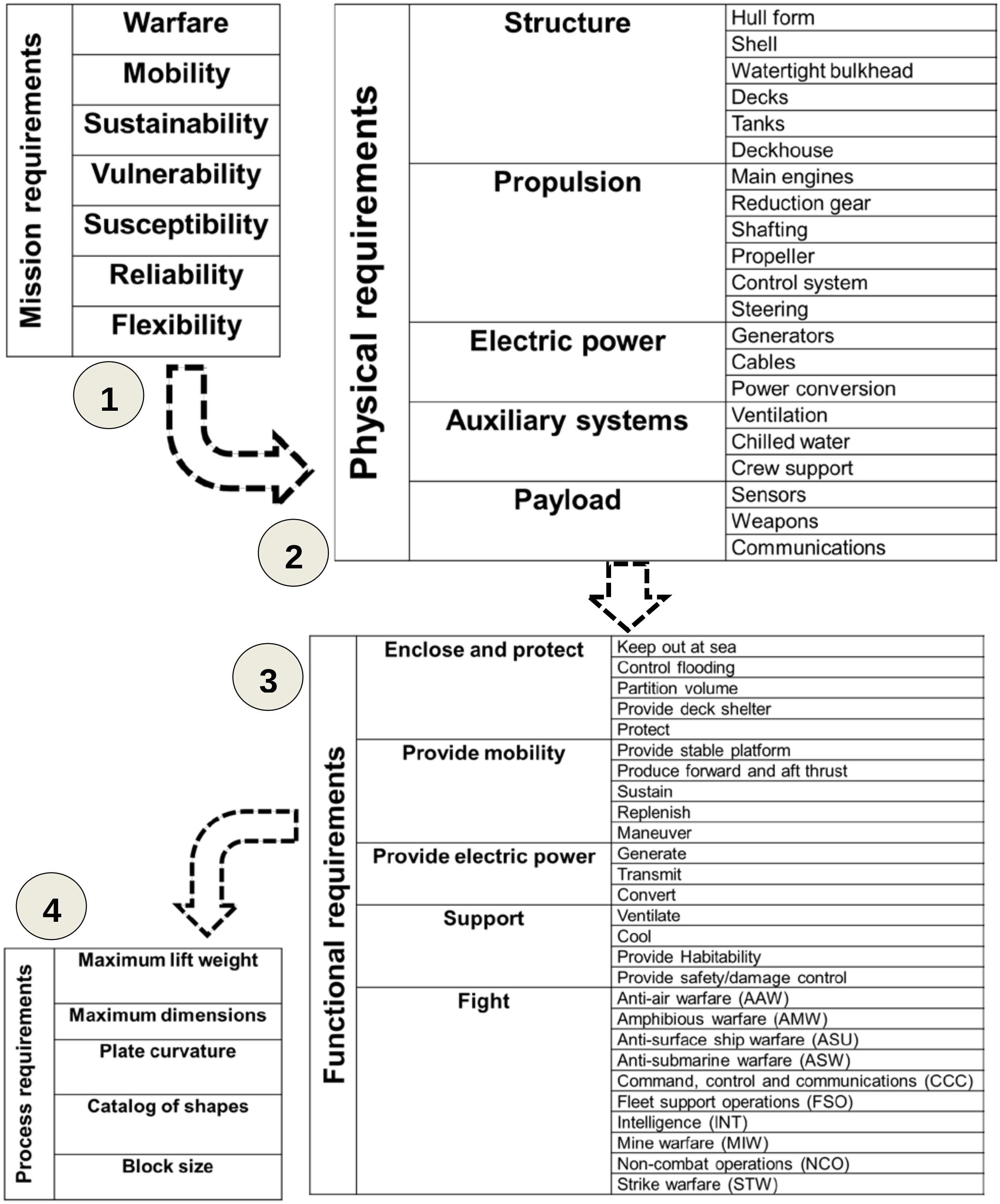

Figure 6 Overall design space with delineated categories

At the given phase of this task, the focus is primarily on the electrical system and other major dependents such as vital loads, propulsion and hotel loads. To simplify the thought process of generating rules and guidelines to be coded for a system-level design and decision-making process, one might pay attention to the procedure used for naval systems engineering.

2.1 Naval systems engineering concepts

Doerry [10] elaborates on the various engineering-standards (IEEE) and Military (MIL) handbooks relevant to electric ship design efforts. At an advanced stage of this research, it is perceived that several other engineering resources would be utilized to extract design evaluation guidelines. However, at this early stage, work needs to be focused to understand naval ship design methodologies (at system, subsystem, device and component levels), so that the best suited approaches could be proposed for building design evaluation rule bases in completeness. The generic thought process to make design decisions at the system-level can be divided into three major categories [10]:

1. **Tasks** – Actions or processes performed as part of an operation. It describes a discrete activity visible outside the command but does not define who or how the activity is accomplished.
2. **Conditions** – Variables of the environment that affect the performance of tasks in the context of the assigned mission. This includes the physical environment, military environment and civil environment. Figure 7 shows the various examples of conditions.
3. **Standards** – These provide the means to express the degree to which the ship must perform a task under a specific set of conditions for a specific mission. This differs from a typical measure of performance (MOP) type metric in that a Standard is an input to the design while an MOP is an output from the design i.e. what the design is capable of doing.
    a. Measures – These provide the dimension, capacity and quantity description. These provide the basis for describing varying levels of task performance and are therefore directly related to a task.
    b. Criterion – This defines the acceptable level of performance often expressed in terms of a quantifiable minimum.

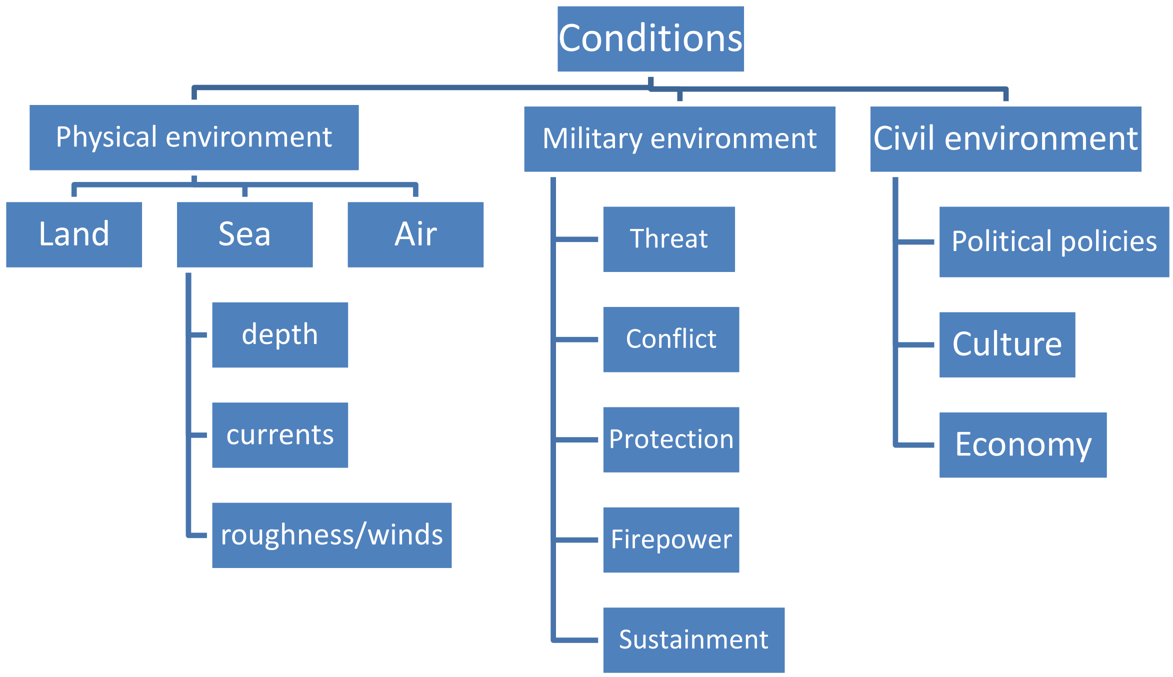

Figure 7 Types of conditions [11]

The idea is to borrow from the well-established naval systems engineering paradigm and adapt the system-level decision making process to adhere to it. An example of applying this paradigm to the specification of design requirements for an MVDC ship power system is given in Figure 8 where a top level matching of tasks, conditions and standards is undertaken. Figure 8 is not a detailed overview of an entire ship design process involving various subsystems, but is an attempt to adhere to the generic thought processes recommended in [10] and overlaying the electrical plant design on it. Moreover, Figure 8 also comments on resources utilized in this research such as IEEE standards and MIL handbooks, thereby showing a degree of correlation.

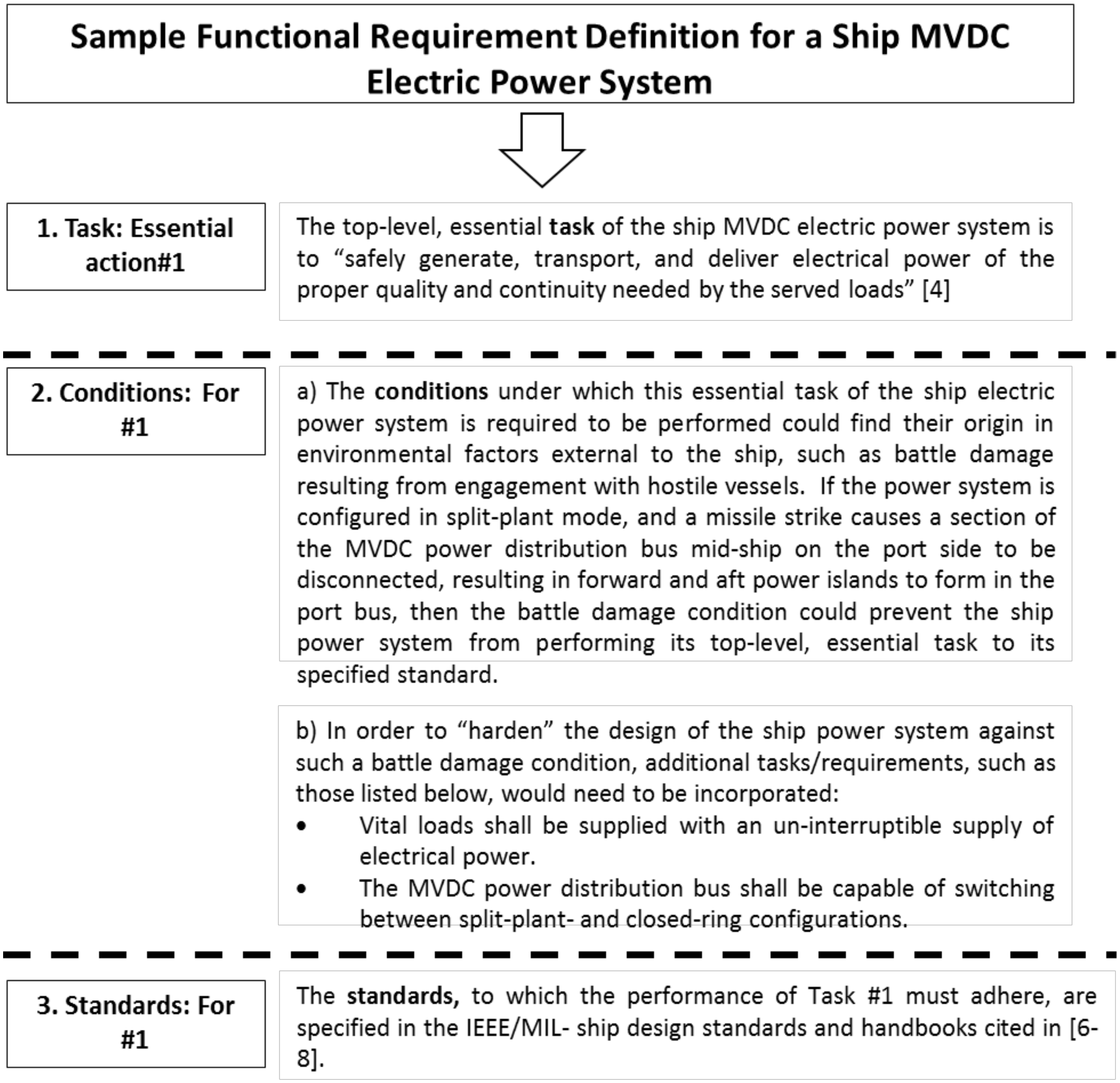

Figure 8 Sample requirement definition for a MVDC shipboard power system

2.2 Proposed approach to generate system-level design guidelines

The definition of "tasks" and the functional requirements of Figure 6 are similar in nature in the sense that both deal with "actions to be performed". Also, the first broad category of Figure 6 is "mission requirements". With this in mind, the first rule proposed is to select a mission type from Table 2.

