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Designing Electrical Power Systems for Survivability and Quality of Service

ABSTRACT

The primary aim of the design of a shipboard electric power system has traditionally been survivability and continuity of the electrical power supply. Survivability relates to the ability of the power system, when damaged by a threat, to support the ship's ability to continue its missions. Power continuity relates to the ability of the power system to reliably provide power to ship systems under normal operations.

This paper proposes new metrics for survivability and continuity of service that enable better definition of power system requirements linked to the operational needs of the ship. For survivability, the threats for which a ship is designed are its Design Threats, and the required residual capability following damage from a Design Threat is the Design Threat Outcome. Quality of Service serves as a metric of the continuity of the electrical power supply under normal operation. Quality of Service is measured in terms of a Mean Time Between Service Interruption (MTBSI). A Service Interruption is defined as any interruption in the supply or deviations outside of normal bounds of power quality that prevent a load from performing its assigned function.

INTRODUCTION

While, the primary aim of the design of a shipboard electric power system has traditionally been survivability and continuity of the electrical power supply, in actuality, ship and electrical system design tends to become rules or features based, rather than outcome based. Survivability for warships, for example, is governed by OPNAVINST 9070.1 (CNO 1988). While OPNAVINST 9070.1 describes the features that different types of ships should have, it only describes the capabilities that a ship should have following weapons impact in very general terms. Likewise, design guidance for electrical power plants is generally based on ensuring generation and distribution equipment is of the appropriate rating, but does not include nor consider equipment reliability or other metrics of power system continuity.

This paper proposes a language for ship requirements documents for describing Survivability and Quality of Service requirements and describes design methods for meeting those requirements. The paper assumes familiarity with the basic concepts of the Integrated Power System as described by Doerry and Davis (1994), Doerry et.al. (1996) and Doerry and Fireman (2006). Focus is on early stage design through the end of Preliminary Design. The paper concludes with recommendations for further development and study.

The views expressed in this paper are those of the author and are not necessarily official policy of the U.S. Navy or any other organization. The intent of this paper is to foster dialogue to gain a better understanding of design for survivability and quality of service.

PROPOSED SOLUTION OVERVIEW

The requirements for new naval ship programs are developed under the Joint Capabilities Integration & Development System (JCIDS). Following an Analysis of Alternatives (AOA), if a material solution is recommended to address a warfighting gap described in an Initial Capabilities Document (ICD), then the specific requirements for the material solution are incorporated into a Capability Development Document (CDD). (CJCS 2005) The author proposes that the CDD specify survivability requirements as a set of Design Threats and Design Threat Outcomes. Additionally, continuity of power should be specified in terms of Quality of Service metrics where the ship's missions are described by a Naval Concept Essential Task List (NCETL). (Doerry 2006) (Doerry and Fireman 2006). These requirements and missions are used by the design engineer in the context of zonal design, to develop the ship and power system design, and are validated during early stage design by modeling and simulation. These requirements are also in a form that lend themselves for conducting operational testing once the ship is built and delivered to the fleet.

DEFINITIONS

Design Threat

A Design Threat is a threat to the ship where a Design Threat Outcome has been defined. Examples of Design Threats could be specific cruise missiles, torpedoes, guns, explosives, weapons of mass destruction as well as accidents such as main space fires, helicopter crashes, collisions, and groundings.

Design Threat Outcome

The Design Threat Outcome is the acceptable performance of the ship in terms of the aggregate of susceptibility, vulnerability, and recoverability when exposed to a design threat. Possible Design Threat Outcomes include:

a. Ship will likely be lost with the loss of over 25% of embarked personnel.

b. Ship will likely be lost with the loss of 25% or under of embarked personnel.

c. Ship will likely remain afloat and not be capable of performing one or more primary mission areas for a period of time exceeding one day.

d. Ship will likely remain afloat and be capable of performing all of its primary mission areas following restoration efforts not exceeding one day using only that external assistance that is likely available within the projected operating environment.

e. Ship will likely remain afloat and be capable of performing all of its primary mission areas following restoration efforts not exceeding two hours using only organic assets.

f. Ship will likely remain afloat and would be capable of performing all of its primary mission areas following restoration efforts (if needed) not exceeding 2 minutes using only organic assets.

g. Ship will likely remain afloat and would likely be capable of performing all of its primary mission areas without interruption.

h. The threat weapon is not considered a significant threat because the probability that the threat weapon would have been defeated before striking the ship is greater than 98%.

