Load Integration, Including Radar and Advanced Weapons

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***Abstract*—This paper summarizes work that addressed issues associated with the integration of various loads on an all-electric navy ship by the Electric Ship Research and Development Consortium (ESRDC) in the last ten years. The loads include ship service loads such as hotel loads, continuous high-power loads such as propulsion, vital high-power loads such as radar, multi-megawatt pulsed loads such as sensors and defensive systems, and very-high power, gigawatt-level, pulsed loads such as electromagnetic rail guns which require energy storage. The integration of energy storage received particular attention due to its vital role and is discussed accordingly. The analyses were conducted through modeling and simulation and complemented by design studies at component and system levels. Typical simulation results representing operational scenarios of various loads and their interaction with the power system are presented.**

I. Introduction

The introduction of electric propulsion into modern naval platforms resulted in a significant increase of installed electric power from few megawatts, found on present-day ships and used mainly for ship services and other loads requiring modest electric power consumption, to several tens of megawatts. This large increase in available electric power and the integration of electric energy storage, enable operation of new systems that require continuous and intermittent electric power.

However, the generation, distribution, and utilization of such large power in a small environment, the multitude of loads with a wide range of power, which spans from watts to giga-watts, the often vital missions these loads need to accomplish, and the hostile environment in which they operate, present serious challenges. These mission-specific loads put constraints on the choice of the power system architecture and its modes of operation, thereby, requiring a power and energy management system to insure an effective coordination of all load demands. A successful load coordination scheme that insures that all the loads fulfill their missions will be a key factor in determining the optimum power system architecture and the most effective control and operating modes.

The paper is organized as follows. A description of some of the loads that operate on a modern all-electric navy platform is given in section II. Factors that determine a successful load integration are discussed in section III. The effects of high-power pulse loads on the power system are given in section IV, and issues associated with the integration of energy storage are discussed in section V. A discussion on the load-centric attribute of an all-electric ship power system is presented in section VI and a conclusion summarizing the work completed so far is given in section VII.

II. Overview of Anticipated Loads on Navy Ships

In addition to conventional loads such as propulsion and hotel loads, several anticipated loads on modern navy ships need large levels of electric power with different power demand characteristics. While some of the large pulsed loads require the use of power conversion modules that can introduce disturbances to the ship power grid, in terms of harmonic distortion for example, other loads are sensitive loads that require clean and uninterrupted power in order to perform their missions. The potentially conflicting requirements among the loads highlight the need for an understanding of load functions and their operating conditions. A brief description of the loads is presented in the following subsections.

A. Propulsion load

Propulsion load is the largest power consumer on board ships requiring an installed power that is commensurate with the ship top speed. For example, ~90% of installed power on an 80 MW destroyer is used by propulsion when the ship is operated at ~31 knots. However, navy ships do not operate usually at their top speed often, as can be seen in Fig. 1, and the typical cruising speed of 20 knots requires only ~14 MW for a destroyer, which is much lower than the installed 80 MW. The available power can be used by other advanced loads as long as the ship does not need to perform evasive maneuvers. In this case maximum propulsion power is needed to accelerate the ship from cruise speed to top speed, a maneuver that takes time to complete because of the ship hydrodynamic resistance. A coordination mechanism that allocates the available power to propulsion load and other

This work was supported by a grant from the Office of Naval Research.

advanced loads, that defend the ship for example, must be developed and used according to the nature of the threats and the advanced loads needed to defend against them.

Electric propulsion load is usually described in terms of a propulsion power train that includes a variable-speed motor drive, a propulsion motor, and a propeller with specific hydrodynamic coefficients that are needed for calculating propeller load torque Q_{Prop} and propeller open water thrust force T_{Prop}.