1. Select a mission (task)	
Mission type	Standard description
ANTI-AIR WARFARE (AAW)	The detection, tracking, destruction or neutralization of enemy air platforms and airborne weapons, whether launched by the enemy from air, surface, subsurface, or land platforms.
AMPHIBIOUS WARFARE (AMW)	Attacks launched from the sea by naval forces and by landing forces embarked in ships or craft designed to achieve a shore presence in a littoral zone. This includes fire support for troops in contact with enemy forces through the use of close air support or shore bombardment.
ANTI-SURFACE SHIP WARFARE (ASU)	The detection, tracking, and destruction or neutralization of enemy surface combatants and merchant ships.
ANTI-SUBMARINE WARFARE (ASW)	The detection, tracking, and destruction or neutralization of enemy submarines.
COMMAND, CONTROL, AND COMMUNICATIONS (CCC)	Providing communications and related facilities for coordination and control of external organizations or forces, and control of own unit's capabilities.
COMMAND AND CONTROL WARFARE (C2W)	The integrated use of psychological operations (PSYOP), military deception, operations security (OPSEC), electronic warfare (EW), and physical destruction; mutually supported by intelligence, to deny information to, influence, degrade, or destroy adversary C2 capabilities while protecting friendly C2 capabilities against such actions C2W is a subset of IW (below) that specifically attacks and protects the C2 target set. Formerly Electronic Warfare (ELW) and subsequently Space & Electronic Warfare (SEW). Information Warfare (IW). Actions taken to achieve information superiority by affecting adversary information, information-based processes, information systems, and computer-based networks while defending one's own information, information-based processes, information systems, and computer-based networks.
FLEET SUPPORT OPERATIONS (FSO)	Naval forces and designated shore facilities providing supporting services other than logistics replenishment to fleet units.
INTELLIGENCE (INT)	The collection, processing, and evaluation of information to determine location, identification, and capability of hostile forces through the employment of reconnaissance, surveillance, and other means.
MINE WARFARE (MIW)	The use of mines for control/denial of sea or harbor areas, and mine countermeasures over, under, or upon the surface.
MOBILITY (MOB)	The ability of naval forces to maneuver and maintain themselves in all situations over, under, or upon the surface.
NON-COMBATANT OPERATIONS (NCO)	Selected operations of a noncombatant nature not clearly categorized in any other warfare mission area. Included in this category are the necessary support requirements and/or special missions that are required of a unit but not directly related to the other Warfare Mission Areas.
STRIKE WARFARE (STW)	The destruction or neutralization of enemy targets ashore through the use of conventional or nuclear weapons. This includes, but is not limited to, strategic targets, building yards, and operating bases from which the enemy is capable of conducting air, surface, or subsurface operations against U.S. or allied forces.

Table 2 Types of mission and their description [12]

This is followed by using the “standards” definition along with measures and criterion. This in a logical sense could point to choosing the basic dimensions of the vessel as listed in Table 3.

2. Select a measure (standard)	
Length	Varying from 300 feet for destroyers to over 1000 feet for aircraft carriers
Beam	Varying from 30 feet to 134 feet.

Displacement	Tonnage of the vessel.
Speed and range	Up to full flank speed of 32kn and range in 1000s of miles will in turn determine fuel capacity.

Table 3 Types of measures for the vessel

Now, the type of propulsion can be selected from the available choices in Table 4. These tie in with the physical requirements of Figure 6 and standards. The speed-power curve is the usual calculation to estimate the power needs of the ship.

3. Select power and propulsion type	
Nuclear	Typically for aircraft carriers
Electric	Envisioned to be the norm for the future

Table 4 Types of propulsion

Further, the propulsion type then dictates the various other equipment necessary, like rectifiers, transformers, motors, etc. Figure 9 illustrates these steps with the eventual stage of reaching specific equipment.

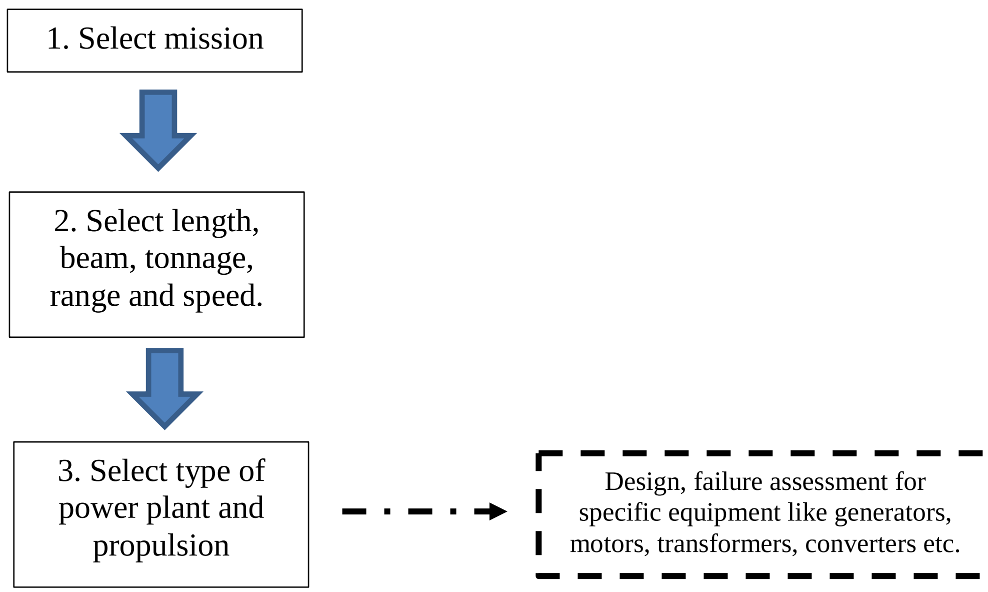

Figure 9 Guidelines for system-level design leading to sub-system level design

Once the user/designer follows the prescribed steps to form a basic outline of the ship design and reaches the stage where individual devices need to be chosen, then the realm of sub-system level design evaluation opens up. This is where, the previous NLP based methodology is helpful in extracting equations to test the chosen equipment for the given:

1. Mission type
2. Physical dimensions of ship
3. Power source and propulsion type

2.3 Risk Assessment and Failure Analysis

The other key aspect of rule-based ship design included in this report is the use of classical failure analysis techniques in order to bring risk assessment functionality into the evaluation of novel ship designs. The rules-based approach to electric ship design outlined in this report is firmly rooted in the necessity to add risk assessment design functionality to the S3D design environment. There is a lack of meticulous studies in the research literature concerning the fundamental principles of fault-related failure modes and risk mitigation methodologies that are inherent in the design of a shipboard electric power system. This observation is highlighted as a major research short-fall in this field.

The logical first step to begin detailed analysis into possible risks associated with novel power system architectures is to perform a reliability analysis of the MVDC ship power system baseline architecture using a well-established risk assessment methodology, such as Failure Mode Effects Analysis (FMEA). In general, FMEA can be used to support maintainability-, testability-, safety- and logistics analyses. When performed in an accurate and timely fashion, FMEA information can be used to:

- Aid in the design of test systems,
- Develop trouble-shooting procedures,
- Plan scheduled maintenance, and
- Develop integrated diagnostic capabilities.

Figure 10 illustrates a proposed approach to enable identification of intermediate and advanced MVDC shipboard power system design rules and recommendations related to the risk assessment of potential design. Subsequently, this forms the input to S3D as a framework of design rules and recommendations with risk assessment functionality. The approach begins with a team of FMEA-experts applying the NLP data-mining techniques described briefly in section-1.7 to the body of IEEE and Military standards and handbooks dealing with relevant information regarding MVDC shipboard power system design. The objective is to extract as much risk-related information as possible that could be termed necessary from a design point of view (i.e. risk-related, system design requirements/rules).

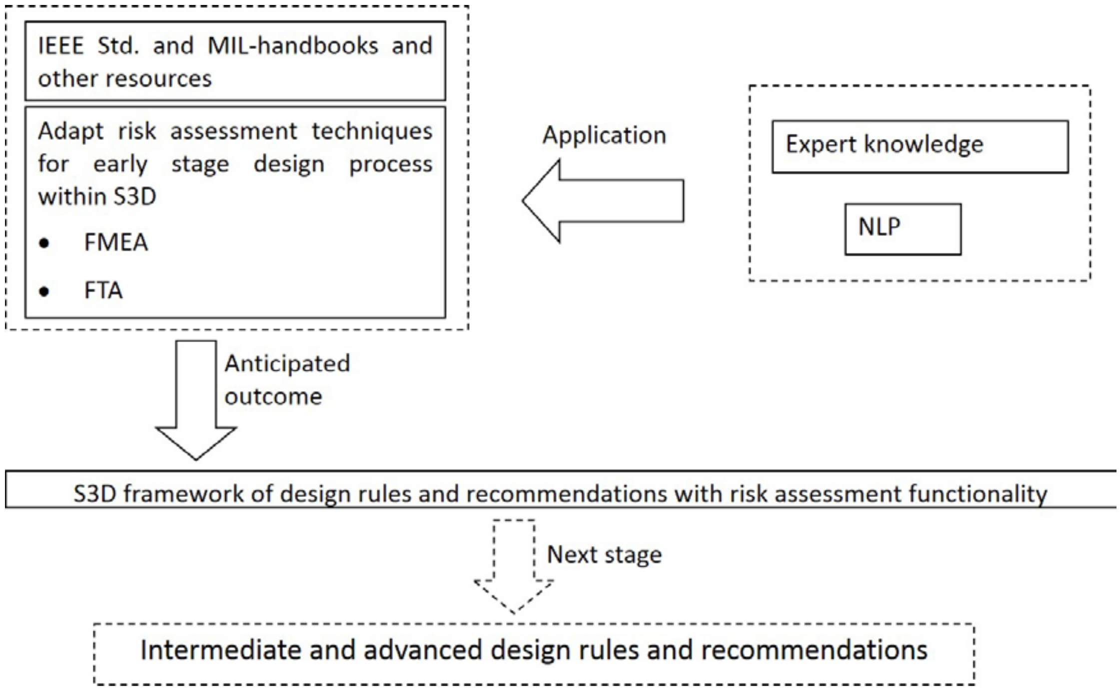

Figure 10 Individual aspects feeding the overall methodology leading to outcomes

An effective FMEA presents an examination of a system's strengths and weaknesses [13] –[16]. These assessments could be done in one of two ways, i.e. via a functional FMEA (F-FMEA) or hardware FMEA (H-FMEA) [17]. As FMEAs are best begun during the conceptual design phase (long before specific hardware information is available), the functional FMEA approach is generally the most practical and feasible method by which to begin. This is especially true for large, complex systems that are more easily understood by function than by the minute details of their operation. When systems are highly complex, the analysis for F-FMEAs generally begins at the highest system level and follows a top-down approach. H-FMEAs typically begin at the lowest piece-part level and use a bottom-up approach. This is done as a means of checking design verification, compliance, and validation.