Note: The term “likely” should be assigned a specific probability of occurrence. A reasonable choice would be to specify that “likely” refers to a probability of occurrence greater than 86%.

The levels of survivability for the design threats can be evaluated using Total Ship Survivability Assessment (TSSA) methods. Yarbrough and Kupferer (2002) provided an example of the TSSA process as applied to a naval ship (JCC(X)) during the concept / feasibility stage of design.

More recently, the Volumetric Integrated Vulnerability Assessment (VIVA) methodology was employed in a congressionally mandated study on alternate propulsion methods for surface combatants and amphibious warfare ships to access the vulnerability performance of multiple concept level ship design. (Naval Sea Systems Command 2007). VIVA uses ship profile and arrangements data developed by ship synthesis programs such as the Advanced Surface Ship and Submarine Evaluation Tool (ASSET), one-line diagrams and deactivation diagrams for the Mission systems (Including Propulsion), electrical distribution, chill water distribution, and firefighting systems (Firemain and AFFF), and threat weapon characteristic data. These inputs are used as indicated in Figures 1 through 3 to determine the Probability of Ship Loss, Mission Loss, and Mobility Loss given that the ship is hit.

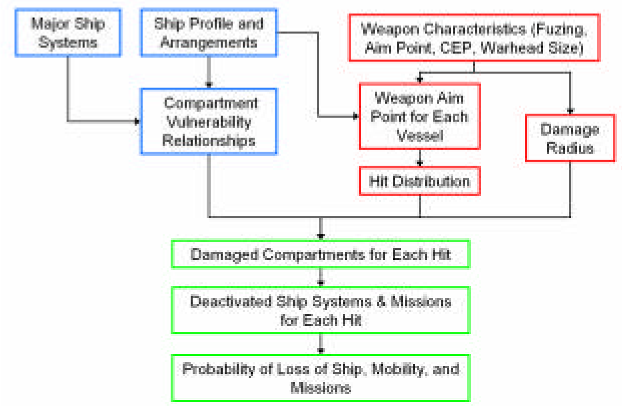

FIGURE 1: Volumetric Integrated Vulnerability Assessment (VIVA) methodology

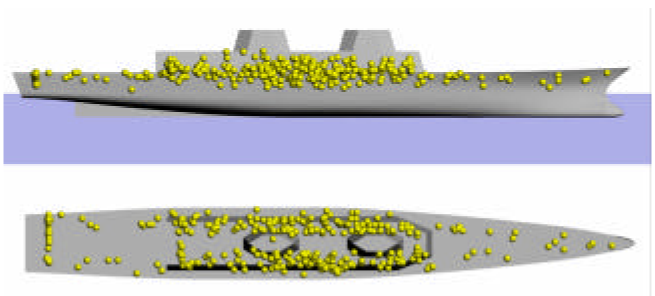

FIGURE 2: Example VIVA Hit Point Distribution

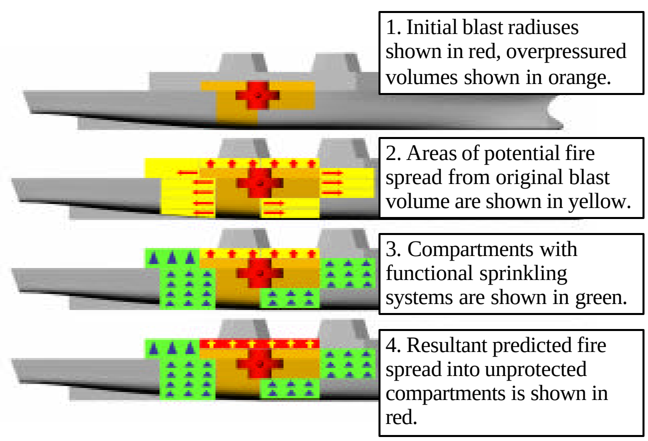

FIGURE 3: Example VIVA damage and fire spread modeling

Over-Matching Threat

An over-matching threat is a design threat where the design threat outcome includes likely loss of the ship.

