MVDC Shipboard Power System Considerations for Electromagnetic Railguns

N. Doerry[1] and J. Amy, Jr.[1]

[1] Naval Sea Systems Command, Washington Navy Yard, DC 20376 USA

Abstract— Affordably integrating an Electromagnetic Railgun (EMRG) into a surface combatant of less than 10,000 mt requires a new approach to shipboard power system design. An AC distribution system would be required to incorporate considerable dedicated power conditioning and energy storage that will present affordability and power density challenges. Migrating the electrical generation and primary distribution system from a traditional 60 Hz system to a Medium Voltage DC (MVDC) system enables the use of a power system – load interface standard that provides the reliability and quality needed by the EMRG while reducing the need for local dedicated power conditioning and energy storage. Recent accomplishments and ongoing trends indicate that MVDC is the most practical means to support high power electric weapons and sensors from both a power system perspective and a total ship perspective.

This paper presents an overview of a shipboard power system architecture. Particular details on the interface between the EMRG and the power system are highlighted. Proposed power interface standards will be discussed as well as the need for and the properties of a control interface between the power system and the EMRG.

I. Introduction

The warships of tomorrow will require ever evolving weapons and sensors to remain militarily relevant over their service life. Many of these weapons and sensors will present large, nonlinear, stochastic, and pulse loads to the power system. With an AC distribution system, warship designs would be required to incorporate considerable dedicated power conditioning and energy storage to adhere to established interface requirements. These dedicated power conditioning and energy storage solutions will present affordability, size, weight, and reliability challenges.

This paper provides an overview of a shipboard MVDC reference architecture that promises to be able to serve large, nonlinear, stochastic, and pulse loads more affordably and with less ship impact than a traditional 60 Hz system. This MVDC architecture is used to discuss design factors required to integrate pulse loads such as the Electro-Magnetic Railgun (EMRG). The detailed rationale for an MVDC architecture as opposed to a traditional AC architecture is provide in [1].

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of the Navy, the Department of Defense, or the U.S. Government.

II. MVDC Reference Architecture

Fig. 1 depicts a reference MVDC architecture for a naval warship with an EMRG based on [1]. Some important attributes of this architecture are:

a. Implementation of IEEE-1826 zonal architecture [2].
b. Number of zones determined by survivability requirements; the six zone design depicted in Fig. 1 is representative, not definitive.
c. MVDC primary power distribution.
d. MVDC interface with sources and loads solely via power electronic converters.
e. Distributed energy storage.
f. Large loads powered simultaneously via both port and starboard MVDC busses.
g. Large sources power simultaneously both port and starboard MVDC busses.

A. Power Generation Module (PGM)

For the near and mid-term, the use of traditional prime movers such as gas turbines and diesel engines is anticipated. The generator will have two independent sets of stator windings, each rated to deliver half the prime mover rating. These generators power independent active rectifiers for powering the MVDC bus. Powering both busses at the same time improves the ability of the system to balance loads, and reduces the impacts of bus faults on the transient performance of the PGMs.

To reduce generator size and to reduce filtering requirements on the active rectifiers, the generators are anticipated to produce AC power at a frequency higher than 60 Hz. Since a constant speed/frequency is not required, the controls for the prime mover and active rectifier can optimize the transient response of the PGM when subjected to pulse loads. In this manner, the stored kinetic rotational energy of the mechanical system and the stored electromagnetic energy in the generator windings can be more fully exploited to support pulse loads than is possible with traditional 60 Hz. generators.

B. Medium Voltage Direct Current (MVDC) distribution

The MVDC distribution system normally operates as independent port and starboard busses: the transverse cross-connect cables in zones 1 and 6 are normally left de-energized. Each bus is rated to handle half of the total electrical load on the ship. The busses are segmented by Bus Nodes which can disconnect faulted sections of the bus or faulted loads. The cross-connect cables in zones 1 and 6 can be used to power portions of the power distribution system that would otherwise be unpowered should one segment of a bus be isolated.

The nominal voltage for the MVDC distribution is anticipated to be one of the following; 6 kV, 12 kV, or 18 kV. Proposed power quality standards are provided by [3]. Based on the current state of power component technology and the anticipated needs of a future all-electric warship, 12 kV is anticipated to result in the most affordable system; 18 kV may prove more affordable in the future. If electric load requirements prove not to be as high as anticipated, a 6 kV system may be most affordable.