Fault tree analysis (FTA) is another risk assessment technique in which the probabilities of a fault event are assigned to compute the overall probability of failure. This analysis, though slightly advanced with respect to FMEA, is able to be adapted to function, as part of an early stage ship design process. This is owing to the availability of failure mode probability guidelines in MIL-handbooks. The next section of this report outlines a candidate FTA methodology presenting the initial results achieved.

3 INCORPORATING FMEA ASPECTS INTO DESIGN EVALUATION

The examples elaborated for the transformer and the motor design in Appendix-B clearly show calculations for computing useful life and ageing of vital components. This essentially integrates an FMEA into the design process. For the future, a similar approach needs to be detailed for other electrical equipment types such as cables, converters, vital loads etc. Also, it is a non-trivial pursuit to aim at utilizing FMEA information in a more sophisticated manner to aid the designer using S3D. This section further sheds light on the standard practices within the realm of reliability analysis using an FMEA approach.

3.1 Two constituents of a detailed FMEA

FMEA can be used to support reliability, maintainability, testability, safety and logistics analyses. When performed in an accurate and timely fashion, FMEA information can be used to aid the design of test systems, the development of trouble shooting procedures, the planning of scheduled maintenance, and the development of integrated diagnostics capabilities. The two broad categories of FMEAs separated by their varying levels of detail are functional-FMEA (F-FMEA) and hardware-FMEA (H-FMEA).

For complex systems, a combination of F-FMEA and H-FMEA may be required which constitutes a detailed FMEA. 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 approach by which to begin with. This could be useful especially for large, complex systems that are more easily understood by function than by the details of their operation. Thus it seems logical that the initial stage of failure analysis for a complex system such as the ship's network must commence at the F-FMEA stage.

3.1.1 F-FMEA

F-FMEA focuses on the functions that a product, process, or service is to perform rather than on the characteristics of the specific implementation. For example, a heater's two potential failure modes would be: “Heater fails to heat” and “Heater always heats”. A generalized interpretation of such statements could be “No output” and “Faulty output” respectively. The F-FMEA would not consider the possible internal component(s) faults/failures that may have caused the heater to malfunction. A similar shipboard power system related example could be of a power converter malfunction. The F-FMEA would consider the functional failure modes as “No output” and “Faulty output” rather than taking into account internal component failure modes like capacitor/diode failures.

Figure 11 shows a simplified line diagram of the zonal shipboard power system network to show the two approaches to FMEA. Table 5 shows the respective terms used in Figure 11.

Bus-S	Starboard side bus
Bus-P	Port side bus
Conv-S	Starboard side dc-dc step down (buck) converter
Conv-P	Port side dc-dc step down (buck) converter
Conv	Intra-zonal converter feeding load

Table 5 Terms used in Figure 11

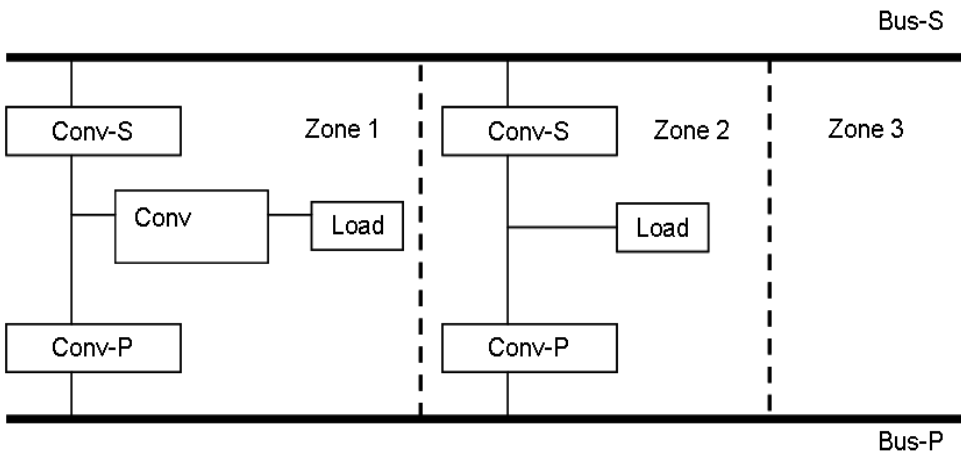

Figure 11 Simple line diagram for zonal shipboard network

F-FMEA at sub-system level		
Function of zone: To provide required voltage and current without interruption to load for desirable operation		
Potential functional failure mode	**Potential functional failure cause**	**Potential functional failure effect**
No power input to load	-No power input in starboard and port busses due to fault/damage to main/auxiliary generators -No power input in starboard and port busses due to distribution module fault/damage -No power input in starboard and port busses due to main converter (that feeds both busses) fault/damage -Fault/damage to both bus converters (Conv-S and Conv-P) resulting in no power output	-Unable to operate load in the zone
Insufficient quality power input to load (or faulty input)	-Insufficient power quality input in starboard and port busses due to fault/damage to main/auxiliary generators -Insufficient power quality input in starboard and port busses due to distribution module fault/damage -Insufficient power quality input in starboard and port busses due to main converter fault/damage -Fault/damage to both bus converters (Conv-S and Conv-P) resulting in poor power quality output	-Possibility of undesirable operation of load -Possible voltage and current fluctuations within zone
Momentary loss of power input	-Power fluctuations due to fault/damage to main/auxiliary generators -Power fluctuations due to fault/damage to distribution module -Power fluctuations in one converter (say port side), thus triggering other converter (starboard side) to supply load. This may cause momentary output voltage dip.	-Momentary input power fluctuation to load -Possible undesirable operation of load due to sudden voltage dip

Table 6 Sub-system level F-FMEA example [17]

F-FMEA at the device level		
Function of starboard converter (dc-dc): To convert dc power from the starboard bus to the desired dc value		
Potential functional failure mode	**Potential functional failure cause**	**Potential functional failure effect**
No output	-No power input in starboard bus due to fault/damage to main/auxiliary generators -No power input in starboard bus due to distribution module fault/damage -No power input in starboard bus due to main converter fault/damage -Internal fault/damage	-No power to load until port side converter supplies load -Momentary input voltage dip to load
Faulty output	-Insufficient power quality input due to fault/damage to main/auxiliary generators -Insufficient power quality input due to distribution module fault/damage -Insufficient power quality input due to main converter fault/damage -Internal fault/damage -Insufficient power quality input	-Insufficient power quality supplied to load -Possible voltage and current fluctuations -May trigger load to be supplied by port side converter due to power fluctuations if voltage dips lower than the port-converter's output voltage

Table 7 Device level F-FMEA example [18]

3.1.2 H-FMEA

H-FMEA examines the characteristics of a specific implementations and components of the entire system. 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. Detailed FMEAs for hardware, commonly referred to as piece-part FMEAs, are probably the most common FMEA applications. They generally begin at the lowest piece-part level and use a bottom-up approach to check design verification, compliance, and validation.

A detailed FMEA is a combination of F-FMEA and H-FMEA. It could be argued that an H-FMEA is extremely detailed. But, in the context of a complex network, an F-FMEA is a logical starting point from where further focus is directed onto the most critical sections/devices in turn leading to a particular device on which to conduct the H-FMEA.

An example of the H-FMEA for the dc-dc buck converter lists the various components and their known failure information in Table 8. Figure 12 shows a standard circuit for a buck converter used as reference for the H-FMEA.

Quantities measured are I_{IN}, I_{OUT}, V_1 *and* V_2

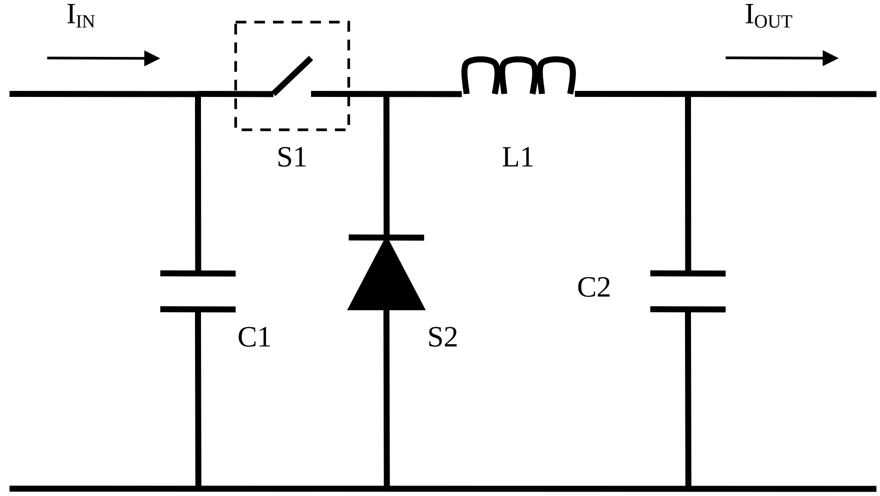

Figure 12 Standard buck converter circuit

Component	Known failure mode
Input capacitor (C1) and output capacitor (C2)	Degrading – Net filter capacitance reduces over time due to leakage
Semiconductor Switch (S1)	1. Short circuit 2. Open circuit
Inductor (L1)	Winding fault - Net inductance was reduces due to short-circuit of windings.
Diode (D1)	1. Short circuit 2. Open circuit

Table 8 Types of failures at component level [19]

Combining the understanding obtained from a superficial F-FMEA and a more specific H-FMEA for the buck converter, a detailed FMEA table could be compiled. Such a detailed FMEA lists component functions and failure causes with effects thus displaying all known theories of what could go wrong, why and its impacts. Such a detailed FMEA for the buck converter is presented in Table 9.

A similarly detailed study could be undertaken for every critical device in the shipboard network. Two examples, shown in Appendix-B, deal with the power transformer and the propulsion motor. Table 10 shows a detailed FMEA (without explicitly listing functions of components for brevity) for the power transformer and Table 11 for the motor.