Quality of Service (QOS)

Quality of Service is a metric of how reliable a distributed system provides its commodity to the standards required by the users. It is calculated as a Mean-Time-Between-Service-Interruption (MTBSI) as viewed from the loads. A failure is defined as any interruption in service, or commodity parameters outside of normal parameters, that results in a mission system not being capable of fulfilling mission requirements. Mission requirements should be considered in terms of the Naval Concept Essential Task List (NCETL) as described by Doerry and Fireman (2006) and Doerry (2005). The time is usually measured over an operating cycle or Design Reference Mission. Quality of Service is a reliability metric, as such the calculation of QOS metrics does not take into account survivability events such as battle damage, collisions, fires, or flooding. Quality of Service does take into account equipment failures and normal system operation transients. A typical cause of normal system operation causing a QOS failure is shifting to/from shore power (without first paralleling) or manually changing the source of power using a manual bus transfer (MBT). Also note that not all interruptions in service will cause a QOS failure. Some loads, such as refrigerators and chill boxes, will keep their contents cold even if power is interrupted for several minutes. In this case, a QOS failure will not occur as long as power is restored in time to prevent significant heating of the contents. Note that the optimal configuration of a distributed system may be different for QOS considerations and for survivability considerations. In the electric plant for example, the most important QOS consideration is the ability to preserve power to loads when a generation element trips off line while damage to the distribution system and the ability to preserve power to vital mission systems loads is of major interest in the survivability analysis. For QOS reasons, many ships operate with their electric plant paralleled in peacetime steaming and only shift to the more survivable split plant configuration under threat conditions.

For electrical power systems, loads can be categorized into three QOS categories: Un-Interruptible, Short Term Interrupt, and Long Term Interrupt

a. Un-interruptible Load

Un-interruptible Load is a proposed QOS term for categorizing electrical loads that can not tolerate power interruptions of 2 seconds. Un-interruptible Loads should be capable of tolerating transient interruptions of power of up to 10 ms in duration to enable standby power systems to switch. Un-interruptible loads are typically provided a Standby Power System, an Un-interruptible Power Supply, or auctioneering DC diodes.

b. Short Term Interrupt Load

An electrical load is classified as a Short Term Interrupt Load if it can tolerate power interruptions greater than 2 seconds but can not tolerate interruptions of 5 minutes or more. 2 seconds is based on providing sufficient time for electromechanical switchgear to clear faults in a coordinated manner, conduct Quality of Service Load Shedding of Long Term Interrupt Loads, and to reconfigure the electrical plant. 5 minutes is a nominal time in which a standby generator should be capable of starting and providing power.

c. Long Term Interrupt Load

An electrical load is classified as a Long Term Interrupt Load if it can tolerate power interruptions greater than 5 minutes. Examples include resistive heaters, chill and freeze boxes, and standby redundant equipment.

d. Exempt Loads

For Integrated Power System (IPS) configurations where propulsion and ship service power are provided by the same set of power generation modules / prime movers, sufficient redundancy in generation is not provided to enable the ship to achieve its maximum speed with any one generator out of service. Propulsion power for IPS ships may thus be split into three categories: Short Term Interrupt Load, Long Term Interrupt Loads, and Exempt Loads. The installed generation capacity of the ship must be capable of supporting the ship service load and all categories of propulsion load with all generators online, and must support the ship service load and all but the Exempt Load with one generator out of service. Unless otherwise specified in the ship's requirements documentation, that portion of propulsion load needed to exceed the minimum tactical speed should be designated exempt.