C. Power Conversion Module: PCM-1A

As depicted in Fig. 2, A PCM-1A is a scalable, modular power converter used to transform the MVDC from the distribution bus to electrical power needed by loads and the Integrated Power Node Center (IPNC). The PCM-1A is anticipated to consist of multiple input modules (I-modules), output modules (O-modules) and energy storage (ES) modules (ESM). As with today, most loads will be provided power via a 440 V 60 Hz. three –phase AC Distribution system powered by one or more O-modules. The IPNC will be powered by either a 440V interface or a notional 1 kV DC interface. Some special loads may be provided power directly from the PCM-1A via a DC interface as depicted in Fig 3. The PCM-1A is anticipated to have a total power rating on the order of one or several MW.

The PCM-1A may contain energy storage to provide power to in-zone loads during fault detection, localization, and isolation and/or to enable single-engine operation by providing backup power while a standby generator comes online. This same energy storage may also be employed as part of a ship-wide energy management strategy to support pulse power loads such as the EMRG.

D. Power Conversion Module: PCM-SP

A dedicated power conversion module is used to convert the type of power provided by the shore power station to each of the two MVDC busses. Shore power will likely be provided as either 4.16 kV or 13.8 kV 60 Hz 3 phase AC power.

E. Integrated Power Node Center (IPNC)

The IPNC incorporates power conversion input modules, output modules, and energy storage to provide dedicated high quality power to specific loads or sets of loads. Within the MVDC architecture, the IPNC is employed as a point-of-use converter for 400 Hz. AC legacy loads and 440 V 60 Hz. AC loads that require un-interruptible power (60 Hz. UI Loads). An IPNC may also be employed to power loads with special power quality requirements.

The IPNC is normally powered directly from the PCM-1A located in the same zone using either a 440 V 60 Hz. three phase AC interface, or a 1 kV DC interface. The choice of interface will be based on cost. A second 440 V 60 Hz. three phase AC interface, powered from the 60 Hz AC Distribution system, provides an alternate source of power.

The energy storage in the IPNC allows the 60 Hz. AC distribution system to reconfigure within ~1 second without impacting un-interruptible loads.

The IPNC is anticipated to have a total power rating on the order of several hundreds of kW.

