Shipboard Electrical Power Quality of Service

CAPT Norbert H. Doerry, USN, *Member, IEEE*, and David H. Clayton, *Member, IEEE*

Abstract – Although the U.S. Navy has decreed that the primary aim of the electric power system design will be for survivability and continuity of the electrical power supply, metrics have never been developed for continuity of service. This paper examines design issues associated with providing continuity of service under other than combat damage conditions and proposes a Quality of Service (QOS) metric to aid shipboard power systems design. This QOS metric is based on the probability that the power system will provide the degree of continuity of power that each load needs to support the ship's missions. The major factors impacting QOS are the ratings, reliability and failure modes of the prime movers, power conversion equipment, and load equipment as well as system configuration. Additionally, while design features for QOS often improve system survivability, different failure modes require the designer to consider both survivability and QOS.

Index Terms – Design Methodology, Energy Storage, Load Shedding, Marine Vehicle Power Systems, Military Equipment, Power Generation, Power System Availability, Power System Control.

I. INTRODUCTION

Historically, even though the principal design considerations for the design of U.S. Navy shipboard electrical power systems has been survivability and continuity of service, demonstrating that a power system provides continuity of service through metrics has not been a standard practice [1]. Instead, prescriptive practices such as use of an N+1 rule for generator selection and sizing were presumed to provide good quality of service. In the past, it has been sufficient to use good engineering judgment and lessons learned from previous designs to ensure acceptable levels of performance are incorporated into each contract design. During the past fifteen years, acquisition reform including Cost As an Independent Variable (CAIV) have put more and more emphasis on design optimization. Appropriate metrics are required to assess cost and operational effectiveness and to support the Government's role of design certification. Additionally, the introduction of all electric auxiliaries (most notably are the large loads associated with resistive heating), zonal architectures, integrated power systems, and DC distribution systems has resulted in power systems very different from the radial power systems for steam ships on which our legacy prescriptive design practices are based. Because prescriptive design practices optimized for the evolving power system technologies planned for the next generation of warships do not exist, it makes sense to rely on performance criteria to assure a well designed power system that does not restrict innovation. To properly specify the work to be performed by the ship design agent and to certify the design, key performance metrics and the means to calculate them become essential.

This paper examines the practical design issues associated with providing continuity of service under other than combat damage conditions and proposes a Quality of Service (QOS) metric to aid in the design, design certification and operation of shipboard power systems. The QOS metric proposed is based on the probability that the power system will provide the continuity of power that each load needs to support the ship's missions. The major factors impacting QOS are the ratings, reliability and failure modes of the prime movers, power conversion equipment, and load equipment as well as system configuration. To properly calculate QOS, the authors propose to classify loads into one of three QOS categories and to modify the Electric Plant Load Analysis (EPLA) process to include the QOS category for each load. The paper concludes with a discussion of the relationship of QOS to ship survivability and suggests future work to institutionalize the use of QOS metrics in ship design.

II. BACKGROUND

Since 1990, the design of naval electrical power systems has evolved from radial distribution systems for ship-service loads to zonal distribution systems that are integrated with electrical propulsion. [2] [3]. Figure 1 is an example of a typical Medium Voltage AC Zonal shipboard electrical distribution system coupled with a hybrid mechanical and electrical propulsion system. Figures 2 and 3 show the typical architectures for an Integrated Power System (IPS) medium voltage bus and for the DC-Zonal Integrated Fight Through Power (IFTP) system respectively.

While integrated power systems and zonal architectures provide significant flexibility and redundancy in providing sources of power for loads, the architectures in themselves do not assure QOS. Because of the relatively low Mean-Time-Between-Failure (MTBF) for prime movers, the most likely power system failure onboard a ship is loss of a generator set. With the migration of steam auxiliaries to all-electric auxiliaries and resistive heaters, as well as the introduction of integrated electric propulsion, the power rating of generator sets has grown significantly in the past fifteen years. These larger generator sets typically have a lower relative rotating moment of inertia, require longer to start and bring online from a standby condition, and typically have an overload rating of 110% vice the 150% of smaller generators. The loss of a large generator presents a number of problems not previously faced. First, it will take longer for the standby generator to come online, Second, since the generator sets are not capable of producing significant overload power, frequency regulation will falter at a lower overload rating. Finally, once frequency regulation fails, it will happen much more quickly because of the lower relative rotating moment of

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inertia. The bottom line is that generator sizing, protective relaying, and power system controls must all be designed holistically to ensure satisfactory Quality of Service.