Propeller torque and ship thrust are given by (1) and (2), respectively; details can be found in [1]. These equations are necessary for a correct assessment of the effects of dynamic events, such as acceleration and deceleration, on the ship power grid.

$$Q_{Prop} = \frac{C_Q(\upsilon)}{\upsilon^2 . \eta_R} \rho D^5 n^2 \quad (1)$$

$$T_{Prop} = \frac{C_T(\upsilon)}{\upsilon^2} \rho D^4 n^2 \quad (2)$$

where,

$$\upsilon = \frac{nD}{\sqrt{V_A^2 + (nD)^2}} \quad (3)$$

D = propeller diameter; n = propeller speed

ρ = sea water density; η_R = efficiency factor

V_A = speed of advance = Vs(1-wt);

Vs = ship speed; wt = wake factor [1].

A typical propulsion load profile for a destroyer can be represented by Fig. 1, which gives % time spent at given speeds, and Fig.2 which shows the cubic-dependence of power on ship speed.

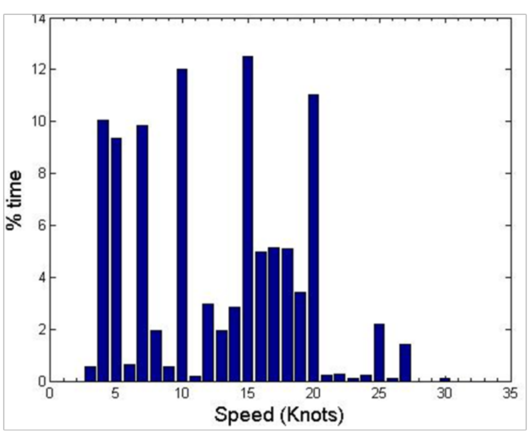

Figure 1. Typical destroyer speed profile.

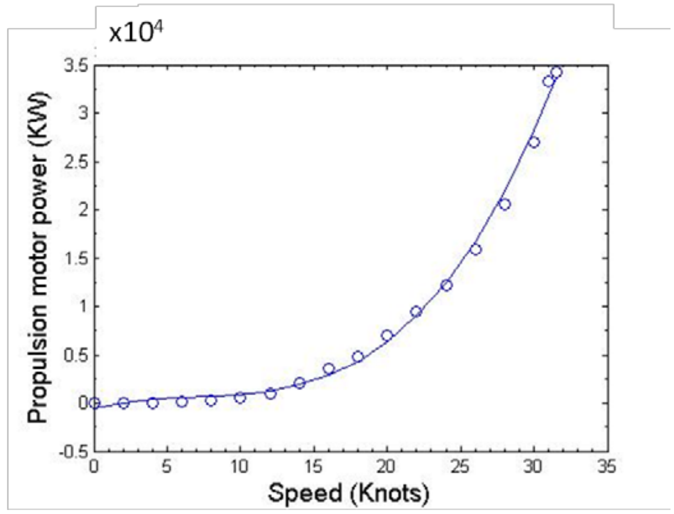

Figure 2. Propulsion power for an 80 MW destroyer (1 propeller)

Electric propulsion has been a very challenging load to integrate in modern all-electric navy platforms. This is because the high-power, 30-40 MW, and low speed, 120-150 rpm, propulsion motors and their drives are very large. Considerable efforts were made to improve power density of this equipment. These include application of advanced technologies such as superconductivity and permanent-magnets for propulsion motors, and development of silicon carbine devices for use in motor drives.

One approach developed by the ESRDC, to improve power density, was to integrate motor drive components into the large and hollow rotor of the propulsion motor, as shown in Fig. 3 [2]. This topology is very promising and warrants further development through modeling, simulation, and laboratory testing of representative concepts.

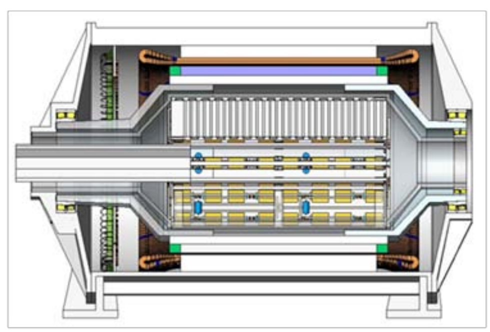

Figure 3. Integrated propulsion motor and drive components for improved power density.