The concept of the Exempt Load is only used in sizing the installed generation capacity of the ship. In operation of the power system, exempt load are treated as long-term interrupt loads.

DESIGNING FOR QUALITY OF SURVICE

QOS Requirements

QOS should be specified in terms of a Mean Time Between Service Interruption. The same MTBSI can be specified for all ship missions, or alternately, different ship missions as described by NCETLs can be provided with different QOS requirements. Because QOS is not a metric that is currently calculated for electric plant designs, establishing a value that is achievable and affordable is not currently feasible. The author proposes that a MTBSI on the order of 30,000 hours (3.4 years) be used until a study of MTBSI versus cost produces a more realistic design requirement.

Understanding Load Needs

Determining the amount of power of each QOS category that must be provided by the Power Generation Modules and each level of power conversion is not trivial. Mission capabilities as described by NCETLs must be mapped to equipment configurations. The impact of power system failures and power system reconfiguration on the mission equipment and the resulting impact on the mission capability must be evaluated. For non-complex ships, modeling the mission systems and loads to determine QOS requirements may be performed through enhancements to the electric load analysis methodology described in DDS 310-1 by assigning each load to a QOS category. In more complex ship designs however, the QOS category for a load may depend on the configuration of the mission system and the amount of redundancy in the mission system configuration. More complex ships may require more advanced simulation methods to determine the impact on mission capability of the loss of power of different durations on one or more mission system equipment.

Power System Equipment Reliability and Redundancy

The power system should be designed such that in normal operation in the absence of equipment failures, QOS failures should not occur. Since QOS does not account for weapons induced damage, the reliability of power system equipment, the systems architecture of the power system, and the power system concept of operation are the primary drivers for QOS provided by the power system. The systems architecture and the power system concept of operations can compensate to a degree for lower than desired power system equipment reliability, but generally at a higher acquisition cost due to added redundancy. The power system concept of operation details which power system components are used as well as their configuration for different mission system requirements. In general, highly reliable components (with a MTBF of much greater than 30,000 hours) do not need redundancy. Components with a low MTBF (well below 30,000 hours), such as gas turbine generators, will likely require redundancy. Other components with intermediate reliability may or may not require redundancy depending on the percentage of time that the component is used according to the power system concept of operation, ship concept of operation, ship operational profile, and ship operational tempo.

Calculating Quality of Service

Before QOS can be calculated, a number of elements are needed:

a. Ship Concept of Operations in the form of percent underway time the ship will be in different operational modes. The fraction of time in an operational mode i is given by $f_{om(i)}$

b. Mission System Quality of Service model for each operational mode. This model will provide a "1" if a QOS failure has occurred for a given set of power interruptions of specified durations to one or more mission system loads (otherwise provides a "0"). The Mission System Quality of Service model is represented by $q_{om(i,pi[k])}$ where i is the operational mode, and $pi[k]$ is a vector of power interruptions for the k mission loads.

c. Power System Concept of Operations that determines which power system components are online and in what configuration for each ship operational mode. $p_{om(i,j)}$ returns the fraction of time that power component j in operational mode i is online.

d. Power system Reliability Model that provides the MTBF r_j for each power component j where time is measured in hours that the component is on (operational time).

e. Power System Fault Effects Analysis that determines for each failure of a power system element j, the vector of power interruptions for each of the k mission loads: $pi_j\,[k]$.

The fraction of time that a QOS failure will occur in response to the failure of power system component j is given by

$$f_{qos(j)} = \sum_{i=1}^{n} f_{om(i)} p_{om(i,j)} q_{om(i,pi_j[k])} \qquad (1)$$

