Operational Vignette-based Electric Warship Load Demand

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Abstract—The design and control of electric warship power systems is a complex, challenging problem and numerous power system architectures, technologies, algorithms, and control schemes have been proposed. Instead of a quantitative assessment of these ideas based on ideal, steady-state conditions, a set of representative operational vignettes that span the entire electric warship mission package is introduced in order to obtain true results. This paper describes a set of realistic test cases that provide load demand dynamics based on a variety of unique scenarios, mission load characteristics, and human-in-the-loop decision-making. Stochastic and deterministic power profiles are established for individual ship systems and mission loads, which are then combined together for a particular scenario. These test cases can be applied to early-stage design trade studies as well as design tool development. For example, various control methods can be benchmarked against the same test cases. In addition to the established test cases, the method used here enables operators to communicate to design engineers how they intend to use the ship (not the other way around).

Keywords—naval power systems; electric ship design; dynamic loads; stochastic loads

I. INTRODUCTION

Multi-mission high energy weapons and sensors on electric warships represent game-changing capabilities to the warfighter [1]. A common challenge to realize this future capability is designing a system architecture that reliably delivers power under potentially disruptive conditions to all loads, including pulse-power mission loads and propulsion [2]-[4]. Adding to the complexity is the nearly stochastic behavior of the aggregate load demand, where the magnitude of a single load can rival a single generation source and significant load variations can occur within very short time durations. During intense operational engagements, electric warships will experience the most demanding and dynamic load behavior – when reliability and resiliency is needed the most.

These load requirements are unique to Naval integrated power systems, and designing a suitable architecture using traditional design methods is not adequate. New metric-based methods and tools have been introduced to address these challenges. Recent results have shown valuable insight into various system architectures under disruptive conditions based on these dynamic mission loads [5]-[8] and the computationally low-cost modeling and simulation techniques they use [9] and [10]. Building on this body of work, a complementary approach for analyzing candidate electrical distribution topologies is introduced in [11] where a representative all-electric-ship load model is proposed.

This paper develops a systematic method for generating appropriately-scaled load demand profiles based on the ship’s intended operational use. By factoring in the operational environment and mission capability of the ship, specific scenario-driven vignettes can be mapped to unique ship-level dynamic load profiles. In this manner, the ship load demand profiles are ideally suited for the early design trade study tools. Herein, a representative power system architecture is proposed with locations for the various generators and loads, so the load profiles also introduce a spatial component to the simulation. With this tool, design studies on power system topology, architecture, dynamic load flow, control, and protection such as in [12] become more realistic and actionable for the early design trade space.

II. LOAD DEMAND GENERATOR FRAMEWORK AND FEATURES

The electric ship load demand assumes realistic operational scenario-driven episodes reflecting actual human-in-the-loop decisions. All loads are characterized and modeled, resulting in a complete set of independent load demand profiles in a given time frame. A principle advantage of this framework is that it focuses on accurate ship-level load dynamics without the need for architecture-specific characteristics, making it ideal for a wide variety of early design trade space studies. In developing the load demand, several key features were considered:

- Scalable: Individual load models can either be lumped-parameter or physics-based, depending on the appropriate trade-off between model fidelity and computation speed. At a minimum, lumped-load parameters include maximum and minimum power ratings for peacetime cruising and battle posture, ramp rates, pulse widths and repetitions.

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• Tunable: The load sampling frequency can be changed for adjustable model fidelity. Twenty samples per second are used for the lumped-parameter ship load model test case herein.

• Stochastic: Load parameters often behave as random variables. The model can introduce randomness to maximum ratings, pulse widths, pulse repetitions, and ship speed. For example, the propulsion load can be mapped to a random speed based on a probability density function of ship speed-time profile collected from actual U.S. Navy destroyer operations [13]. In the same manner, histogram data can be used to predict the number of times a pulse load will cycle.

• Expandable: The model is modular, making it easy to add or remove loads to define a new set of ship loads or include battle damage to the scenario.

III. NOTIONAL NAVAL POWER SYSTEM BASELINE

The notional all-electric ship baseline developed by the Electric Ship Research and Development Consortium (ESRDC) is a medium-voltage dc (MVDC) topology shown in [11] and re-envisioned in [12]. It features a 4-zone, 2-bus dc distribution system fed by two main turbine generators (MTG) and two auxiliary turbine generators (ATG). The complete load set consists of propulsion, service, radar, and three high-energy mission loads spatially separated throughout the ship for increased survivability as shown in Fig. 1. Zonal loads (ZL) and the Radar (R) are fed from the main buses by converter modules (CM).

To demonstrate the scalability of the load generation model, a comparison between two ships is presented with the same set of mission loads, but a different scaling of power requirements. Ship A is a notional near-term platform described in [9], with a total installed power of 82 MW. By comparison, Ship B is smaller in displacement, total propulsion power, and total installed power (48 MW), but its mission loads are representative higher-power, far-term, multi-mission pulse loads similar to those described in [14].