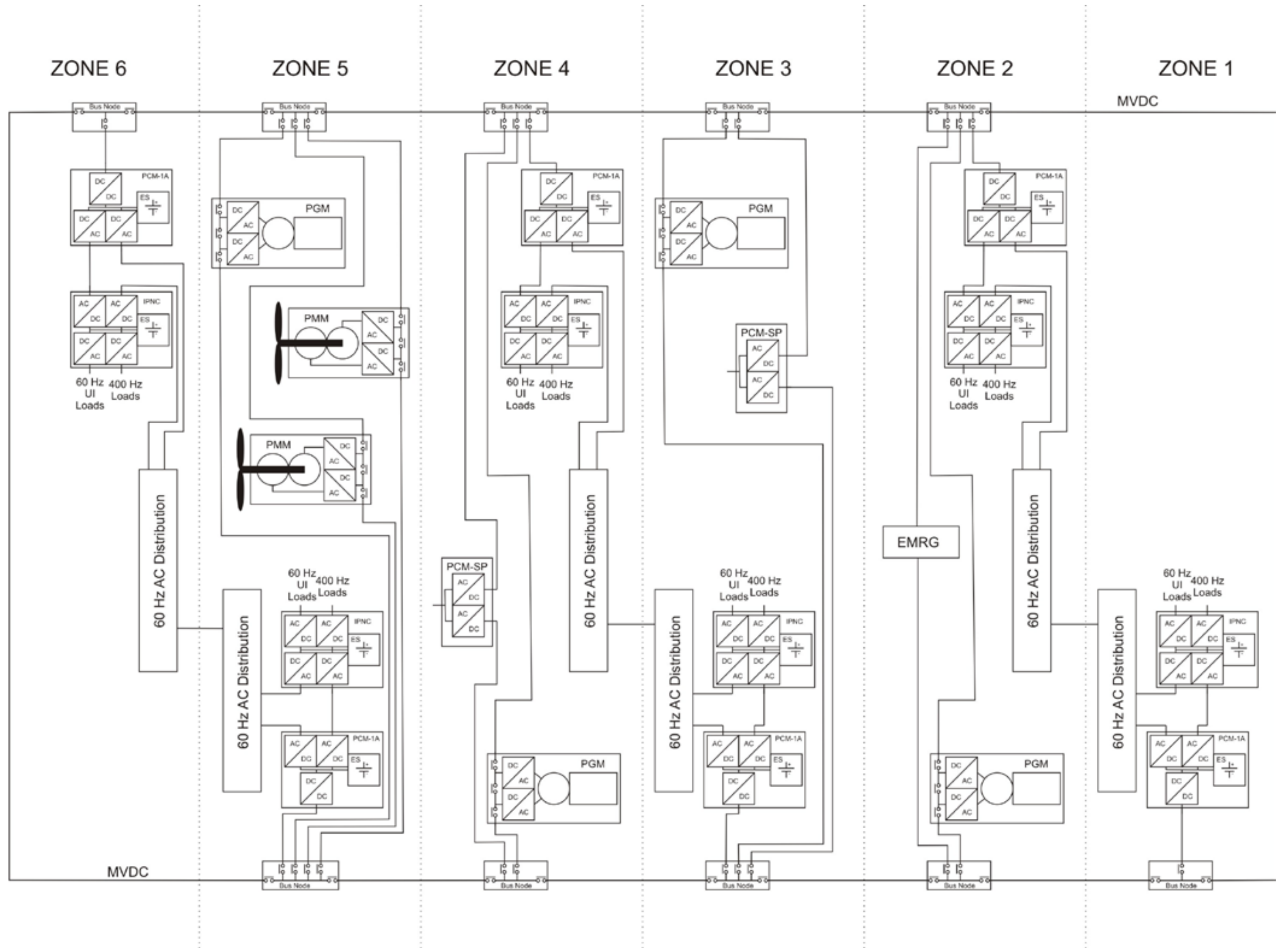

Fig. 1. MVDC Reference Architecture

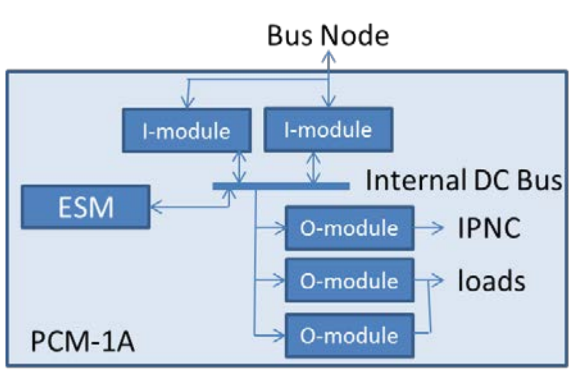

Fig. 2. Notional PCM-1A Architecture

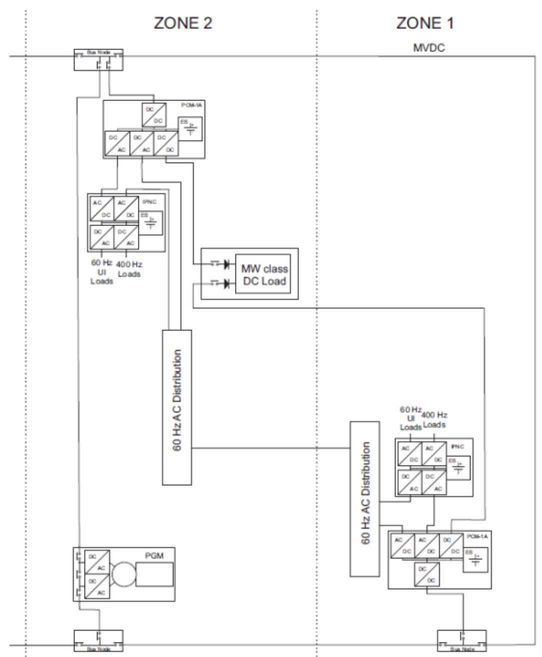

Fig. 3. PCM-1A powering special loads

F. Electromagnetic Railgun (EMRG)

Fig. 4 depicts a notional power architecture for an EMRG. Two PCM-1Bs are employed to buffer the power required by the pulse forming network from the power system. The PCM-1B is anticipated to be similar to the PCM-1A, but have a total power rating on the order of tens of MW. The amount of energy storage, and the interface between the energy storage and the Pulse Forming Network (PFN) are design elements that must be accomplished as part of the overall system design. The amount of energy storage is a strong function of the ability of the power system to accommodate pulse loads. A properly designed MVDC system should result in a requirement for less energy storage than a comparable AC system.