The fraction of time that component j is on is given by

$$f_j = \sum_{i=1}^{n} f_{om(i)} p_{om(i,j)} \qquad (2)$$

The MTBF of component j based on calendar time instead of operational time is given by

$$r_{c(j)} = \frac{r_j}{f_j} \qquad (3)$$

Since the reciprocal of MTBF is the failure rate, then the QOS failure rate due to each power system component is given by:

$$\frac{1}{QOS_j} = \frac{f_{qos(j)}}{r_{c(j)}} \qquad (4)$$

Thus the QOS provided to the mission system due to the failures of all power system components (measured as a MTBSI) is given by

$$\frac{1}{QOS} = \sum_{j=1}^{m} \frac{f_{qos(j)}}{r_{c(j)}} \qquad (5)$$

$$QOS = \frac{1}{\sum_{j=1}^{m} \frac{f_{qos(j)}}{r_{c(j)}}}$$

The difficulty with this method is that predicting the MTBF for equipment is not easy. Generally it is only known to a certain confidence level because testing becomes very expensive in both time and money to establish high confidence levels.

This method also assumes that the mean time to repair (MTTR) a power system component is very small compared to the MTBF such that the probability of multiple failures is so small that these cases can be ignored. It also assumes that the power system is designed such that under all conditions without a power system component failure, there are no Quality of Service failures.

An alternate method for calculating QOS would require creating an interconnected model of the power system and mission system and using Monte-Carlo or other stochastic simulation methods to predict the MTBSI without resorting to the simple summations and fixed failure rates used in the method above. The assumptions on MTTR and no QOS failures under non-failure conditions can also be relaxed.

Sizing Power Generation Modules

The rating of all Power Generation Modules must be sufficient to meet the worst case load (including margin and service life allowances) under the Ship Concept of Operation. Because the reliability of a Power Generation Module will generally be considerably less than the QOS requirements, one must design for the condition where a Power Generation Module goes down for maintenance. For IPS ships, the largest individual power generation module should have a rating less than the total Exempt Load. For non-IPS ships, an additional power generation module is required such that the remaining capacity after loss of the highest rating power generation module is sufficient to meet the worst case load.

In determining the number and type of power generation modules, the power system engineer should also understand the fuel consumption curves of each power generation module to ensure that the resulting system will be optimally efficient over the Ship Concept of Operation using the Power System concept of Operations. A composite specific fuel consumption curve showing the total electric plant's specific fuel consumption (amount of fuel consumed divided by [power times time]) vs total electrical load

Some ships will have special operating modes, such as low signature mode, which can only be met with a fraction of the installed power generation modules. The requirements must be very clear as to the QOS requirements and mission capabilities that must be achieved under these special modes of operation to preclude either over-designing or under-designing the power system.

Sizing Zonal Distribution Equipment

Properly sizing zonal distribution equipment is not as straightforward as one may think. Power electronics do not have an inherent overload capability. Instead electronic power conversion equipment must be designed (and priced) for the worst case loading condition … whether under normal operations or in a fault reconfiguration procedure. The problem of sizing distribution equipment consists of two problems: predicting the maximum load under normal conditions, and predicting the maximum load due to the failure of another power system element.

Traditionally, loads have been amalgamated for power generation sizing purposes using load factors as part of an electric plant load analysis described in DDS 310-1 (Naval Sea System Command 1980). This methodology however, only works if the largest individual load is much smaller than the power generation capacity and there are many loads. The presumption is that with the large number of small loads, the variance of the total load will be small compared to the average of the total load and when added to the average load, is well within the overload capability of the prime movers and generators.

Within the power distribution system however, the number of loads energized by a power distribution element may not be large, and the largest individual load maybe a significant fraction of the total load for the power distribution element. For these situations, a stochastic approach has been proposed by Amy (2005). Alternately, the inability of a power system to serve all loads can be treated as a power system failure (that may or may not lead to a Quality of Service failure) and incorporated into a stochastic Quality of Service model.

In general, power system design should use redundancy to address power system components that are not highly reliable. This redundancy could be provided within a power system module (such as providing N+1 inverter modules within a power conversion module), or by providing redundant power system modules (such as providing loads with two sources of power). Often, providing the N+1 component redundancy will be the cheapest solution. However, survivability requirements may drive one to providing loads with two sources of power. If survivability drives one to provide the two sources of power, then one should take advantage of this and not additionally provide the N+1 component redundancy within the modules.