The propulsion load can use several types of variable speed drives including cycloconverters, matrix converters, and current source converters. However, pulse width modulated (PWM) voltage source converters are the most frequently used propulsion drives because of their good dynamic performance and robustness [3].

With electric propulsion, it is necessary that the drive system be able to absorb energy from the propeller when the ship is brought to a fast stop. There are two ways this can be achieved. The first is to regenerate energy into the ship ac supply, which requires a motor drive with bi-directional power flow capability. The second is to dissipate the energy in braking resistors which results in additional thermal loads. Advantages and disadvantages of these two methods are major design drivers for the propulsion system.

The energy stored in the motor, shafting, and propeller can in principle be used to support other functions such as short-term load smoothing, for example, but the energy involved is relatively small, typically few tens of mega-joules. This is in contrast with the energy stored in the ship linear motion which is typically ~ 1000 MJ for a destroyer. Further discussions on this topic can be found in [3],[4] and more general discussion related to propulsion load can also be found in [5], [6].

B. Ship service loads

Ship service loads include hotel loads and other equipment such as motors and power converters, that are necessary for day-to-day operation of the ship. There are different types of loads that often require various power conversion modules to provide the type and level of power they need. An example of a set of service loads for a medium voltage dc distribution architecture (MVDC), with zonal distribution characteristics [7], is shown in Fig. 4. Typical load values and types for a notional 80 MW destroyer are given in Table I [7]. Several sets of these loads are usually grouped in 3 to 4 zones, typically totaling several mega-watts for a modern destroyer. In this zonal distribution approach the port and starboard longitudinal main busses are used to supply load zones separated by watertight bulkheads.

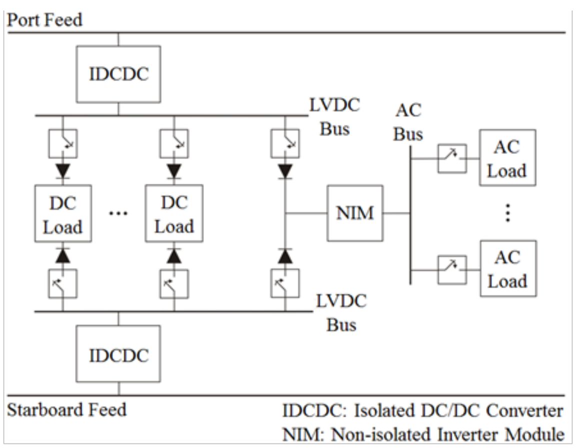

Figure 4. Zonal load distribution with typical ship service loads for a notional MVDC power system architecture.

Table I.

Type	Battle (kW)	Cruise (kW)	Load category	Voltage\Frequency
DC	150	70	DC loads 1	800V\dc
DC	615	0	DC loads 2	800V\dc
AC	715	640	Type 1 AC loads	3Ø\450Vac\60Hz
AC	400	390	120/208 Vac loads	3Ø\450Vac\60Hz
AC	910	275	Non-vital type 1 AC	3Ø\450Vac\60Hz
AC	0	7	Non-vital AC loads	3Ø\450Vac\60Hz
Total	2790	1382		

The composition of running loads changes minute by minute and represents a mixture of constant impedance, constant power, constant current, and induction machine loads. Further discussion on the ship service loads can be found in [8].

C. Radar load

The radar load on an all-electric destroyer is anticipated to consume few megawatts of dc power operating at a voltage of several tens to few hundred volts. Typical values for a notional destroyer [7] are 2.85 MW when operating in cruise mode and 3.75 MW when operating in battle mode. Power conditioning modules are needed to convert power from medium voltage ac or dc busses to the required lower dc voltage. In addition, the radar is a vital load that requires power on a continuous basis. Multiple feeds that enable rapid power transfer from different ship locations are necessary. The radar also has access to energy storage in order to remain operational in case of a temporary blackout.