In addition to powering the PFNs, the PCM-1Bs are also employed to provide power to the remainder of the gun-mount equipment.

Under normal conditions, the EMRG is powered by both MVDC busses. In abnormal conditions, the EMRG may be powered by a single bus, but may be power limited resulting in a lower than normal firing rate.

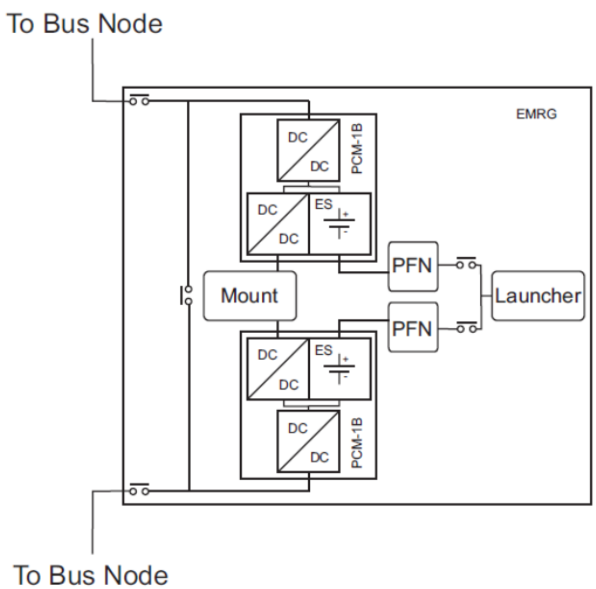

Fig. 4. Notional EMRG Architecture

G. Propulsion Motor Module (PMM)

A PMM is an example of a large load (greater than several MW). Large loads should connect to both MVDC busses via bus nodes. Under normal conditions, large loads should balance power drawn from the two busses.

H. 60 Hz AC Distribution

The 60 Hz. AC distribution system employs traditional circuit breakers, load centers, and power panels to power legacy 60 Hz. loads. The 60 Hz. AC distribution system can cross-connect with an adjacent zone in the event the in-zone PCM-1A is inoperative. When powered from the adjacent zone, the 60 Hz. AC distribution system provides a second source for the in-zone IPNCs.

III. CHARACTERIZING PULSES

Historically, the dynamic performance of an electric load has been limited by fixed values in interface standards. This traditional approach would result in pulse loads incorporating considerable energy storage to meet these fixed values. Within an MVDC system, an opportunity exists to reduce the total amount of energy storage in the system, and the system cost, by negotiating allowable pulse characteristics during ship operations based on the capability of the electric plant and the needs of the pulse load at any given time. For this negotiation to take place, a common definition for the nomenclature defining a pulse is needed.

Fig. 5 depicts the proposed nomenclature for a generalized power pulse as a waveform with respect to time. Variations in pulse shapes that adhere to the same nomenclature are shown in Fig 6. The exact shapes of the power pulses experienced on the PFN side and the power system side of the PCM-1B is unknown, but are expected to be describable using this nomenclature.