Energy storage can be a useful tool for buffering loads from power system interruptions. In the context of Quality of Service, energy storage is useful for:

a. Providing power to un-interruptible loads during power system reconfiguration and fault isolation. In this context, the power requirements are determined by the amount of un-interruptible loads, and the energy requirements (in terms of hold up time) is only on the order of seconds. This will only work if the power system is configured such that the stored energy is dedicated to only un-interruptible loads. High power, short hold up time energy storage requirements generally drive one to flywheel or capacitor based solutions.

b. Providing power to un-interruptible and short term interruptible loads due to loss of prime mover. In this case, the required hold up time is on the order of 5 to 30 minutes for a relatively high level of power. If the entire ship's un-interruptible and short-term interruptible loads can be powered by the energy storage, then the ship can safely operate in a "single engine" cruise mode without sacrificing Quality of Service.

DESIGNING FOR SURVIVABILITY

Survivability Requirements

Ship survivability is more than just incorporating features into a ship design. For maximum effectiveness at lowest costs, survivability should be an important consideration for the design of the system architecture of each mission and distributed system as well as the physical arrangements of system elements on the ship. Furthermore, alignment of the different systems architectures is needed; distributed and mission systems should not be designed completely independently of each other.

Ideally, the ship survivability requirements are defined by the "customer" in terms of Design Threats and Design Threat Outcomes. In reality, the ship designer may have to develop the Design Threats and Design Threat Outcomes and gain concurrence from the "customer." To reduce the analytical and design costs, define the fewest design threats necessary to properly characterize the survivability requirements. The set of design threats should stress different aspects of the ship design, but should not include overmatching threats. Likewise, design threats should be chosen that can be properly modeled in the survivability analysis. In some cases, especially when designing for future weapons capabilities, developing a hypothetical design threat with assumed properties may prove beneficial.

For many early stage studies, determining which of the design threat outcomes constrain the design is of great interest. Response Surface Methodologies may prove useful for these types of studies.

Zonal Design

The basic concepts of Zonal Design and its relationship to survivability (and Quality of Service) are described in detail in Doerry (2006). Once a ship concept of operation has been defined and the survivability requirements articulated in the form of Design Threats and Design Threat Outcomes, the following design process is recommended for early concept and feasibility studies:

a. Identify zone boundaries. Zones should be large enough such that weapons induced damage for non-overmatching threats will not span more than two adjacent zones. Zones should align with watertight bulkheads. There should be enough zones such that sufficient mission capability will survive the loss of any two adjacent zones. For most surface combatants, 5 to 7 longitudinal zones typically provides sufficient arrangement flexibility while preserving survivability performance.

b. Define a notional architecture and concept of operation for each distributed system.

c. Identify and allocate Mission System elements to zones. For Mission Systems that are expected to operate as part of a Design Threat Outcome to a challenging Design Threat, the mission system should include sufficient redundancy and spatial separation such that the mission system capability is preserved with the loss of all mission equipment in any two adjacent zones.

d. Create a list of equipment to implement the notional distributed system architecture and mission systems. Ensure the distributed system components have sufficient capacity to meet margined load and service life requirements.

e. Incorporate the equipment from the notional architecture into the appropriate ship synthesis model.

f. Analyze the synthesized ship in terms of Quality of Service and Survivability (using tools such as VIVA) to verify requirements are met. Identify cost and performance drivers to identify potential changes to the ship configuration to better meet ship concept requirements at the lowest cost. This optimization process can be accomplished manually, or may employ methods such as design space explorations, genetic algorithms, Monte Carlo methods, or gradient methods.

Source – Load Alignment

If one were able to economically match electrical system generation capacity to load capacity within each zone, survivability would be enhanced because zonal survivability would not require zones to interconnect. Interconnections would be provided to achieve QOS requirements with minimum additional capacity. Shiffler (1993) proposed such an architecture for a zonal firemain.

Because of size and weight considerations as well as arrangement challenges associated with intakes and uptakes, the physical location of electrical power generation modules is constrained in the design of a ship. Given these constraints, the ship designer should attempt to locate Power Generation Modules in the same zones as large or critical electrical loads such as propulsion, high power sensors, mission systems, or electric weapons.