A. Service and Radar Loads

The topology in [11] contains 22 lumped-parameter loads spread proportionally throughout each zone, representing a full composition of ship-wide ac and dc service loads. The conversion modules (CM) shown in Fig. 1 are converting the dc bus voltage to the appropriate load voltage (ac or dc) in each zone. There are two states in the service load model. The “cruise” state represents the load demand during peaceful transit, while “battle” represents an increase in service load demand due to the need for added redundancy and survivability. For example, all firemain, seawater, and chill water pumps will be operating and cross connect valves closed during battle conditions. The service load model can add random fluctuations for lumped-parameter models or specific load profiles for detailed models if greater detail is needed. Herein, the service load demand is modeled as the aggregate of the 22 lumped loads in [11].

The radar model is similar to the service load model in that it operates at a “cruise” level when in a peacetime transit condition. Then, the load demand increases for “battle” condition where backup systems are energized for maximum redundancy and operating at full capacity.

B. Mission Loads

There are three high power mission loads in the ship set that are directly fed from the bus and identified as “ML1”, “ML2”, and “ML3” in Fig. 1. They are characterized by peak power, pulse duration, and slew rate as shown in Table I. The mission loads are shown in two locations to represent the physical layout, but the power level shown represents the total of each mission load in both locations; the power could go to either location or be split between the two.

Another characteristic of the mission load model is that the power and duration of each mission load can be modeled stochastically. Mission load 1 has a defined pulse duration (3s), and these pulses occur in sequential groups. The number of pulses in a group can be represented using the binominal distribution for the number of sequential pulses $N$.  

| TABLE I. THREE MISSION LOADS (MLX) FOR NOTIONAL SHIPS A AND B |
|---------------------|----------|-----------|-----------|
|                     | Peak (pu %) | Duration (sec) | Slew (pu/sec) |
| ML1                 |           |            |            |
| Ship A              | 24.4      | 3          | ± 1.22     |
| Ship B              | 41.7      | 3          | ± 2.50     |
| ML2                 |           |            |            |
| Ship A              | 0.9       | Various    | ± 1.22     |
| Ship B              | 43.8      | Various    | ± 2.50     |
| ML3                 |           |            |            |
| Ship A              | 0.6       | Various    | ± 1.22     |
| Ship B              | 4.2       | Various    | ± 2.50     |
The parameters for ML1 are $n=10$ and $p = 0.45$. This distribution is shown in the top of Fig. 2. For each operation, the power of each mission load can vary. As ML1 operates using groups of pulses, each pulse is assumed to be at the same power level. ML1 and ML2 exhibit similar characteristics in the power they use in that they typically operate near their max power (1.0 pu). The probability of operating at a given per-unit power level $Pwr$, termed the probability density function, is modeled with the Beta distribution,

$$
\Pr(Pwr = x) = \frac{x^{\alpha-1}(1-x)^{\beta-1}}{B(\alpha, \beta)}
$$

where $B(\alpha, \beta)$ is a normalization constant to ensure the total probability integrates to 1. The parameters $(\alpha, \beta)$ characterize the distribution and are 2 and 0.2 respectively.

The length of each pulse for ML 2 and 3 is represented by a truncated version of the Gaussian normal distribution. We assume there is some minimum practical activation time, as well as a maximum operational time due to cooling or other limitations.

The probability of a given operating duration $D$ is

$$
\Pr(D = x) = \frac{1}{\sigma} \phi \left( \frac{x-\mu}{\sigma} \right)
$$

$$
\Phi \left( \frac{b-\mu}{\sigma} \right) - \Phi \left( \frac{a-\mu}{\sigma} \right)
$$

where $\phi$ is the standard normal Gaussian distribution and $\Phi$ is its cumulative distribution. The mean and variance are $\mu$ and $\sigma^2$ respectively, while $[a,b]$ is the valid interval. ML2 has mean 30, variance 20, and operates between 2 and 60 s. ML2 has mean 120, variance 150, and operates between 5 and 300 s. These distributions are shown in Fig. 3.

C. Propulsion Load

The propulsion system consists of two propeller shafts connected to two spatially-separated motor and motor drive systems. The system interface to the power distribution system is shown as the Propulsion Motor Drive (PMD) interface off the port and starboard dc buses in Fig. 1. The total notional ship power versus speed curve is found in [11] and is a nearly cubic curve with 73.7\% (pu \%) at a max speed of 30 knots. Note that for Ship A and Ship B, the propulsion load characteristic is assumed to be similarly scaled and therefore maintains the same per-unit values. Additional parameter settings, such as slew rate for modeling increasing and decreasing speed, are nominally set to $\pm 1.5$ MW/sec for Ship A and $\pm 2.0$ MW/sec for Ship B.