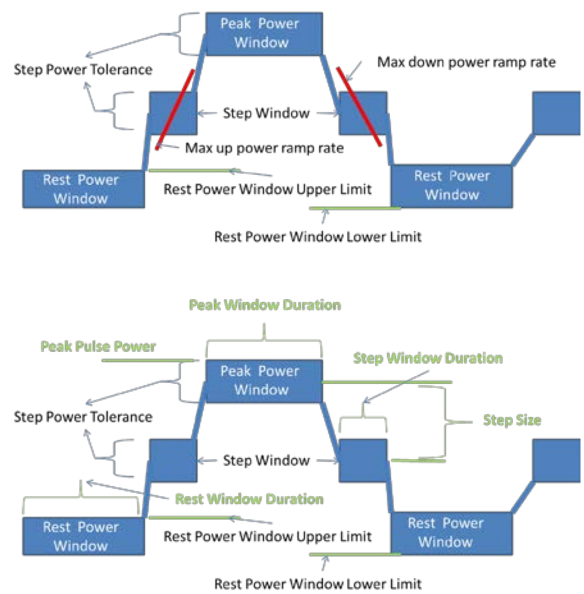

Fig 5. Pulse Nomenclature

A. Rest Power Window

The Rest Power Window is pre-defined by bounding lower and upper waveform value limits. A pulse starts when the waveform exceeds the upper limit of the Rest Power Window.

B. Step on the Leading Edge of a Pulse

A Step in the leading edge of a pulse starts when either of the following two conditions holds:

- If the slope of the waveform, since exiting the Rest Power Window or the most recent step, is ever greater than the Maximum up power ramp rate, then the step starts when the slope of the waveform returns to the Maximum up power ramp rate.
- If the slope of the waveform, since exiting the Rest Power Window or the most recent step, never exceeds the Maximum up power ramp rate, then the step starts when the slope of the waveform is zero.

The end of a step occurs when the value of the waveform is greater than the Step Power Tolerance plus the minimum value of the waveform since the start of the step.

If the value of the waveform is less than the maximum value of the waveform since the start of the step minus the Step Power Tolerance, then have a Peak Power Window instead of a step. This point ends the Peak Power Window.

C. Step on the Falling Edge of a Pulse

A step on the falling edge of a pulse starts when either of the following two conditions holds:

- If the slope of the waveform, since exiting the Rest Power Window or the most recent step, is ever greater in magnitude than the Maximum down power ramp rate, then the step starts when the slope of the waveform returns to the Maximum down power ramp rate.
- If the slope of the waveform, since exiting the Rest Power Window or the most recent step, never exceeds in magnitude the Maximum down power ramp rate, then the step starts when the slope of the waveform is zero.

The end of a step occurs when the value of the waveform is less than the maximum value of waveform since the start of the step minus the Step Power Tolerance or if the value of the waveform is equal to the upper limit of the Rest Power Window.

If the value of the waveform is greater than the minimum value of the waveform since the start of the step plus the Step Power Tolerance, then have a local minimum step. This point ends the local minimum step.

D. Step size

The size of a step is determined by subtracting the mid values of the step windows. The mid value is easily calculated by adding (falling edge) or subtracting (rising edge) half of the Step Power Tolerance from the value at the exit of the step. For the Rest Power Window, use the midpoint between the upper and lower bounds as the window mid value.

E. Classification of parameters

To determine the step windows and values, the following parameters must be specified:

- Upper and Lower limits for the Rest Power Window
- The maximum up power ramp rate and the maximum down power ramp rate
- The Step Power Tolerance

With these parameters defined, then the following can be determined:

- Rest window duration
- Step window duration
- Peak window durations
- Step sizes
- Peak Pulse Power

These values can be compared to specified values for:

- Minimum pulse rest time
- Minimum step hold time
- Minimum peak hold time
- Maximum Step Size
- Maximum Peak Pulse Power

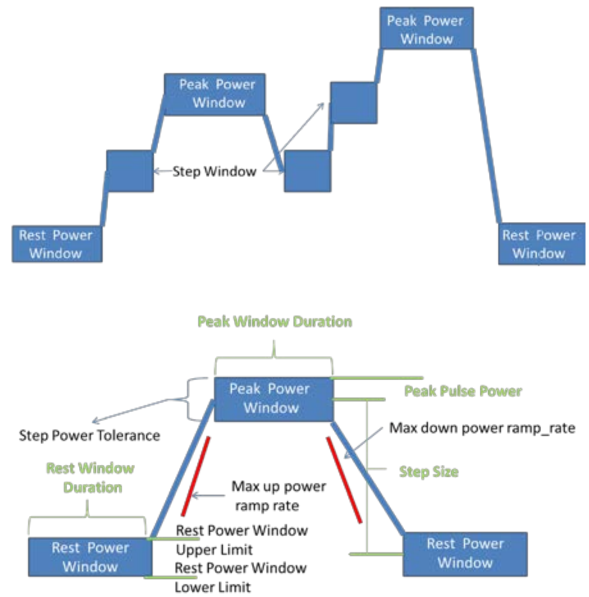

Fig. 6. Pulse Load Variations

IV. POWER SYSTEM IMPACT OF PULSE LOADS

Power management, as practiced in contemporary U.S. Navy ships' electric power systems, is focused upon adjusting on-line generating capacity to ensure the following inequality remains true.