Standard buck converter detailed FMEA				
Output from F-FMEA	The zonal buck converter is a vital device feeding all loads (vital or non-vital)			
Individual component details	**Function**			
Input capacitor	• High frequency filtering • Energy storage at input side			
Power electronic switch	Switching action to step down voltage			
Freewheeling diode	Provide current path during switch's off state			
Inductor and output side capacitor	• Inductor-capacitor (LC) filter to reduce output ripple • Provide current during switch's off state			
Component	**Known failure mode**	**Known failure cause**	**Failure effect**	
			Immediate	**Eventual**
Input capacitor (C1) and output capacitor (C2)	Chemical/physical/mechanical/thermal: • Degrading • Loose contact	• Leakage over time • Worn contacts • Vibrations	Net filter capacitance reduces over time due to leakage	Loss of filtering and drop in efficiency
Power electronic switch (S1)	Electrical/thermal/mechanical: • Short circuit • Open circuit (most likely)	• Over-voltage/current • Physical shock	No switching action	Converter completely fails
Inductor (L1)	Physical/electrical: • Winding fault	• Leakage over time • Worn contacts • Vibrations	Net inductance reduces due to short-circuit of windings.	Loss of filtering and current path leading to converter failure
Diode (D1)	Electrical/thermal/mechanical: • Short circuit • Open circuit (most likely)	• Leakage over time • Worn contacts • Vibrations	No current path during S1-off state	Converter failure

Table 9 Detailed FMEA for the buck converter [19]

In Table 10, the two shaded rows shed light on the failure mode being excess temperature (thermal). This can be corroborated with the calculations in Table 17 (Appendix-B) where the endeavor to estimate the winding hotspot temperature eventually enables the prediction of useful life of the transformer.

Standard power transformer detailed FMEA				
Component	**Known failure mode**	**Known failure cause**	**Failure effect**	
			Immediate	**Eventual**
Solid insulation	Physical chemistry	Excessive moisture	Reduce the dielectric & mechanical strength of paper	Mechanical damage & fault in insulation
Oil insulation	Physical chemistry	Particle contamination	• Reduce the electrical strength & breakdown voltage Increase the • dielectric loss of oil	Overheating & short circuit in the transformer
Windings	Mechanical/thermal • Open contact • Fused	• Loose clamping • Excess heat build up	Winding deformation	High through current faults, high inrush currents, protective relay tripping
Tank	Chemical/physical	Insufficient maintenance	Corrosion	Leakage
Bushings	Physical chemistry	Lack of maintenance	• External contamination, • Discharge current on the external surface of insulation	Short circuit, personnel safety
Core	Thermal	Frame to earth circulating currents	Increased core temperature	Loss of efficiency
Diverter switch	Electrical	Worn contact	High carbon build up	Possible flash over

Table 10 Detailed FMEA for power transformer [20]

The shaded rows of Table 11 highlight the bearing and the winding failures for a motor. A common failure mode here is thermal caused by high temperature, which much like in the transformer case needs to be measured or estimated. Table 19 (section-1.4.2) shows calculations that provide estimations of the temperature to help predict the number of failures of the motor due to these components in a given operational time horizon.

<table>
<tr><th colspan="5">Standard electric motor detailed FMEA</th></tr>
<tr><th rowspan="2">Component</th><th rowspan="2">Known failure mode</th><th rowspan="2">Known failure cause</th><th colspan="2">Failure effect</th></tr>
<tr><th>Immediate</th><th>Eventual</th></tr>
<tr><td>Windings</td><td>Mechanical/thermal/ electrical:
• Open winding
• Shorted winding</td><td>• Insulation breakdown
• High ambient temperature
• High altitude
• Mechanical overload
• Frequent stops and starts
• Dirt buildup on cooling fins
• Vibration
• Mechanical shock</td><td>• Motor does not start
• Sparking at brushes</td><td>Complete motor failure</td></tr>
<tr><td>Bearing</td><td>Mechanical:
• Worn bearing
• Spalling
• Creeping or spin</td><td>• Excessive static load
• Belt misalignment
• Frequent starts and stops under heavy loads
• Lubrication problem
• Contamination
• Overloading
• High temperature</td><td>• Noise
• Heat build up
• Armature rubbing stator</td><td>Motor seized and complete failure</td></tr>
<tr><td>Housing</td><td>Mechanical</td><td>• Fatigue
• External shock
• Excess vibration</td><td>• Dust build up
• Shorted or seized</td><td>Unable to operate motor safely</td></tr>
<tr><td>Armature shaft</td><td>Mechanical:
• Cracked rotor lamination</td><td>• Fatigue
• Misalignment
• Bearing failure</td><td>• Seized
• Armature rubbing stator</td><td>Could be a resultant of bearing failure and hence multiple fault scenario</td></tr>
<tr><td>Brushes</td><td>Mechanical/electrical:
• Wear
• Fail open</td><td>• Improper maintenance
• Contamination
• High temperature
• Improper contact pressure</td><td>• Excessive sparking
• Chatter or hissing noise</td><td>Motor runs too fast or too slow under loading
Motor won't run at all</td></tr>
</table>

Table 11 Detailed FMEA for electric motor [21-23]

3.2 Potential uses of general FMEA results

It can be seen that the output of the detailed FMEAs could be used as design recommendations to the user in S3D. One can refer to Table 17 and Table 19 to assess how knowledge from a detailed FMEA can be adapted and applied in an iterative design scenario.

FMEA in general follows the methodology of breaking down a system into smaller functional parts. In other words, an overall network is broken down into devices and devices in turn into components. Then, a piece by piece failure analysis is commenced keeping in mind the local and global effects of the considered failures along with causes. This piece-wise approach helps build up fault related understanding at various complexity levels of a system. Table 12 summarizes the outcomes of a detailed FMEA and its relevance to this research task.

Outcome of analysis	Potential application of information	Relevance to this research work	Level of application
Single out system areas which could have power quality issues due to multiple power conversions.	This knowledge is useful to judge which zones may be most critical from the power quality point of view.	Helps evaluate the S3D user's choice of power conversion equipment which are vital to realize the benefits of the integrated zonal distribution approach.	Intermediate
Rank zones as per importance depending on constituent loads.	This knowledge may prove useful during operations like load shedding for example.	Ties in with the naval systems engineering design paradigm to carry out system-wide tasks under specific conditions and maintaining standards. In this sense, the rank of the zone would determine the conditions and standards that define it, in turn dependent on its constituent loads.	Intermediate
Gives insight into breaking the zonal system into smaller parts for a more exhaustive failure study	This knowledge is useful when trying to apply well known traditional diagnostic methods with modifications if needed. This may in turn aid in the diagnostic technique selection process.	More detailed evaluation of power system design. This is an advanced stage application perhaps at a more sophisticated level of S3D development.	Advanced
Able to provide network topology information.	This knowledge is useful to the monitoring system, which could be fed to supervisory control architecture for more informed decision support.	This application too is advanced for the current stage of this work.	Advanced

Table 12 Potentially useful outcomes of integrated FMEA

3.3 Criticality analysis

In addition to a detailed FMEA, it is useful to add criticality estimation. This could be accomplished in two ways:

- Fault tree analysis (FTA)
- Failure mode effect and criticality analysis (FMECA)

3.3.1 FTA

In an FTA, an exhaustive study is done to trace fault events and in the process assigning probabilities of occurrence. This mathematical inclusion equips the user to estimate the criticality of a fault/failure based on how likely is it to happen.

Figure 13 shows a fault tree for the transformer winding where the various causes lead back to the considered failure mode. The term "p_x" indicates the probability of occurrence of a fault cause. Ultimately, the overall probability is found out by multiplying individual probabilities at each stage.

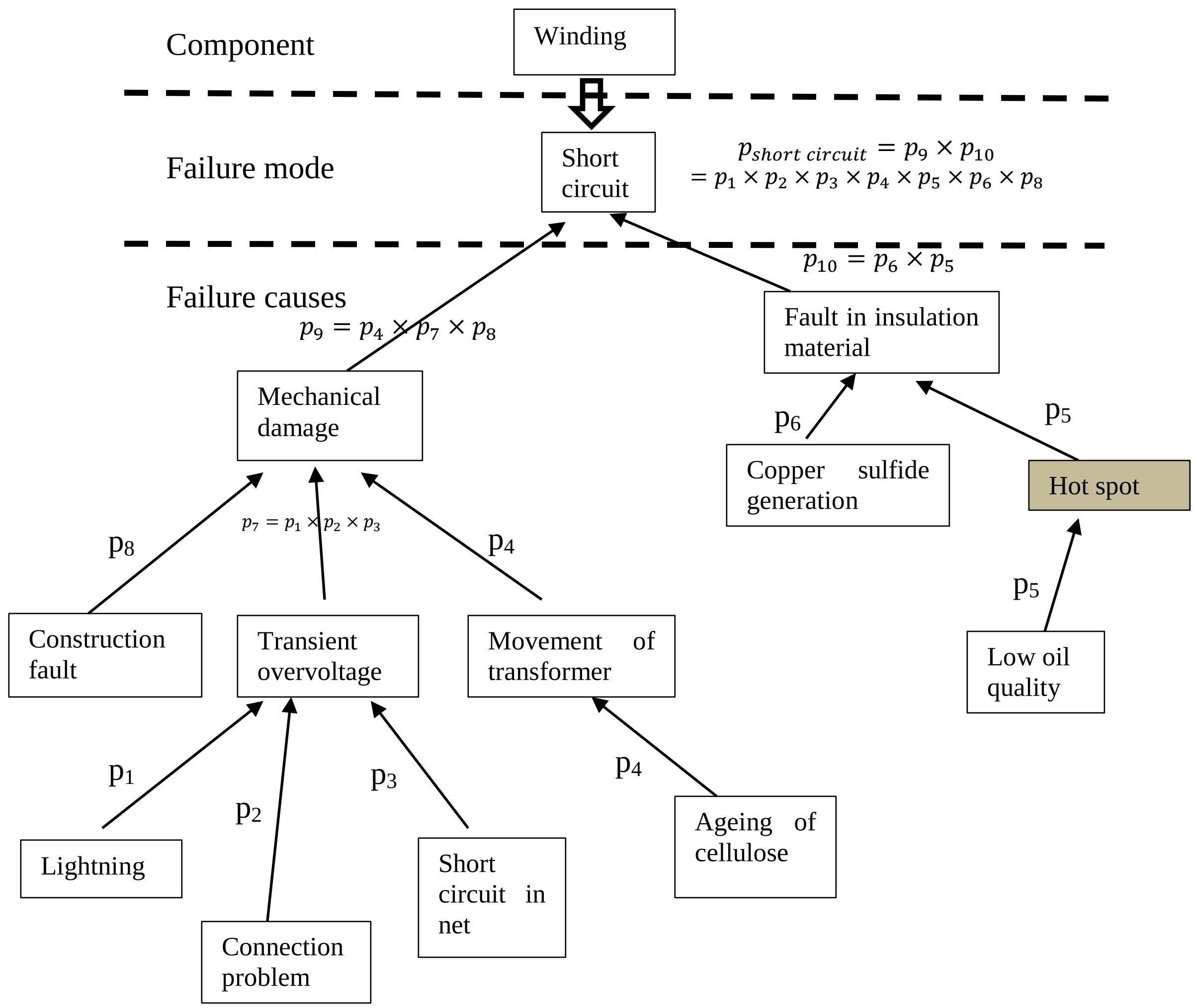

Figure 13 FTA for transformer winding [24]

For each pertinent failure mode associated with a component or device, an FTA can be conducted with probability information. This further strengthens the aim of evaluating a design based on choice of components and devices to build an overall system.