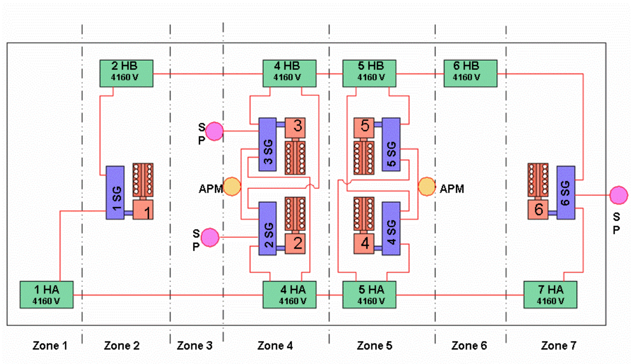

Fig. 1. Notional AC-Zonal Distribution System

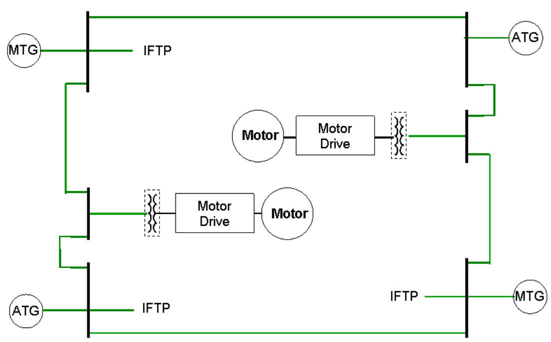

Fig. 2. Notional IPS Medium Voltage AC Distribution System

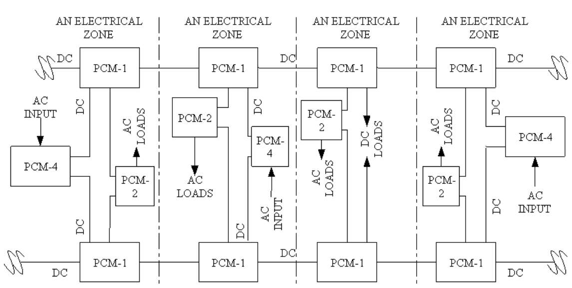

Fig. 3: Notional Integrated Fight Through Power System

III. DISCUSSION

A. Quality of Service

Quality of Service is a metric of how reliable a distributed system (electrical power system) provides its commodity (electrical power) to the standards required by the users. It is calculated as a (MTBF) of the power system as viewed from the loads. A failure is defined as any interruption in service, or commodity parameters (Power Quality) outside of normal limits, that results in the load equipment not being capable of operating properly. The time is usually specified by an operating cycle, Design Reference Mission (DRM), Concept of Operation (CONOPS) or an Operational Architecture. Quality of Service is a reliability-like 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 the shifting of sources for the commodity such as 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 differ for QOS considerations and for survivability considerations. In the electric plant for example, an 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.

B. Un-interruptible Load

Un-interruptible Load is a proposed QOS term for categorizing electrical loads (Other proposed QOS load categories are Short-Term Interrupt and Long-Term Interrupt loads). An electrical load would be classified as a Uninterruptible Load if it 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. Uninterruptible loads are typically provided a Standby Power System, an Uninterruptible Power Supply, or auctioneering DC diodes. Quality of Service Load Shedding is not performed on Uninterruptible Loads (Quality of Service Load Shedding is explained in paragraph III F).

C. 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 cannot tolerate interruptions of greater than 5 minutes. The two second limit 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. The five minute limit is a nominal time in which a standby generator should be capable of starting and providing power. Quality of Service Load Shedding is not performed on Short Term Interrupt Loads.