Present Actual Load < 0.95 x (Online Generating Capacity)

Adjusting on-line generating capacity, starting or stopping a generator, is done usually by an engineering watchstander, sometimes through automatic controls. When the Present Actual Load approaches equality in the relationship above, then the engineering watch officer considers, based upon anticipated ship operations or Captain's orders, starting another generator. When Present Actual Load is much less than the Online Generating Capacity, at least an integral multiple of ninety percent of the generators' rating less, then the engineering watch officer considers stopping a generator. Automatic controls go through similar algorithmic 'reasoning', perhaps rules-based, to initiate changes in the Online Generating Capacity.

On those ships where a "load dispatcher" is employed, the role of the "load dispatcher" is to ensure that the inequality above remains true, particularly when a "large" electric load is turned on. Were the Present Actual Load to be 250kW less than equality in the relationship above, and a 300kW electric load turned on, then the equality would not be true; the electric power system would be on the verge (?) of being overloaded, with undesirable consequences – shutdowns and/or load shedding. Hence, "large" electric loads must receive authorization from the "load dispatcher" (again, usually a watchstander) before drawing power; this authorization is usually verbal. There is no hardware associated with the actions of the "large" electric load relative to the "load dispatcher". It is possible an untrained Sailor could turn on the "large" electric load without communicating with the "load dispatcher". In such a situation where the "load dispatcher" observes the electric power system as being close to equality, then the engineering watch officer confronts the choice between starting a generator or not authorizing the next "large" electric load. This choice must consider present ship operations, Captain's orders, equipment capacities and likelihoods (perceived reliability).

In classic naval electric power systems, there is no problem here, especially if all of the ships' generators are available. There is no problem even if one of the ships' generators is unavailable for preventive or corrective maintenance. This is because of how the generators' ratings are developed.

$$\text{Generator Rating} \geq ((1+\text{Service Life Allowance}) \times ((1+\text{Margin}) \times \text{Maximum Load})) \div (0.95 \times (n-1))$$

In this relationship, n is the number of generators. The Maximum Load has historically been calculated using the DDS 310-1 [7] load factor method. Importantly, this technique for calculating the Maximum Load is based upon a time average, over a relatively long period of time (~a day or diurnal cycle), of electric power drawn by the load. For as long as the majority of electric loads on a ship, especially the "large" electric loads, are relatively slowly varying, this approach to the size and number of generators on a ship has ensured that sufficient generating capacity is almost always available to power all electric loads. Here, slowly varying is taken relative to some, small, integral number of 60 Hz. cycles. This has been the case with the majority of electric loads up until the recent past.

Hence, up through the present, only two power management control actions have been available. One, bring online or take off-line a generator. Two, voluntarily inhibit starting a "large" electric load for an arbitrary amount of time. Also of note, both of these power management control actions occur in the t2 (Generator Start Time, see [2]) time scale. Hitherto, this has sufficed for power management.

Just what has changed, and, how does this affect the design of naval ship electric power systems? Two sets of technologies have changed: the electric loads and the electric power system. The electric loads have developed much faster (relative to a 60 Hz. cycle) dynamic behavior than in the past. The electric power system has evolved from being comprised of an AC generator, circuit breakers, switchgear and maybe a transformer supplying electric loads, to a power electronic power converter populated system.

The faster dynamic behavior of modern electric loads means that the difference between their 'peak' electric power drawn and their long-term average electric power drawn is significant. Hence, in the design of the ships' electric power system capacities, the 'peak' electric power to be supplied is the design driver, not the long-term average. This raises questions that the Navy's electric power system designers must address, such as the relevance of the relationship above used to determine the generators' ratings. A related question arises from the faster dynamic behavior of modern electric loads; the prime movers typically used on naval ships, especially when driving rotating electric generators, do not respond to changes in output power as quickly as the modern electric loads' power draw changes. A mismatch in dynamics can exist.