3.3.2 FMECA

As per [25],

"The failure mode, effects and criticality analysis (FMECA) is an essential function in design from concept through development. To be effective, the FMECA must be iterative to correspond with the nature of the design process itself. The extent of effort and sophistication of approach used in the FMECA will be dependent upon the nature and requirements of the individual program. This makes it necessary to tailor the requirements for an FMECA to each individual program."

This is an extension of a detailed FMEA by adding a term commonly known as risk priority number (RPN) [26]. The RPN consists of three elements:

• Occurrence (O) – how likely is the cause to occur and result in the failure mode?
• Severity (S) – how serious are the end effects?
• Detection (D) – how likely is the failure to be detected before it reaches the customer?

These indices are usually rated on a 1-10 scale and are described in more detail below. The risk priority number is the product of these three items.

$$RPN = O \times S \times D$$

Using an RPN based measure; one can prioritize which failure mode requires immediate attention while some could be relatively less severe. In contrast to the FTA approach, the FMECA guides the designer in a logical way through the design selection space to obtain a de-risked system. However, for a complete evaluation, both FTA (probability) and FMECA (RPN) approaches in combination are worthy of further investigation.

4 DISCUSSION AND CONCLUSIONS

As a recap, following is the year-wise list of proposed deliverables:

- **Year 1 (FY 2014)** – A basic system **design rule base** and **FMEA framework** ready to be implemented into S3D
- **Year 2 (FY 2015)** – Basic design rules and basic FMEA implemented and tested in S3D
- **Year 3 (FY 2016)** – Expanded design rules and FMEA incorporating lessons learned in Y1 & Y2 implemented in S3D

This subsection highlights the current work done and the near term future plans (3-6 months) for FY 2015.

4.1 Current status of work done

4.1.1 Design guidelines rule base

The methodology applied in this research uses well known techniques to generate design guidelines at two broad levels of the ship design process namely system-level and sub-system level. The methodologies used are summarized as follows:

1. **NLP based extraction for sub-system design equations** – Here, vast resources exist in IEEE standards and MIL handbooks which were tapped using NLP techniques to narrow down and quicken the search for important and relevant data. This helped extract specific design related equations which helped calculate failure rate and ageing for equipment commonly used for shipboard applications.
2. **Naval systems engineering based approach for system-level design guidelines** – In this case, well known naval practices for designing vessels were merged to form a cohesive set of steps. This proposed approach uses ideas from established procedures to design ships. However, they needed to be merged with sub-system design and logically the entire process as a whole falls into a systematic sequence.

4.1.2 Failure analysis framework

As mentioned in section-3, an FMEA is integrated into the design process owing to the nature of the equations selected. For added user information, the following data could be provided to educate the designer in S3D:

1. What is likely to fail – Based on the failure mode information, e.g. motor's winding and bearing.
2. Why does something fail – Based on causal information for failures
3. Effect of failures – This is present in standard FMEA for equipment.
4. Recommendations – These have been shown in Table 17 and Table 19 and could be linked with the detailed FMEAs presented in Table 10 and Table 11.

4.2 Continuation of work using similar approach

As of now, work is ongoing to combine recommended guidelines and failure information to enable accurate evaluation of a design. Examples displaying this approach are shown for the motor and transformer example in Appendix-B. Similar efforts are needed for other vital devices of the shipboard power system such as:

- Power converters
- Turbine-generators
- Disconnect switches
- Distribution and transmission modules (cables, switchboards etc.)
- Energy storage
- Weapons systems

4.3 Future work for FY 2015

The next stage of this task is the testing of the design evaluation approach presented here in the S3D environment. This will require inputs from the programmer's side as well. The work to be carried out under the broad umbrella of "*testing within S3D*" for the near term (3-6months) could be briefly categorized as follows:

1. **Consolidating system-level design guidelines** – The aim of this subtask would be to form rules and recommendations to guide a hypothetical S3D user from the very first decision/choice to design a ship as explained in section 4. These set of guidelines aid the user to use prior knowledge coupled with freedom of choice to enable evaluating a standard ship design as well as a novel design.
    - *The challenge* – The main issue in this case is the seamless integration of system and subsystem level design rules/recommendation/guidelines.
    - *Iterative testing* – This will involve several runs of tests on the S3D portal to check performance and logic.
2. **Use of FTA and FMECA** – As mentioned in section 3.3, FTA and FMECA are added failure analysis methodologies which aid in evaluating a system from the probability of failure point of view. FMEA by definition lists pertinent issues but does not mathematically indicate their likelihood of occurrence. Adding this measure would further make the evaluation of design more robust. At this point, the examples shown in Appendix-B incorporate the useful life and occurrence of failures. Further research is needed to use the available resources in a criticality based evaluation scheme to assess designs in S3D.

It is important to note that at this stage of the research, the pertinent goal is to explore ways of enhancing existing capabilities and functionalities of S3D (refer Figure 1) by incorporating design evaluation functionality into S3D. An ultimate goal for the future could well be to develop a comprehensive S3D environment with detailed analysis functionalities with accurate design evaluations for electric ships. However, at this stage of the research, it is still imperative to gain an understanding of various methodologies that could drive accomplishing feasible goals by laying out the building blocks of a design-evaluation capable system..

Figure 14 shows a proposed Gantt chart for the near-future plans.

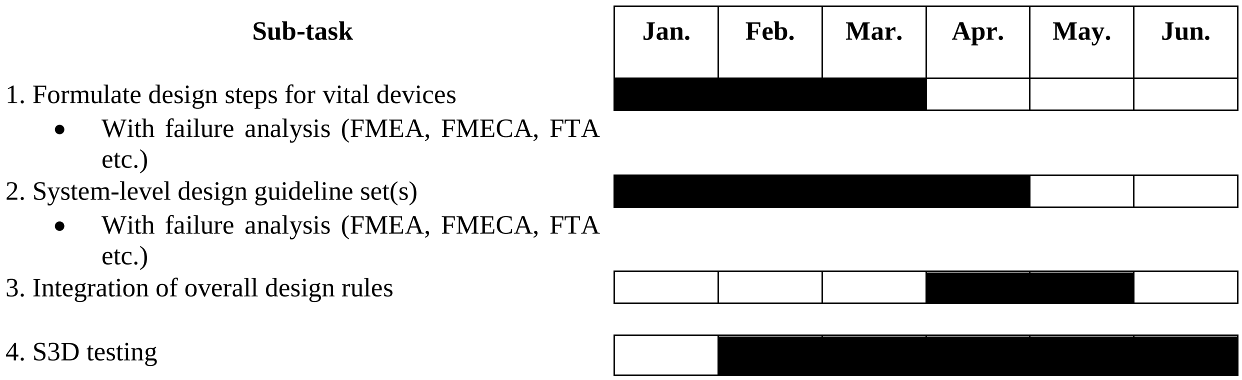

Figure 14 Gantt chart for near term plans

4.4 Conclusion and summary

The work done reported in this document explains in detail the following subtasks:

1. **Extracting design guidelines from known and well-established engineering resources** – This has been reported through section-1 and Appendix A. An NLP based approach is an excellent tool to quicken this subtask considerably. A detailed example is provided in Appendix A.
2. **Failure assessment** – Knowledge about faults and failures using tools such as FMEA, FTA and FMECA enable de-risking the design in addition to evaluating it using standard equations. This has been detailed in section-3 and as mentioned, a failure assessment feature is in general integrated within design evaluations as shown in Appendix-B.

This approach of beginning with an NLP tool to help the research team in searching useful design related information will be continued for other vital devices and components. A similar tool appropriately modified could also be used to tap into the generally data-rich FMEA databases for future use.

As the FY-2014 deliverable clearly states to possess ***"A basic system design rule base and FMEA framework ready to be implemented into S3D"***, the work done explained earlier clearly identifies a set of rules that enable evaluating a transformer and a motor, both detailed in Appendix-B and incorporating a FMEA based failure assessment along with design recommendations that can be derived (Table 17 and Table 19). It is anticipated by the team at

CAPS-FSU that a start-to-end design code could be readily implemented into S3D that enables a user to

- Select equipment (e.g. transformer, motor)
- Select loading scheme
- Evaluate equipment as per loading (using design equations)
- Iteratively make changes if necessary (using recommendations)

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6 APPENDIX A

Following subsections show an example of NLP based data-mining outputs for the IEEE C57.91-2011[6] and MIL-217F [7] and the process identified as "worth investigating", along with the information found on such highlighted pages.

6.1 Code used and its functions

The statistical software package "R" was used to process .pdf copies of IEEE standards and MIL handbooks. The code used is provided below:

```
library(tm) # Framework for text mining.
library(xlsx)
#Directories
pdfDir<-"pdfs";
regStr<-'(\\W|^)rights\\s{0,3}reserved(\\W|$)';
	cname <- file.path(".", pdfDir);
	stds<-Corpus(DirSource(cname),readerControl=list(reader=readPDF));

	stds <- tm_map(stds, tolower);
	stds <- tm_map(stds,removeWords,stopwords("english"));
	stds <- tm_map(stds,removeWords,stopwords("S3D"));
	stds <- tm_map(stds,stripWhitespace);
	stds <- tm_map(stds,removePunctuation);
	stds <- tm_map(stds,removeNumbers);

for(n in 1:length(stds))
{
	i1 <- grep(regStr,stds[[n]],perl=TRUE);

	STDpages <- list();
	STDpages[[1]] <- stds[[n]][1:i1[1]];

	for(m in 2:length(i1))
	{
		STDpages[[m]] <- stds[[n]][i1[m-1]:i1[m]];
	}

	pages.corpus<-Corpus(VectorSource(STDpages));

	tdm <- TermDocumentMatrix(pages.corpus);

	tfidf<-weightTfIdf(tdm,normalize=TRUE)
	TfIdf<-data.frame(word=names(sort(rowSums(as.matrix(tfidf)),
			decreasing=TRUE)),freq=sort(rowSums(as.matrix(tfidf)),decreasing=TRUE));

	new.tdm<-inspect(tdm[row.names(head(TfIdf,dim(tdm)[1])),dimnames(tdm)$Docs]);

	for(j in 1:dim(new.tdm)[1])
	{
		idocf=which(new.tdm[j,]!=0);
		docf=length(idocf);
		for(k in 1:docf)
		{
			new.tdm[j,idocf[k]]<-log2(new.tdm[j,idocf[k]]/docf);
		}
	}
	bestpage<-sort(colSums(new.tdm),decreasing=TRUE);
	fn<-sprintf("Results/%s.xlsx",dir(cname)[n]);
```

```
        write.xlsx(bestpage,fn);
}
```

This R code performs the following functions:

1. **Processing the corpus** – The .pdf copy of the resource underwent preliminary word-processes in the order given
    a. convert to lower case
    b. remove stop words
    c. remove punctuations
    d. remove digits and numbers
2. **Word weighting** – The remaining contents after the above order of processes was weighted using a logarithmic formula known as Term-Frequency Inverse Document-Frequency (tfidf).

    $$WW_{tfidf} = \log\frac{tf}{df}$$

    where;
    $WW = word\ weight$
    $term\ frequency = tf = no.of\ times\ a\ term\ or\ word\ appears\ on\ a\ page$
    $document\ frequency = df = no.of\ times\ the\ same\ term\ or\ word\ appears\ in\ the\ entire\ resource$

The words are arranged as per descending WW thus indicating their importance to the subject matter of the resource. Further, the maximum number of important words per page helps rank individual pages based on the information it is likely to contain.