D. 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. Quality of Service Load Shedding is performed on Long Term Interrupt Loads. Generally, standby generators should come on line within 5 minutes and restore power to

Long Term Interrupt Loads in less than five minutes. Once an interruption reaches 5 minutes in duration, the electrical plant shifts to Mission Priority Load shedding (explained in paragraph III G). Lower Mission Priority loads are shed while higher mission priority loads that are long term interrupt loads are restored.

E. Exempt Long Term Interrupt Loads

Certain long-term interrupt loads may be exempted from QOS calculations. For IPS configurations, 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, non-exempt Long Term Interrupt Loads, and exempt Long Term Interrupt 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 Long Term Interrupt Loads with one generator out of service. Unless otherwise specified in the ship's requirements documentation, all Long Term Interrupt propulsion loads should be designated exempt.

The concept of the "Exempt Long Term Interrupt Load" is only used in sizing the installed generation capacity of the ship. In operation, Quality of Service and Mission Priority load shedding is not sensitive to the Exempt Long Term Interrupt Load designation.

F. Quality of Service Load Shedding

Quality of Service Load Shedding occurs when online power generation capacity is insufficient to service all loads. During Quality of Service load shedding, sufficient Long Term Interrupt Loads are shed until the online power generation capacity is sufficient to meet the power demand. If shedding of Long Term Interrupt Loads does not sufficiently lower the power demand, then Short Term Interrupt loads and Un-interruptible loads are shed based on Mission Priority Load Shedding. The start of a standby generator is also initiated to increase online power generation capacity. If after five minutes power has not been restored to Long Term Interrupt Loads, Mission Priority Load Shedding is initiated. This may result in restoring power to higher priority Long Term Interrupt loads by shedding power to lower priority Short Term Interrupt and Un-interruptible loads.

G. Mission Priority Load Shedding

If power generation or distribution capacity is not sufficient and cannot be made sufficient to meet demand within the quality of service power interruption time interval, a Quality of Service failure will occur. Mission Priority Load shedding ensures that the lowest priority loads for a given operational condition suffer the quality of service failure, while the highest priority loads maintain continuity of service. This generally means that at the end of the Long-Term Interrupt interruption interval of 5 minutes, lower mission priority Un-interruptible and short-term interrupt loads are shed to enable restoration of service to higher priority long-term interrupt loads.

H. Design Reference Mission

A Design Reference Mission (DRM) is a timeline consisting of a sequence of planned operations of the ship conducted during a specified mission duration. The DRM is used to help determine which equipment should be operational and the probability that a given power system element will fail in calculating Quality of Service metrics. For a robust ship design, multiple DRMs may be used to stress different aspects of the ship design.

The role of a DRM may be fulfilled by Operational Architecture views if a DoD Architecture Framework is used. Specifically, well defined Operational Activity Models (OV-5) and Operational Activity Sequence and Timing Descriptions (OV-6A, 6B, and 6C) should satisfy the requirements for a DRM [4].

I. Survivability

Survivability for future ship designs will likely be defined by Design Threats and Design Threat Outcomes. 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.

The Design Threat Outcome is a metric for total ship survivability and is defined as the acceptable performance of the ship in terms of the aggregate of susceptibility, vulnerability, and recoverability when exposed to a design threat. Design Threat Outcome definitions could include statements such as:

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

The levels of survivability for the design threats can be evaluated using Total Ship Survivability Assessment (TSSA) methods [5]. The assessment of susceptibility should include Quality of Service to ensure the availability of threat deterrent systems that are dependent on electric power. The assessment of vulnerability should include the effect on mission capability of the design threat with respect to Quality of Service failures. Analysis of Quality of Service failures and their impact on mission capability is also important in the assessment of recoverability.