Modern shipboard electric power systems are populated by power electronic power converters, such as in Figure 1; such systems, whose capacities, particularly in terms of current, are limited by the safe operating areas of the power electronic switches within them, have very little overload capability. Hence, their internal control systems must very closely and rapidly ensure that the electric power they are conducting does not exceed their capacity; this means that the inequality discussed at the beginning of this section, which defines classic naval power management and governs on-line generating capacity, has an analog within each power electronic power converter operating in the electric power system.

Consideration of the foregoing concerns leads to important conclusions for the design of the electric power system. If the classic naval power management approach is used in the future, then in calculating the Maximum Load, the 'peak' electric power drawn by the fast modern electric loads, such as the EMRG, must be used, not the long-term average electric power drawn by the electric loads. This will greatly increase the required Generator Rating and all of the power electronic power converters' required current capacities. If the classic naval power management approach is used during operations in the future, then on-line generators would be kept lightly loaded so as to allow "large" electric loads' 'peaks' to be accommodated by the electric power system's power electronic converters. Both of these considerations argue, on the basis of affordability, for changing the navy's approach to power management.

In terms of changing the approach to selecting Generator Rating, consider making the Generator Rating an independent variable. In other words, the ship designer selects how many and the ratings of the generators to be installed in the ship; the electric power system designers and mission system designers then must work within that constraint. Making the number and rating of the generators an independent variable definitizes that cost element and its effect on the ship design; this can be done affordably.

How would this approach affect the electric power system and mission system designs? Fixing the installed generating capacity and acknowledging the presence of power electronic converters in the electric power system, with their constrained power (current) capacity, would very likely demand that real-time power and energy management be developed. Instead of the inequality above being managed in the t2 time frame, perhaps the equality below (or something like it) will have to be implemented in a sub-t1 time frame and recursively throughout the electric power system.

Online Generating Capacity + Available ESM Discharge + Available Actual Propulsion Load Decrement – Present Actual 'Rest' Load = Available Pulse Load + Available ESM Charge

The electric power system design would have to enable real time control of (1) online generator capacity, (2) ESM state of charge, and (3) delivery of power for propulsion. The mission system design would have to operate within the constraint of the real time Available Pulse Load.

This is very different from past and present practice. Implementing such an approach would necessarily affect the development (technical content in contracts) of both the ship power system design and the mission system design.

V. System Stability and Controls

The increasing population of power electronic power converters and power supplies found in naval ships has, over the past decades, led to the use of advanced stability analyses and techniques for ensuring electric power system stability, [4]-[6]. (IEEE P45.1, a standard currently under development, is anticipated to specifically address stability analysis for shipboard power systems) Particularly useful have been Frequency Domain techniques to establish small-signal, linear stability. Typically, a detailed, non-linear model of the electric power system is linearized about a relevant equilibrium (steady-state operating point); then, the linearized model is analyzed to assess the location of system eigenvalues. While such will continue to be an essential element of electric power system design, the introduction of very 'large' pulse loads may challenge the assumptions underlying the small-signal, linearized model of the system's behavior during and just after the very 'large' pulse load. Development and application of nonlinear, large-perturbation stability techniques will be necessary.

Between adopting a new approach to power management with the necessity of managing stored energy, all while ensuring stable electric power system behavior during very 'large' pulse loads, the articulation of a pulse power interface standard that includes a logic (control) interface between the electric power system and the mission systems becomes absolutely necessary so that the design of each may proceed. This control interface must be focused upon those system quantities that are being 'controlled', namely, energies and the rates of change of energies. As the sources, users and manipulators (power electronic power converters) are located throughout the ship and at different levels within the electric power system, it should be apparent that this confronts the electric power system and mission systems designers with a challenging distributed control design problem.