D. Free electron laser

The free electron laser (FEL) is a pulsed power defensive system that is anticipated to be installed on future Navy ships. It is a complex and highly inefficient system. For example, it requires about 25 MW of power to produce a 3 MW laser beam. It consists of a large ring where electrons are injected and accelerated to very high energies requiring radio-frequency, optical, cryogenic, and control equipment to create, condition, focus, and launch the laser beam, Fig. 5. It has several sub-loads, as described in Table II, that operate at different times during the conditioning and operating cycle.

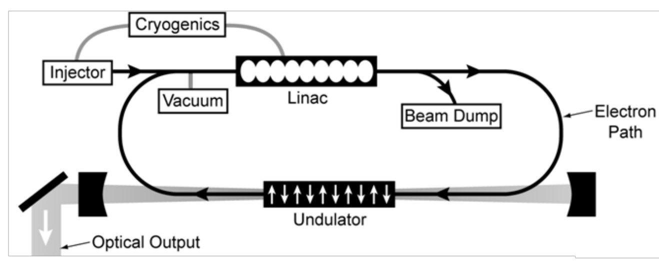

Figure 5. Free electron laser system layout.

Table II.

FEL load definitions					Modes of operation (required power in KW)				
					Pier side	Under way	Operational readiness	Hot standby	Engage-ment
Z6L1	Filament	10KW	AC	4.16kV\60Hz	10	10	10	10	10
Z6L2	RF	16MW	DC	45 kV	-	-	80	16000	16000
Z6L3	Beam dump	7.7MW	AC	4.16kV\60Hz	-	-	38.5	7700	7700
Z6L4	Cooling	300kW	AC	4.16kV\60Hz	300	300	300	300	300
Z6L5	Cryogenics	1MW	AC	450V\60Hz	100	1000	1000	1000	1000
Z6L6	Beam control	20KW	AC	450V\60Hz	-	-	-	-	20
Z6L7	Vacuum	5kW	AC	450V\60Hz	5	5	5	5	5
Z6L8	Beam optics	1KW	AC	112.5V\60Hz			1	1	1
Z6L9	Computers	5KW	AC	112.5V\60Hz	5	5	5	5	5
Z6L10	Housekeeping	5KW	AC	112.5V\60Hz	5	5	5	5	5
Z6L11	Wiggler	~0	DC	600 V	-	-	-	-	-
Total power during each mode of operation (kW)					425	1325	1444.5	25026	25046
Transition times					days	hours	minutes	seconds	seconds

E. Active armor

Active armor is a defensive system that is designed to dynamically prevent damage to the ship by incoming threat.

There are several types of active armors. Electromagnetic armor uses an electric discharge between two plates to create an intense magnetic field which interacts with the charged particles of the penetrating jet, thereby disrupting it and reducing its damaging effects. Reactive armor creates an explosion in the opposite direction of incoming plasma jet created by the incoming round. Smart armor uses sensors to determine the nature of the incoming threat and select the appropriate defensive measures. Parameters of these systems are not well documented but we anticipate that their power needs would be in the several hundred kilowatts to low megawatts range with ~ 10 kV dc voltage and an engagement time of few seconds.

F. *Electromagnetic rail gun*

The advent of the all-electric ship and advances in electromagnetic launch technology prompted an interest in the development of long-range naval rail guns. Advantages of this weapon system include range, lethality, improved time-of-flight, smaller and safer magazines, and cost as compared to conventional systems with similar performance. A high-firing-rate electromagnetic (EM) rail gun system (~ 10 rounds/minute), with a 200-500 km range, will require installed prime power in the range of several tens of megawatts, which is commensurate with ~100 MW power level projected for future destroyers. For the range of interest mentioned earlier, a projectile's muzzle energy of ~50-100 MJ requires a power supply that can deliver several mega-amperes of currents to the rails in few milliseconds, and at medium voltages (several kV). This translates in pulsed power supplies of the order of several giga-watts. This requirement, clearly, shows that some sort of energy storage onboard ships is necessary in order to satisfy the requirements of rail gun systems on naval platforms. The amount of stored energy depends on the rail gun firing rate and the maximum number of shots that can be stored. Potential energy storage systems include flywheels, capacitors, batteries, superconducting magnetic storage systems, and fuel cells. Some of these technologies are mature and well tested with improving performance, while other are still under development.