IV. QOS AND ELECTRIC PLANT DESIGN

As defined above, QOS is specified as a Mean Time Between Failure (MTBF). In developing a power system design, what value for MTBF should one use for QOS purposes? The authors contend that a reasonable value is in the vicinity of 30,000 hours (3.4 years). Since an electrical distribution system must function all the time, operational time is the same as calendar time. Thus, on average, each load on the ship would experience one or fewer QOS failures during the nominal 2 to 3 year tour of duty of the ship's crew. An isolated failure is generally accepted by the crew as an anomaly, whereas, repeated failures are not viewed favorably.

Calculating the QOS of a power system can be greatly simplified if the Mean Time to Repair (MTTR) and Mean Logistics Delay Time (MLDT) of equipment are sufficiently short as compared to the Mean Time Between Failure for the equipment to achieve a very high Operational Availability (A_o) [6].

$$A_O = \frac{MTBF}{MTBF + MTTR + MLDT} \tag{1}$$

If every element of the power system can achieve an A_o of greater than about 0.995 and the failures are random and independent, then the probability of multiple simultaneous failures is sufficiently low therefore these cases can be ignored. This means that for QOS calculations, one need only examine the impact of each power system element failing by itself, although, QOS Analysis should examine multiple simultaneous failures for power system elements with an A_o less than about 0.995.

In general, one should design the electrical plant using reliable components and sufficient redundancy and reconfigurability to minimize the cases where the failure of a single element of the power system will result in one or more Quality of Service failures.

For most naval power systems, the prime movers are either gas turbines or diesel generators. While a sufficiently high Operational Availability is achievable for these prime movers, their MTBF can typically be measured in the thousands of hours. Hence the power system design must provide sufficient capacity, redundancy and reconfigurability to achieve the desired 30,000-hour QOS MTBF.

With all generators online, the power system should have sufficient capacity to serve the worst case load. With all but any one generator online, the power system should have sufficient capacity to service the worst case load less the exempt long-term interrupt loads. Normally, non-IPS ships will not have exempt long-term interrupt loads and the criterion is in effect an N+1 rule. For IPS ships, the exempt long-tem interrupt loads are normally a portion of the propulsion load, ensuring sufficient capacity with one or more generators off line for ship service loads.

For systems without energy storage modules, under any normal operating condition, generators should be sized and the power system configured such that the loss of each online generator by itself results in sufficient remaining online generation capacity to service all Un-interruptible and short term interrupt loads. (See Option A of Figure 4)

For systems with energy storage modules, under any normal operating condition, generators should be sized and the power system configured such that the loss of each generator by itself results in sufficient remaining online generation capacity plus energy storage power capacity to service all Uninterruptible and short term interrupt loads. The energy capacity of the energy storage module should account for:

- A generator set tripping off line repeatedly after being loaded. One should assume that the generator trips offline 3 times for 5 minutes in duration, with each trip occurring in less than a minute after it is brought on line
- Recharging the energy storage module should be accomplished as quickly as possible but should not require the shedding of any other load. Limiting the recharge time to under four to six hours is reasonable.

Option B of Figure 4 shows how an energy storage module can augment a small generator set to provide hold up time to short term interrupt and Uninterruptible loads until a sufficiently large standby generator is brought online. Option C of Figure 4 shows how a larger energy storage module can enable single engine cruise operation by providing sufficient capacity to service all Uninterruptible and short term interrupt loads until a sufficiently large standby generator is brought online.

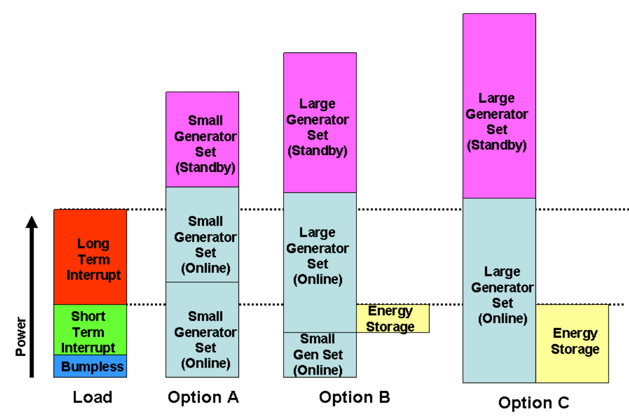

Figure 4: Generation Capacity Options

Where possible, power electronics conversion devices should incorporate hot-swappable power modules and sufficient installed redundancy and capacity to enable replacement of failed modules without suffering a Quality of Service failure. Alternately, the power electronics conversion devices should be significantly more reliable than the target QOS MTBF of 30,000 hours.