6.2 Snapshot of results: IEEE Std.C57.91-2011

IEEE Std.C57.91-2011 and MIL-STD-217F were the major design related references used to form guidelines for a transformer and propulsion motor evaluation respectively. This subsection succinctly explains results for IEEE Std.C57.91-2011. Using the R-code and its functionalities mentioned in section-6.1, the results shown in Table 13, Table 14 and Table 15 were obtained for IEEE Std.C57.91-2011.

Table 13 shows the top 6 results for most keywords on a page for IEEE Std.C57.91-2011. A different sorting scheme produces results per keyword as shown in Table 14 for the same resource. Both these views provide ready information that point to important pages in the text. Table 15 shows the $tf - idf$ measure and sorts the pages as per decreasing value of this metric. In other words, it indicates pages as per importance based on the keywords it contains.

The results across Table 13 to Table 15 help the researcher to focus the search and quicken it in at least 2 ways:

1. **Frequency metric (simple)** – This approach is based on how many keywords (words remaining after process 1 of 8.1) appear on a page. This is a relatively simple measure but helps relegate pages with lesser number of keywords while the ones with the most keywords are identified.
2. **Weighted metric (complex)** – Using the output of keywords, this weights them according the $tf - idf$ measure thus providing a second perspective that's relatively more complicated. Both in tandem are a reliable methodology for the researcher to focus his/her search for the most relevant pages of a resource thus greatly reducing time spent and increasing efficiency.

NLP based mining results for IEEE Std. C57.91-2011		
pg#	keyword count	keywords
112	294	ac temperature load loading rise transformers rated winding transformer time life insulation loss guide hottest average regulators apply limited rights authorized licensed restrictions step reserved temperatures mineral cooling aging heat power cycle normal data rating tank spot test total current distribution system voltage initial strength thermal effect standard based conductor obtained windings duct tests content follows part systems water determined ultimate range rate ratio hours between characteristics curve operating location temp mode result results tensile point times duration electric report tested determine mechanical number planned cycles conservative dielectric manufacturer selected short failure guides long model short base degree design discussion research through regulator hottest next thermally cellulose oxygen previous subject controlled full materials measurement step exceed found large line material preservation epri first function insulating long curves expected functional limit manufacturers models recent reduction retained similar term estimate evaluation included lampe reaction review significant single three analysis form hour located mineral points polymerization purpose reported chemical code force future individual length longer obtain reach revision sample series theory aged circuit close fabre fiber frequency good investigators loaded loss oxidation reached refer shroff spicar task transformer typical alternate characteristic established impulse initially measure oxygen person predicted respective significantly stannet thermocouples throughout true water work closely continue continued control defined degradation disc down early establish exceeding except failures find fully history investigation life members modern principal principles received responsible select short subjected typically carefully contain containing contribute exact exactly follow functionality particularly predict purposes recommendation related show showed subsequent time visual wind €œlife action agents anticipated arbitrarily back beavers cell cellulosic chains comparison constituent cooling cycle cycling define enough entity examination expect expectation fact findings glucose immersed individually insulation leslie ling loss manufacture mechanisms molecule monitor others personnel project rabb ranges refe relate restrict rings short
115	249	% ac temperature load loading rise transformers rated winding transformer time life insulation loss guide hottest average regulators apply limited rights authorized licensed restrictions step reserved mineral aging equation heat power normal data rating tank spot test value factor distribution conditions system moisture operation voltage strength effect standard based equivalent duct general tests content part systems water considered weight rate ratio higher curve increase operating location temp mode result results tensile basis calculated point reference times calculate condition deterioration lower mechanical level acceleration approximately conservative manufacturer selected service failure guides long model base case high increased estimated levels regulator units years applied hottest cellulose ducts oxygen previous subject sealed step various additional excess found give material preservation small variable criteria criterion function long absolute carried curves definition expected functional limit manufacturers models produce reasonable recent reduction retained similar estimate evaluation lampe main present significant cumulative experience form mineral slightly testing addition cause individual internal metallic obtain rates reach relationship vary chosen fabre formed good loaded loss oxidation refer residual shroff simple stated transformer typical critical directly earlier excessive open oxygen pichon products relative smaller stannet tube variables varying water accelerated approximate continue continued control down early extremely failures filled life modern place previously proportional reflect select stress subjected typically utilities version year conservator contents direct evaluate investigated older particularly possibly rule safety selection study sumner time wind acker attack bassetto cell confirm demonstrated expect expectation extreme fact half immersed insulation ling lockie loss manufacture portion refe relation rence restrict
69	247	ac temperature load loading rise transformers winding transformer life insulation loss guide hottest average regulators apply limited rights authorized licensed restrictions step reserved temperatures mineral aging equation power normal rating nameplate annex calculation spot test current following factor system operation voltage thermal program effect equivalent conductor windings duct general change prior part systems evolution considered effects computer ratio limits risk clause increase temp pressure result results greater point electric stray bushings calculate continuous electrical bushing determine mechanical level conservative manufacturer short type failure short design determining high increased levels reduced regulator required users years applied components forced hottest normative thermally daily ratings subject equal full step excess found give lead types insulating upgraded approach associated consideration limit manufacturers recent similar term applicable engineers included present second single three conductors experience forced form increases leads mineral parts cause chemical expansion force forced metallic board changer changers circuit close considerably good loaded loss require transformer typical accepted capabilities concerning construction critical excessive major making philosophy reduce spray alan ansi balance causes check checked considerable cooler decrease down early failures great interruption life margin modified reflect relay risks short steps stress structures typically utilities year areas assessment bushing compute concern controversial customers equally flux follow knowledge older once particularly physical planning programs sense source stressed subsequent wind agree agreed agreement area attention back cable clearly common confirm conservatively desirable fact forced forced fouling gained greatest highly immersed insulation knowledgeable ling loss manufacture paid physically rarely reed relief restrict settings short
38	242	ac temperature load loading transformers rated winding transformer ambient time life insulation loss guide hottest average regulators apply limited rights authorized licensed restrictions step reserved temperatures mineral heat power cycle normal constant data rating tank nameplate spot test current factor maximum distribution conditions system operation voltage strength thermal effect expectancy based equivalent conductor obtained duct general tests change overload considered effects information rate ratio characteristics curve operating temp mode pressure result greater assumed electric bushings condition continuous deterioration electrical bushing usually mechanical equipment conservative dielectric manufacturer service short failure limitations model short base case degree design determining account heating regulator units years hottest operated daily output subject controlled measurement sealed step assume give large lead transient criteria insulating accuracy associated expected factors limit manufacturers models produce reduction term basic operations present single amount cases conductors consulted cumulative form leads mineral operate cause caused expansion force future indicated length obtain revision vary wide accurate accurately affect changer changers circuit close indicate loaded loss month produced resulting stated transformer unusual characteristic continuously designs directly established measure recommendations varying ansi closely continue control disc down establish generally great life limitation principal revisions short stress usual widely year allow allowance bushing cables direct elevated forces formation hand investigated knowledge laboratory mathematical necessarily practical predict reactors recommendation related sense sufficient time wind cable causing consult cycle disturb electromagnetic element expect exposure fact gaskets heavy immersed induced insulation item loss manufacture mechanically months movement relate relates restrict short
17	241	ac temperature load loading rise transformers rated winding transformer ambient time life insulation loss fluid guide regulators apply limited rights authorized licensed restrictions step reserved temperatures mineral cooling aging heat power normal rating tank nameplate annex calculation total current factor position conditions system operation voltage strength thermal effect based conductor duct general eddy change contact part evolution loads considered effects resistance ultimate calculations rate ratio higher hours period risk between clause increase temp pressure result results basis calculated greater point electric bushings calculate condition deterioration electrical bushing mechanical contacts equipment level percent conservative dielectric failure limitations long base degree determining discussion high increased through levels reduced regulator units years next adjacent ducts provided ratings subject materials step additional application exceed excess large lead material preservation small transient capacity considerations insulating long consideration definition factors influence limit produce term depending regulation significant conductors form further hour mineral operate parts periods recognized addition auxiliary cause currents expansion force insulated internal metallic problem provide reach applications changer changers exceeds frequency loaded loss parameters produced transformer highest listed major note products reduce significantly smaller structural true ansi build causes control disc down failures great heated involve life limitation local noted risks runaway year arcing areas bushing concern contribute decomposition describe event flux forces formation integrity once parameter possibility possibly problems reactors time wind area cooling define depend dropping electromagnetic extreme fact gaskets holding immersed insulation ling list localized loss megavoltampere overcurrent recognize region relief restrict
42	227	% ac temperature load loading rise transformers rated winding transformer ambient time life insulation loss guide hottest average regulators apply limited rights authorized licensed restrictions step reserved temperatures mineral aging cycle normal rating nameplate bottom spot test value factor position distribution conditions system operation voltage paper thermal effect expectancy specific based emergency obtained duct general change contact overload loads considered information range rate ratio higher limits period between characteristics increase temp mode result basis greater condition continuous deterioration usually lower number cycles increment percent conservative manufacturer service short limitations short base degree design determining high increased variation regulator units users hottest thermally ducts previous ratings full measurement sealed step various application excess give large variable function limiting upgraded limit reasonable term applicable calculating designed significant single three consulted cumulative form mineral cause caused obtain provide rates restricted wide affect carry changer expressed indicate loaded loss percentage practice transformer bottom characteristic construction continuously covered critical designs differences measure products relative significantly taking variables build check checked circulation defined disc down early establish exist great history life limitation local margin practices short usual voltages affected allow allowance buildings chart combinations formation moderate multi sacrifice show tend time understood variations walls wind advantage building cable clearly common commonly consult contemplated cover cycle define designer deteriorates elevation estimating expect extreme fact immersed increments insulation intended loss manufacture phase rence restrict short

Table 13 Top-6 keyword results for IEEE C57.91-2011

Keyword or symbol															
<	>	%	+	±	temperature	loading	rise	transformers	winding	transformer	ambient	time	life	insulation	loss
Frequency in text															
23	9	60	144	8	548	296	296	251	250	384	192	227	136	121	194
Respective page numbers															
104	103	114	103	43	79	12	93	120	82	120	93	78	24	120	77
103	89	43	104	36	85	39	79	39	83	53	25	82	111	116	19
102	90	24	102	113	78	43	92	13	85	13	29	97	116	111	85
23	102	51	63	0	82	45	91	54	84	39	79	89	38	17	95
32	0	52	30	0	84	48	63	69	79	54	92	48	46	38	24
60	0	74	64	0	25	44	29	16	77	55	63	85	120	55	86
84	0	111	65	0	88	46	33	36	81	106	91	108	12	56	97
0	0	115	67	0	28	42	108	106	32	111	94	21	20	115	101
0	0	116	108	0	39	49	31	112	33	112	97	24	56	16	102