VI. Pulse Power Interface Standard

As depicted in Fig. 1 and Fig. 4, the interface between the EMRG and the power system is at the MVDC bus (via the bus node) as input to the PCM-1B. The voltage characteristics of the MVDC bus are anticipated to conform to an interface standard that is not sensitive to whether the load is a pulse power load or not. A pulse load however, will have a current and power profile not typical of other loads. To best match the capabilities of the power system with the preferences of the EMRG, the pulse power interface standard should enable a negotiation of the pulse characteristics:

a. Lower Limit for the Rest Power Window
b. Upper Limit for the Rest Power Window
c. Maximum up power ramp rate
d. Maximum down power ramp rate
e. Step Power Tolerance
f. Minimum Pulse Rest Time
g. Minimum step hold time
h. Minimum peak hold time
i. Maximum step size
j. Maximum peak power

During the system design stage, a continuous range or a set of discrete points must be defined for each of the pulse characteristics. The combinations of these ranges / sets define an interface space.

In operation, the EMRG provides the power control system a function or table to indicate the EMRG preference between 0.0 and 1.0 for each point in the interface space for the current operational mode of the EMRG. A preference of 0.0 indicates the EMRG cannot operate successfully with this combination of pulse characteristics. A preference of 1.0 indicates the EMRG can operate successfully with 100% capability with this combination of pulse characteristics. A preference between 0.0 and 1.0 indicates some level of degraded performance.

The power control system develops an analogous function or table to indicate the power systems capability (between 0.0 and 1.0) to support each point in the interface space for the current operating point and generator line-up. A capability of 0.0 indicates the power system is not capable of complying with the pulse characteristics. A capability of 1.0 indicates the power system is fully capable of complying with the pulse characteristics without impacting other loads. A capability between 0.0 and 1.0 indicates the degree to which other loads are impacted on the ship.

In establishing the pulse characteristics operating point, a rules based approach will likely be initially employed. A representative rule set could be:

a. If one or more points in the interface space has preference of 1.0 and a capability of 1.0, choose one of the points based on a rule intended to maximize robustness.
b. Otherwise, if some points have a preference of 1.0 and a capability greater than a threshold, then chose the point with a preference of 1.0 and with the highest capability.
c. Otherwise, choose the point with the largest product of preference and capability.

In the future, an optimization algorithm may be implemented. Additionally, if rule "a" is not implemented, then the power control system would be expected to reconfigure the electrical plant and/or bring online additional generation capacity to enable switching the operating point in the interface space to where rule "a" can be implemented.

Once the point in the interface space has been determined, it is conveyed to the EMRG controller which must then constrain the power drawn from the MVDC bus to remain within the limits.

VII. Conclusion

The introduction of large, nonlinear, stochastic, and pulse loads into future naval power systems will require changes in the way power systems are designed, analyzed, specified and operated. This paper has presented a reference MVDC system for supporting these loads, characterized a pulse and offered an approach to negotiating pulse characteristics between a load and the power system, and has presented the opportunities and challenges in designing, specifying, and controlling these future power systems.

REFERENCES

[1] N. Doerry and J. Amy Jr., "The Road to MVDC," presented at ASNE Intelligent Ships Symposium 2015, Philadelphia PA, May-20-21, 2015.
[2] IEEE 1826-2012, "IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW," Approved 22 June 2012.
[3] N. Doerry and J. Amy Jr., “DC Voltage Interface Standards for Naval Applications,” presented at 2015 IEEE Electric Ship Technologies Symposium, Old Town Alexandria, VA, June 21-24, 2015.
[4] Middlebrook, R. D., “Input Filter Considerations in Design and Application of Switching regulators”, IEEE Industry Applications Society Annual Meeting, 1976 Record, pp. 366-382.
[5] Lewis, L.R., B.H. Cho, F.C. Lee, and B.A. Carpenter, “Modeling, Analysis and Design of Distributed Power Systems,” IEEE Power Electronics Specialists Conference, 1989. PESC'89. Vol I, pp.152-159.
[6] Sudhoff, S., S.D. Pekarek, S.F. Glover, S.H. Zak, E. Zivi, J.D. Sauer, and D.E. Delisle, "Stability Analysis of a DC Power Electronics Based Distribution System" SAE Technical Paper 2002-01-3184, 2002, doi:10.4271/2002-01-3184.
[7] Naval Sea Systems Command, "Design Data Sheet: Electric Power Load Analysis (EPLA) for Surface Ships," DDS 310-1 Rev 1, 17 September 2012.