Among these energy storage technologies, flywheels are the most promising. In this particular application, they operate as high-power pulsed alternators that can provide several mega-amperes of pulsed current necessary to accelerate the projectiles to the desired hypersonic velocity (~Mach 5-7). The advantages of a high-speed flywheel energy storage system are particularly attractive if additional constraints, such as high power density and efficiency, are taken into account. A discussion on energy storage needs and requirements for use on naval platforms can be found in [3].

For a flywheel-based EM rail gun system with the parameters listed in Table III, the required stored energy is ~ 800 MJ. For this configuration, 8 high-speed alternator sets are needed, with each storing 100 MJ with a power capability of ~3 GW. Each 100 MJ alternator set consists of a rectifier, a 6.25 MVA motor drive, a 5 MW high-speed permanent-magnet charging motor, a 2.2 GVA alternator modeled as a wound-field synchronous generator, a second rectifier, and a power switch. A Matlab\Simulink model of such a system is in Fig. 6 with the expanded pulse power supply showing the 8 machine sets one of which is expanded showing the components of each machine set [9].

Table III.

Projectile muzzle energy	64 MJ
Shot rate	12 rounds/minute
Energy storage	Rotating machines
Total energy	800 MJ
Total system efficiency	41 %
Alternator speed	18,000 rpm
Number of alternators	8
Number of shots stored	5
Required charging power	5x8 = 40 MW
Pulse duration	9 ms

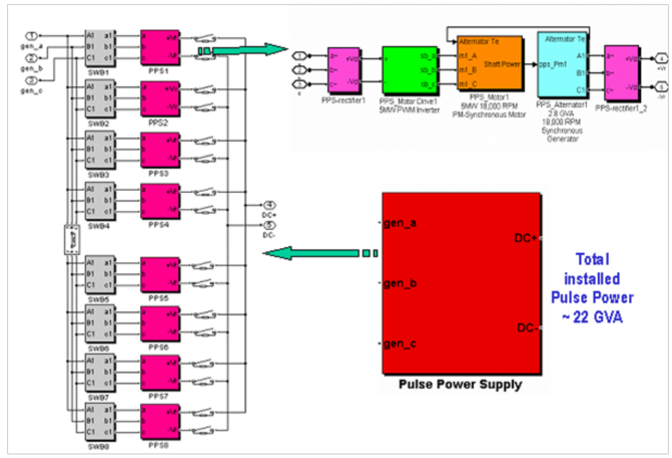

Figure 6. Model of an 800 MJ flywheel-based rail gun system.

G. *Electromagnetic launchers*

Electromagnetic launch systems (EMALS) include launchers to catapult aircrafts from navy carriers and missile launchers. In such systems it is more efficient to use energy storage than to extract power directly from the ship power grid. An option is to store energy in high-speed flywheels and deliver it to linear motors, to drive a catapult for aircraft launch, or to missile launchers. Typical power and type of such systems are few tens of megawatts and ~ 10 kV dc, respectively, with an engagement time of few seconds.

Practically all of the advanced systems discussed in the previous sections, including the radar system, use energy storage but not necessarily at the same time. This fact incited the consideration of coordinating these various loads so that they can share a single energy storage system. This will be discussed in the next section.

III. LOAD INTEGRATION FOR OPTIMUM OPERATION

Among the various advanced systems considered in this paper the EM rail gun is the only system for which energy storage is necessary. This is because the giga-watt power level it needs is not available within the ship power grid. As discussed earlier, the other systems need power levels in the tens of megawatts which are available within the installed power onboard destroyers. However, extracting power directly from the ship power grid would be to the detriment of propulsion, a situation that is not desirable when the ship needs to take evasive action while using these advanced weapons to defend itself. In addition, high-power transients can disrupt the power system as well. Therefore, it is preferable to have an energy storage system, sized for the EM gun system, that can be shared by the other systems.