Table 14 Individual keyword results for IEEE C57.91-2011

Pg.no.	TFIDF value (highest to lowest)
18	-68.8999
19	-107.797
47	-115.634
24	-117.567
33	-123.851
51	-131.417
71	-137.587
32	-139.724
15	-148.222
17	-149.657

Table 15 tf-idf metric, top-10 results

Quantity	Equation to evaluate design found in text resource	NLP identification
Estimate $\Delta\Theta_{TO}$ ^{0}C, $\Delta\Theta_H$ ^{0}C, Θ_H ^{0}C	Equations 1a, 1b, 2 and 3 respectively: $\Delta\theta_{TO,U} = 29.87K_U^2 + 6.13$ $\Delta\theta_{TO,i} = 29.87K_i^2 + 6.13$ $\Delta\theta_{TO} = 0.25\Delta\theta_{TO,U} + 0.75\Delta\theta_{TO,i}$ $\Delta\theta_H = 28.6K^{1.6}$	Pg.31-35
Estimate heat generated per temperature rise	Equation 4 $q = \left[\frac{\Delta\theta_{TO}}{K}\right]^{1.25}$ where K = p.u. load	Pg.20, and Table 20 on pg.34
Calculate aging acceleration factor per temperature rise	Equation 5 $F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right]}$	Pg.20
Calculate equivalent aging per loading cycle	Equation 6 $F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA}\Delta t_n}{\sum_{n=1}^{N} \Delta t_n}$	Pg.21

Table 16 Identification of useful information through NLP

7 APPENDIX B

This section shows the next stage in the overall analysis focusing on utilizing the information provided in the previous NLP centered methodology. The goal here is to demonstrate the extraction of a design evaluation approach by applying known equations to devices thereby computing useful life and other service related data.

7.1 Utilizing the results

The major advantage of using the approach based off NLP is the reduction in man-hours spent to read resources. The results readily produce a list of pages from a standard which have are likely to contain useful information pertaining to the following broad categories:

1. **Limits and tolerances** – General minimum and maximum values of engineering applications such as:
    a. Temperature
    b. Pressure
    c. Dimensions
    d. Electrical quantities
2. **Recommended practices** – Certain well known industrial norms such as:
    a. Power distribution architectures
    b. Cooling methods
    c. Physical installations

Using the page # output from Table 13 and Table 14, one could corroborate the keywords found on said pages in order to estimate its contents. Examples have been shaded in Table 13 and Table 14. Table 13 indicates page #17 to be important. Table 14 corroborates this output by identifying the keyword “insulation” appearing on page #17. As a conservative approach, one could browse ±5 page # from the one identified to patch up information. In this case, the pages highlighted range between pages #13 to page # 25 which have the following keywords/symbols on them:

[***<, %, temperature, transformer, life, insulation, loss*** **]**

These words in a logical sentence could indicate a certain engineering tolerance or limit for transformer life and insulation loss. As the particular page # are an output, one can immediately turn to these pages in the text (in this case IEEE Std.C57.91-2011) and find relevant information. As a further reference, the following relevant results (in Table 15) were obtained that lead to Table 17.

The above, could be further cross-referenced with the results in Table 15. Eventually, the researcher looking for design guidelines within a text resource typically going into at least over 100pages would focus on roughly 20% of the total pages. This in our experience transformed an initial average of 2hour per 150pg. resource to a maximum of 30min. after utilizing the NLP-based search focusing approach.

An identical approach is used for MIL-217F which pertains to the motor design evaluation equations. Further, for other vital devices such as radars, power converters, cables etc. their respective resources are being processed as per aforementioned methodologies.

7.1.1 Transformer design assessment equations

The major reference for design related equations for transformers was obtained from IEEE Std. C57.91-2011. The transformer's per unit insulation life curve (Figure 15) relates it to the winding hottest-spot temperature.

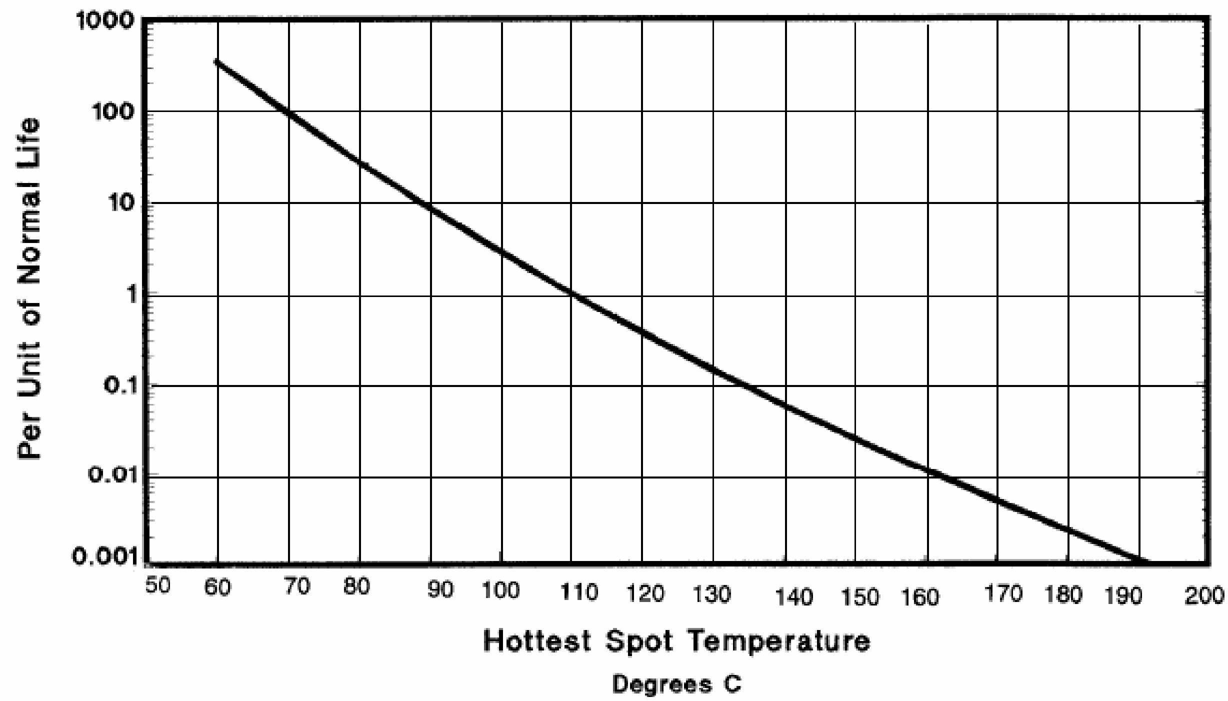


Figure 15 Transformer insulation life [6]

Per unit life of the insulation forms the basis to compute the aging acceleration factor show in Figure 16. This dependency makes the winding hot-spot temperature a crucial entity to estimate for which, the standard provides equations.

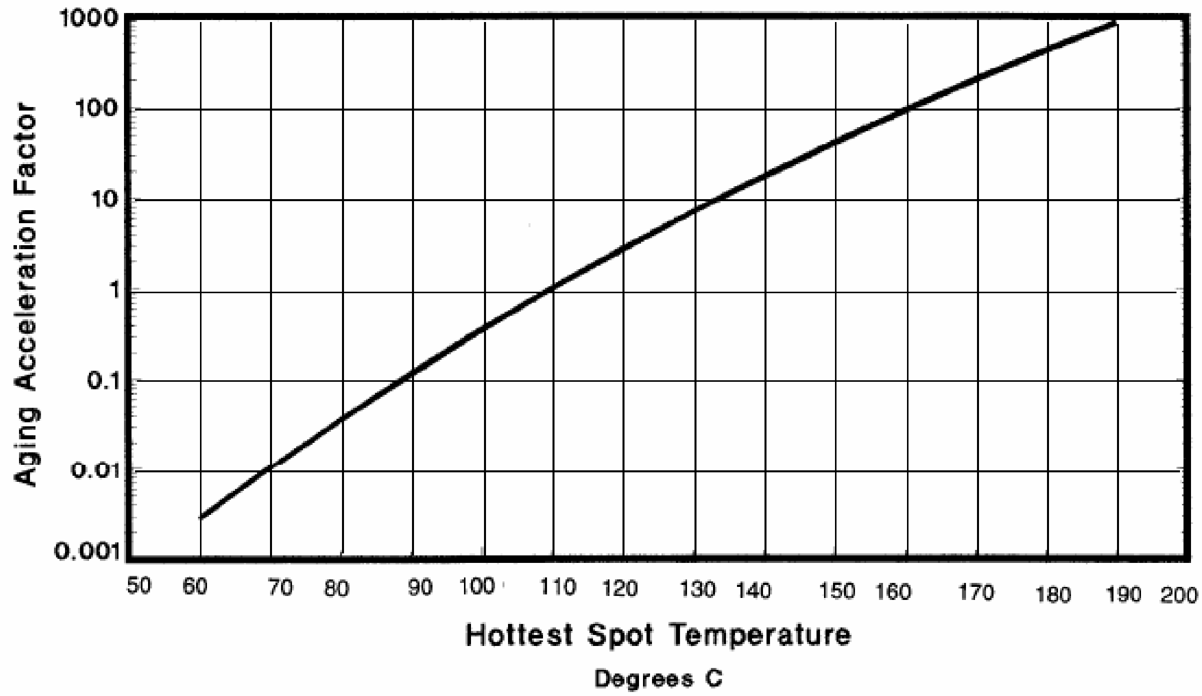


Figure 16 Ageing acceleration factor [6]

Table 17 shows the steps to evaluate a transformer. The first step is to select a loading cycle. [6] forms a basis of this analysis which ends with a design recommendation after going through relevant equations that estimate hotspot temperature values.