To maximize the amount of long-term interrupt loads, loads that have multiple levels of operation may designate different QOS categories to each level. For example, IPS designs could assign QOS categories to different increments of propulsion power: sufficient power to maintain steerageway could be short term interrupt, the remaining propulsion power required to maintain the ordered speed would be long-term interrupt. Likewise, the design of the electrical lighting in a space should enable assigning half as long term interrupt loads and the other half as short term interrupt loads. The loss of half the lighting in a space for 5 minutes should not significantly impact the ship's operations.

From the discussion above, designing the electric plant for QOS requires knowledge as to the total anticipated load in each QOS category for various operational conditions. The authors propose that this data be captured as an additional field in the Electric Plant Load Analysis (EPLA). The EPLA is currently used to size distribution system equipment, power cables, and generation capacity. Extending its functionality to include QOS information should not be difficult.

V. QOS AND ELECTRIC PLANT CONTROLS DESIGN

Electric Plant Controls play a critical role in achieving QOS. The power system must also be controllable to enable both QOS load shedding and Mission Priority Load Shedding. Load shedding can be accomplished by opening a switch or circuit breaker in the power system, or by sending a control command to the load to shut down. To enable the loads to shut down in an orderly and safe fashion, this latter method is preferred if the load supports this capability.

Figure 5 shows the expected response of the control system to loss of an online generator in a notional three generator set plant. The immediate reaction of the system is to shed sufficient Long Term Interrupt loads fast enough to prevent overloading the remaining online generator and causing it to trip off line as well. The control system must reconfigure the electrical distribution system to ensure all Short Term Interrupt loads are restored within 2 seconds. Additionally, the standby generator is commanded to start and come online. Within five minutes, the Standby Generator should be operational and the Long Term interrupt loads restored.

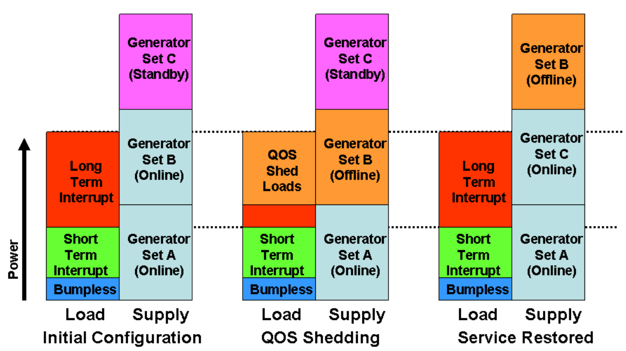

Fig 5. Control System Response to Loss of 1st Generator

Figure 6 shows the expected response of the control system to loss of a second generator set. In this case, we start where Figure 5 ends: Two Generators online and one offline and inoperative. Upon loss of the second generator, the immediate response is identical to Figure 5: Sufficient Long Term Interrupt Loads are shed and the system reconfigures to restore Short Term Interrupt loads within 2 seconds. If after diagnosing the two offline generators and determining that neither can be started, or if the five minute window is about to expire, the control system shifts to Mission Priority Load Shedding. Low Priority Un-interruptible and Short Term Interrupt loads are shed to provide power to higher priority Long Term Interrupt Loads.