Because of the reduced need for intakes and uptakes, fuel cells in the future may enable a closer matching of loads with power generation. Due to their slow dynamic response time, fuel cells may have to be integrated with energy storage to provide adequate transient response.

Spatial Redundancy

Mission Systems that are required to survive a design threat, as well as distributed systems should be architected to enable spatial redundancy. Spatial redundancy enables the mission system or distributed system to operate without the equipment in any two arbitrary adjacent zones. If the mission systems and supporting distributed systems are all spatially redundant, and therefore provide zonal survivability, then the mission system will survive the design threat, assuming damage control efforts are sufficient to prevent spread of damage outside the damaged zones.

Spatial redundancy of mission systems also improves Quality of Service by reducing the impact of a distributed system failure on the ability of the system to perform its mission.

Forward Propulsors

Historically, most surface combatants have employed twin shafts to provide redundancy, improve maneuverability at low speed, and for survivability. Recent analysis (NAVSEA 2007) has shown that applying spatial separation to propulsors can enhance survivability while maintaining redundancy, maneuverability at low speed and reducing acquisition and lifecycle costs. The configuration studied included an electrically driven forward propulsor capable of propelling a ship to 12-15 knots along with a traditional mechanical drive and rudder aft. Variations of this concept may also prove advantageous. Because gas turbines and diesels have a relatively low MTBF, the reliability of the single propulsion shaft aft can be improved over the use of a single prime mover by using either 2 prime movers mechanically connected via the reduction gear, using 1 prime mover and an electric motor (hybrid plant), or using 1 or 2 electric motors.

Additional technical development of forward propulsors is needed to optimize efficiency, reduce noise, increase shock tolerance, and reduce cost. Historically, the need to keep sources of noise as far from the forward sonar dome as possible has ruled out the effective use of forward propulsors for all but emergency operation. Newer sonar technologies are enabling the naval architect to now consider using forward propulsors.

FUTURE WORK

A number of tasks still need to be accomplished to institutionalize the use of Quality of Service, Design Threats, and Design Threat Outcomes into ship design. Among these tasks are:

a. For future ship designs, having the customer (OPNAV) express survivability requirements in terms of Design Threats and Design Threat Outcomes. Ideally this would be codified in a revision to OPNAVINST 9070.1.

b. Developing inexpensive and quickly executed methods to model the impact of survivability and Quality of Service on distributed systems during early stage design. Goal is to produce “Good answers Fast” with a minimum of resources.

c. Developing repeatable processes for predicting Design Threat Outcomes during Preliminary / Contract Design. The processes should be fast enough to complete as part of a typical 8 to 10 week design cycle iteration. The time allocated to analysis is usually on the order of 4 to 6 weeks.

d. Developing repeatable processes for specifying and predicting Quality of Service metrics for distributed systems.

e. Develop repeatable processes for verifying prior to ship acceptance, that the ship will meet Quality of Service and Survivability requirements.

f. Development of a military qualified forward propulsor in the 5 to 10 MW.

CONCLUSIONS

Achieving Quality of Service and Survivability requires a design process that incorporates these concepts into the systems architecture of a ship’s power system and mission systems.

While it is relatively straightforward to design an electrical system to provide a given level of Quality of Service, translating the mission system needs into Quality of Service requirements and providing the least cost solution to meet these QOS requirements is non-trivial. This paper provides a simplified approach for modeling QOS and suggests alternate ways to model QOS with greater precision.

Survivability requirements should be specified in terms of design threats and design threat outcomes. Analysis tools such as VIVA are enabling the use of outcome based metrics to guide design, rather than feature-based specifications. In power system design, the use of zonal design methods, along with aligning the power system architecture with the systems architectures of other distributed systems and mission systems can improve survivability.

Finally, spatially separating propulsors by installing an electrically driven propulsor forward and a single shaft aft can improve survivability while reducing acquisition and lifecycle cost and maintaining reliability.

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