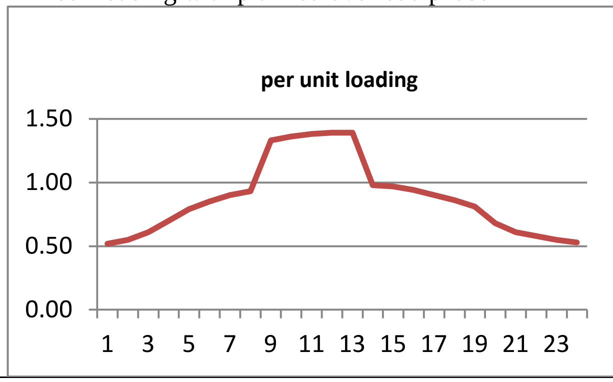
Design steps	Equation and design basis [IEEE Std. C57.91-2011]	Result
Set loading scheme and cycle time	24 hour loading with planned overload phase 	5-6 hour overloading period
Estimate $\Delta\Theta_{TO}$ ^{0}C, $\Delta\Theta_H$ ^{0}C, Θ_H ^{0}C	Equations 1a, 1b, 2 and 3 respectively: $\boldsymbol{\Delta\theta_{TO,U} = 29.87K_U^2 + 6.13}$ $\boldsymbol{\Delta\theta_{TO,i} = 29.87K_i^2 + 6.13}$ $\boldsymbol{\Delta\theta_{TO} = 0.25\Delta\theta_{TO,U} + 0.75\Delta\theta_{TO,i}}$ $\boldsymbol{\Delta\theta_H = 28.6K^{1.6}}$	Every 2 hours, refer table 2
Estimate heat generated per temperature rise	Equation 4 $q = \left[\frac{\Delta\theta_{TO}}{K}\right]^{1.25}$ where K = p.u. load	Every 2 hours, refer table 2
Calculate aging acceleration factor per temperature rise	Equation 5 $F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right]}$	Every 2 hours, refer table 2
Calculate equivalent aging per loading cycle	Equation 6 $FEQA = \frac{\sum_{n=1}^{N} FAA\,\Delta tn}{\sum_{n=1}^{N} \Delta tn}$	2.9
Calculate estimated loss of life % per loading cycle duration	Equation 7 $\%Loss\ of\ life = \frac{FEQA \times 24 \times 100}{Normal\ insulation\ life}$	0.1
Calculate total life assuming identical loading cycle each day	Equation 8 $Life = \frac{100\%}{\%Loss\ of\ life} \times \frac{1}{365.25} years$	2.8 years
Remarks and design recommendation	**Nominal operating life is 180,000 hours or 20.55 years. Based on calculated values:** **Life is reduced by a factor of almost 10** **Heat to be removed per 24 h cycle is nearly 2 kW** **Change loading scheme** **Provide a cooling method more effective than natural air**	

Table 17 Transformer selection and loading scheme design example outcome using proposed methodology

Table 18 shows the per unit loading values, ambient temperature chosen and estimated quantities using formulae from Table 17.

In this design example, per unit loading is set at different hours and ambient temperature is considered constant at 30^{0}C while all other quantities in this table have been estimated using design equations from IEEE standard C57.91-2011.							
Hour	**per unit loading**	**Ambient temperature** $\boldsymbol{\Theta_A}$	**Transformer top oil rise temperature** $\boldsymbol{\Delta\Theta_{TO}}$	**Winding hot spot temperature rise**	**Winding hot spot temperature** $\boldsymbol{\Theta_H}$	**Aging acceleration factor F_{AA}**	**Heat dissipation in W**

		^{0}C	^{0}C	$\Delta\Theta_H$ ^{0}C	^{0}C		
1	0.52	30.00	14.45	10.99	55.44	0.01	62.48
2	0.55						63.21
3	0.61	30.00	18.13	16.17	64.30	0.01	65.22
4	0.70						69.26
5	0.79	30.00	25.52	22.06	77.58	0.03	74.24
6	0.85						77.94
7	0.90	30.00	30.74	25.47	86.21	0.08	81.2
8	0.93						83.24
9	1.33	30.00	59.58	46.78	136.36	12.46	114.42
10	1.36						116.98
11	1.38	30.00	63.23	48.44	141.67	19.91	118.72
12	1.39						119.59
13	1.39	30.00	56.6	27.70	114.30	1.55	119.59
14	0.98						86.75
15	0.97	30.00	33.82	25.91	89.73	0.12	86.05
16	0.94						83.94
17	0.90	30.00	29.81	22.47	82.28	0.05	81.2
18	0.86						78.58
19	0.81	30.00	24.29	15.44	69.73	0.02	75.42
20	0.68						68.28
21	0.61	30.00	16.99	11.97	58.96	0.01	65.22
22	0.58						64.12
23	0.55	30.00	15.01	10.36	55.37	0.01	63.21
24	0.53						62.74
Σ = 24						Σ = 34.26	Σ = 1981.6

Table 18 Per unit loading, constant quantities and estimated quantities for transformer

7.1.2 Propulsion motor design assessment equations

Design equations to estimate wearing and ageing effects on pertinent parts of a standard AC-motor were found in MIL-217F. The model utilized here is dictated by two pertinent failure modes, bearing and winding failures. Calculations are listed step-wise in Table 19.

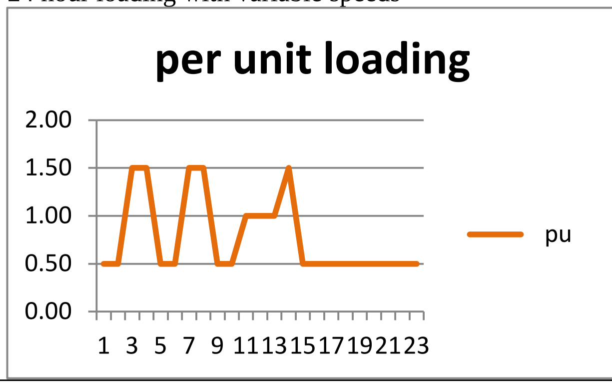
Design steps	Equation and design basis [MIL 217F]	Result
Set loading scheme and cycle time	24 hour loading with variable speeds  	5-6 hour overloading period
Estimate $\Delta\Theta_{TO}$ ^{0}C, $\Delta\Theta_H$ ^{0}C, Θ_H ^{0}C *[SAME AS IN TRANSFORMER DESIGN]*	Equations 1a, 1b, 2 and 3 respectively: $\boldsymbol{\Delta\theta_{TO,U} = 29.87K_U^2 + 6.13}$ $\boldsymbol{\Delta\theta_{TO,i} = 29.87K_i^2 + 6.13}$ $\boldsymbol{\Delta\theta_{TO} = 0.25\Delta\theta_{TO,U} + 0.75\Delta\theta_{TO,i}}$ $\boldsymbol{\Delta\theta_H = 28.6K^{1.6}}$	Every 2 hours, refer table 4
Estimate heat generated	Equation 4 $q = \left[\frac{\Delta\theta_{TO}}{K}\right]^{1.25}$	Every 2 hours, refer table 4
Calculate aging factor for winding	Equation 9 $\propto_{W\ overall} = \frac{1 + time\ step}{1\ \ ,\ time\ step}$	18776.50
Calculate aging factor for bearing	Equation 10 $\propto_{B\ overall} = \frac{1 + time\ step}{1\ \ ,\ time\ step}$	78255.10
Calculate estimated number of failures for an operation time of t = 180,000 hours	Equation 11 $\lambda_P = \left[\frac{t^2}{{\alpha_B}^3} + \frac{1}{\alpha_W}\right] \times 10^6$ failures per 10^6 hours	120.9 per 10^6 hours of operation
In a given year with 8760 hours	$Failures\ per\ year = \frac{8760\ \times 120.9}{10^6}$	1.06
Remarks and design recommendation	**Nominal operating life is 180,000 hours or 20.55 years. Based on calculated values:** 1. The propulsion system i.e. motor will fail at least once a year for the given loading cycle 2. Heat to be removed per 24 h cycle is nearly 2 kW 3. Performance may be improved by providing better heat removal that might reduce the failure rate	

Table 19 Propulsion motor selection steps using design and failure estimation equations

Table 20 shows iterative calculations to estimate the hotspot temperature. These values could then be used to calculate the total heat dissipation at every hour (or measuring period).

A critical assumption here is the use of transformer design equations for estimating the winding temperature. The terminologies and design equations are identical to those in Table 18								
Hour	**per unit loading**	**Θ_A ^{0}C**	**$\Delta\Theta_{TO}$ ^{0}C**	**$\Delta\Theta_H$ ^{0}C**	**Θ_H ^{0}C**	**α_W (hour) [MIL 217F pg.148]**	**α_B (hour) [MIL 217F pg.148]**	**Heat dissipation in W**
1	0.50	30.00	13.6	9.44	53.04	250711.60	78255.10	62.48
2	0.50							63.21
3	1.50	30.00	73.34	54.72	158.06	4344.30	78255.10	65.22
4	1.50							69.26
5	0.50	30.00	13.6	9.44	53.04	250711.60	78255.10	74.24
6	0.50							77.94
7	1.50	30.00	73.34	54.72	158.06	4344.30	78255.10	81.2
8	1.50							83.24
9	0.50	30.00	13.6	9.44	53.04	250711.60	78255.10	114.42
10	0.50							116.98
11	1.00	30.00	36	28.60	94.60	38182.20	78255.10	118.72
12	1.00							119.59
13	1.00	30.00	45.34	54.72	130.06	10417.60	78255.10	119.59
14	1.50							86.75
15	0.50	30.00	13.6	9.44	53.04	250711.60	78255.10	86.05
16	0.50							83.94
17	0.50	30.00	13.6	9.44	53.04	250711.60	78255.10	81.2
18	0.50							78.58
19	0.50	30.00	13.6	9.44	53.04	250711.60	78255.10	75.42
20	0.50							68.28
21	0.50	30.00	13.6	9.44	53.04	250711.60	78255.10	65.22
22	0.50							64.12
23	0.50	30.00	13.6	9.44	53.04	250711.60	78255.10	63.21
24	0.50							62.74
Σ = 24								Σ = 1904.94 W

Table 20 Per unit loading, constant quantities and estimated quantities for propulsion motor

Equation 12: for computing winding wear factor

$$\propto_W = 10^{\left(\frac{2357}{\theta_A+273}-1.83\right)}$$

Equation 13: for computing bearing wear factor

$$\propto_B = \left[10^{\left(2.534-\frac{2357}{\theta_A+273}\right)}\right.$$

7.2 Assumptions and modifications

The equations that aid in estimating the motor failure rate include winding failure mode as one major factor. With a chosen loading cycle, the operating temperature of on-line rotating machinery changes with time, this in turn determines their ageing. As [7] provides no time dependent equations to link loading with temperature, equations from [6] for transformer-windings have been used. This assumption has been used only for the estimation of winding temperature for the motor with change in loading (speed). Since the transformer equations provide a method to compute the winding temperature, the same method has been utilized for the motor windings.

Upon inspection, it might be said that the modification used above may give extreme results. In other words, it could potentially be less severe than the failure calculations for the motor indicates. Table 21 is from [6] which show the winding and bearing factors as calculated at set temperature intervals of 5^0C.

The major issue with the type of computation shown in Table 21 is that one cannot estimate what the component temperature would be for different loading cycles. Equations 12 and 13 depend on the value of temperature to provide further values that in turn determine the failure rate. As a result, at this stage in this research, transformer winding hotspot temperature equations have been borrowed to be utilized for the motor windings.

Temperature near component/device (^{0}C)	α_W **(hour) [equation 12]**	α_B **(hour) [equation 13]**
55	226973.8	43841
60	177042.8	34605.8
65	139114.7	27347.8
70	110083	21700.9
75	87697.8	17312
80	70316	13890.5
85	56728.2	11210.4
90	46037.7	9099.5
95	37574.4	7427.4
100	30834.4	6095.5
105	25436.1	5028.5
110	21088.6	4169.1
115	17568.9	3473.3
120	14704.7	2907.1
125	12362.7	2444.1
130	10438.5	2063.7
135	8850.4	1749.7
140	7534	1489.5
145	6438.1	1272.8
150	5522.1	1091.8
155	4753.5	939.8
160	4106	811.8
165	3558.6	703.6

Table 21 Time independent calculations for motor winding and bearing wear factors [6]