IV. OPERATIONAL VIGNETTES

Six variants of a notional 10-minute operational vignette were considered to simulate the ship’s multi-mission capability and to severely – realistically – stress the integrated power system. The sequence of service, radar, mission, and propulsion load levels are shown in Table II. Here, service and radar loads begin at cruise-level and then transition to battle condition in support of an imminent operational threat engagement. Through a series of simulated detect-to-engage sequences and human-in-the-loop responses, the ship then initiates a series of pulse power multi-mission loads. Mission load characteristics in Table I are identified as a number of pulse repetitions shown in Table II and based on the density function equation (1). The pulse duration of Mission Load 1 is set to 3s, while Mission Load Two varies as a probability density function described in equation (3) and are set at 45, 15, 30, and 20 s.

![Fig. 2: Pulse load characteristics of ML1. The load operates with groups of pulses. The probability distribution for the number of pulses in a group is shown in the top plot. The power of the pulses in a given group is the same, but can vary for each group of pulses. The cumulative probability distribution for the pulse power is shown in the bottom plot. One can interpret this plot as the probability the pulses have a given output power or less. For example, there is only a 25% probability the power will be less than 0.9 pu.](image)

![Fig. 3: Probability distribution of operating time for ML2 and ML3. Both distributions follow a Truncated Gaussian Normal distribution with different parameters.](image)
Likewise, Mission Load Three pulse durations are set to 200 s and 120 s based on the same density function.

Propulsion power is the largest single load demand, so three degrees of propulsion maneuvering were used for comparison, as shown in Table II and in Fig. 4. From this plot, the impact ship speed has on available power can be readily seen. Ships A and B undergo the same operational scenario with constant, moderate, and aggressive propulsion load dynamics for a total of six variants based on the same operational vignette. The individual service, radar, mission, and propulsion load sequences are added, resulting in the total ship load demand profile for each variation.

V. RESULTS

The total load demand profile for six operational vignette variants described in Table II is shown in Fig. 5. Ship A, the electric ship with near-term mission loads and 82 MW of total installed power, is in the first column of results while Ship B, the smaller displacement and smaller installed power (48 MW) with higher pulse loads is shown in the second column. From the left column to the right in each row, the dashed line across the unity per unit power indicates the total installed power (1.0 pu) for Ships A and B. The rows of load profiles from top to bottom indicate the propulsion load dynamics of increasing ship maneuvering speeds.

For Ship A, the total peak load demand is well within the total installed power envelope at most speeds and only just begins to exceed it at its top speed (maximum propulsion load). If historical speed-time profiles are used, then probabilities can be quantified and speed envelopes can be established to mitigate the risk of exceeding the power generation capability of the ship. Localized energy storage can also be added to buffer the pulse loads from the bus and allow for ideal generator loading.

For Ship B, the total peak load demand begins to exceed the total installed power even at a low, constant speed. In order to realize this ship’s power system architecture, energy storage is not only necessary to buffer the pulse loads from the bus as discussed for Ship A, but also to store large quantities of energy to support the total ship load demand. By integrating the power profile, these results can be interpreted as an energy management problem, where storage capacity, type, and location can be studied.
Fig. 5: Total Load Demand Profiles for Ships A (left column) and B (right column) under constant speed (a,b) and moderate (c,d) or aggressive (e,f) maneuvering. Note the vertical axis values are the same for both columns, but change with each row. A dashed horizontal line indicates 1.0 pu generation power. Exceeding this threshold requires either more installed generation capacity or energy storage.
VI. CONCLUSIONS AND FUTURE WORK

In the larger body of work on developing early design tools for power system architecture assessment such as in [5]-[12], the premise that early design trade space studies should not assume a constant steady state condition is established. Rather, basing assessments on realistic dynamic loading under potentially disruptive conditions is most appropriate.

In this paper, a systematic method for generating total ship load demand profiles based on its intended operational use is introduced through a representative test case of six variants. The operational vignette represents a multi-mission situation where human-in-the-loop decisions drive the dynamic sequencing of service, radar, mission, and propulsion loads. Stochastic models are presented for various mission load power demands and durations. In so doing, the full ship load set spans the overall load demand profile. One advantage of this framework is that it focuses on accurately capturing ship load dynamics while severely stressing the power system. Since the notional power system baseline architecture is generally defined, it does not assume vendor-specific characteristics or point design solutions, which makes it ideal for early design trade space studies on architecture or control [15].

The set of load profiles are specified here as raw power demand from the perspective of the dc bus without considering the buffering effects of local energy storage. When viewed this way, integrating the total power profile provides insight into understanding energy storage characteristics such as capacity, charge rates, discharge rates, and power interconnect ratings. For future work, we anticipate a major area of research will develop around the best locations for energy storage units and tradeoff studies, one can add energy storage to the model at will. For example, adding localized storage at each mission load will limit the impact on the main bus, while adding centralized storage will require high-capacity interconnects.

REFERENCES