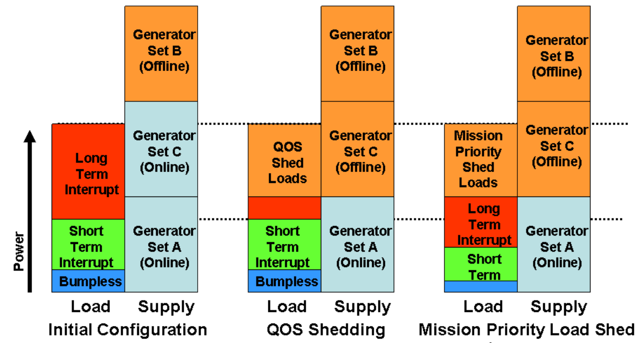

Fig. 6. Control System Response to Loss of 2nd Generator

Ideally, the machinery control system would continually perform contingency planning in the background to develop an optimal response to likely casualties. In the case of Figure 6, if the machinery control system can quickly (in less than a second) determine that neither of the offline generators could be started, then it could skip the QOS Load Shedding step and transition directly to Mission Priority Load Shedding.

VI. SINGLE ENGINE OPERATIONS

Single engine operations are being considered to save fuel especially in IPS plants where large single generators can offer a significant combination of mobility and other operational capability. A Quality of Service analysis should include mission CONOPS and plant reconfiguration scenarios and single engine operations offers challenges to electric plant design and control.

VII. QOS AND SURVIVABILITY

Warship Electric Plant design must account for Survivability in addition to QOS. Many of the features provided to achieve QOS requirements will make the ship more survivable, however only designing for QOS is not sufficient. In particular, the failure modes considered for QOS purposes are significantly different from those that must be considered for survivability. As stated previously, designing for Quality of Service is largely a matter of accounting for the failure modes of the least reliable equipment in the power system, and ensuring that the system responds in a manner such that loads do not experience a Quality of Service failure. The probability of failure for power system equipment under battle damage conditions is not directly related to reliability. Furthermore, battle damage usually results in multiple simultaneous faults, generally concentrated in a specific damaged geographic part of a ship. For QOS calculations, the failure of highly reliable distribution system equipment such as transformers, cabling, and switchgear, if sized properly, is not of significant concern. On the other hand, the failure of these devices is highly probable in a battle damage scenario.

For future warship designs, ship survivability will likely be specified in terms of a Design Threat Outcome when subjected to Design Threats. If a ship is expected to remain afloat and recover from damage, then the size, location, redundancy, physical properties and geographic location of power system components as well as the reconfigurability and fault isolation capability of the system design become very important. Non-redundant mission critical Short-Term and Long-Term interrupt loads may be provided with multiple sources of power to enable their continued operation if undamaged when subjected to a design threat. Zonal ship design considerations to address survivability and quality of service issues are discussed in [7].

VII. FUTURE WORK

The concept of Quality of Service as presented in this paper has not been developed sufficiently for institutionalization into the ship design process. This lack of formality should not prevent ongoing ship designs from considering or using QOS in their system design. Additional tasks that should be completed as quickly as possible include:

- Gain a better understanding of power system equipment failure modes and their impact to QOS to determine appropriate MTBF and Ao to use in QOS calculations.
- Understand the impact of the failure of Un-interruptible loads on the QOS of other aggregated Uninterruptible loads.
- Develop specific design guidance for classifying loads into Uninterruptible , short-term interrupt, and long term interrupt loads.
- Develop estimating relationships for determining the electrical load in each of the different categories to assist in early stage ship design. Incorporate QOS based design into early stage ship design tools.
- Gain industry feedback on the proposed methodology presented in this paper in preparation for developing modifications to the Naval Vessel Rules (NVR).
- Modify the requirement for the Electric Plant Load Analysis to include fields for QOS category.
- Develop in-zone distribution and control architectures and concepts to minimize the cost of implementing both QOS and Mission Priority load shedding.
- Develop Cost Estimating Relationships to reflect the proposed changes in power system design.

VIII. CONCLUSIONS

Designing shipboard power systems for QOS will ensure that under normal operating conditions that the ship will likely be able to perform its mission. Because of the changing characteristics of the prime movers, distribution systems, and loads, past practice will no longer suffice to achieve a good design. Using a design method that accounts for QOS, such as the one proposed in this paper, is vitally important in meeting the Navy's objective for continuity of the electrical power supply.

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X. BIOGRAPHIES

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