A. Power sharing through common use of energy storage

The following example demonstrates the use of a common energy storage system by a rail gun and an FEL in a scenario where the ship is performing evasive actions, firing an EM gun round and several FEL shots. The exercise consisted of providing power to accelerate the ship to full speed, reduce ship speed to cruising speed to free-up power for charging the EM gun energy storage system, charging the EM gun, firing an EM gun shot, and without recharging, firing 4 FEL shots. The section of the model where this scenario was implemented is shown in Fig. 7 [9]. The EM gun power supply block is the same as the pulse power supply block of Fig. 6.

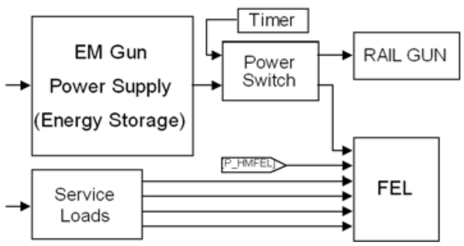

Figure 7. Model set-up of integrated EM gun and FEL systems.

Some results of the analysis are summarized in Fig. 8 which shows power consumption during this scenario by propulsion, EM gun, and FEL systems. This result showed that power can be shared effectively, through a common energy store, by the EM gun and FEL systems while coordinating available power with propulsion load. The energy consumed by the EM gun and the FEL during the firing cycle is shown in Fig. 9, along with the rotor speed profile [9].

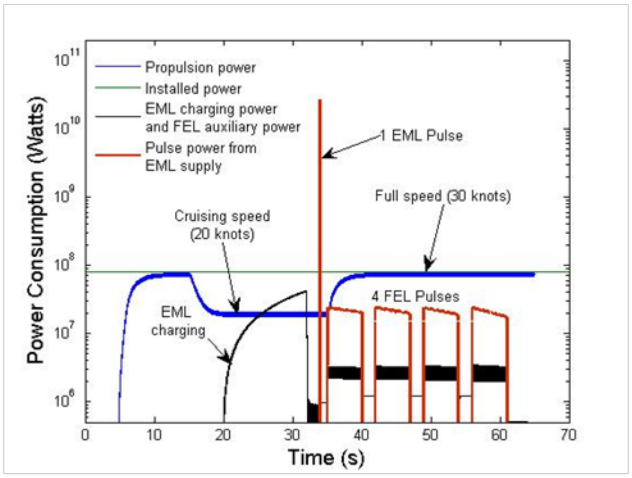

Figure 8. Power coordination during EM gun and FEL operation, sharing same energy store, while ship is in motion.

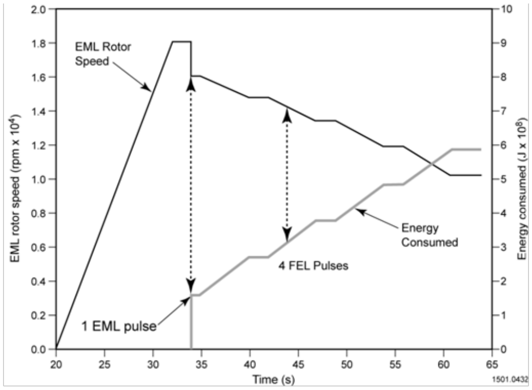

Figure 9. Energy consummed during EM gun and FEL operation, and corresponding rotor speed.

Figure 9 shows that even after one rail gun round and four FEL discharges, the rotor retains more than 50% of its initial speed. At this point the operator can take additional FEL shots or proceed to recharge the EM gun energy storage system by extracting power from the ship grid causing the ship to slow down, momentarily, until the recharging cycle is completed. Further discussions can be found in [9].

B. Power transfer

One of the advantages of integrated power in all-electric ships is the ability to transfer power from one location of the ship to another where malfunction or hostile action caused temporary or permanent loss of power. In such situation, coordination among various loads is necessary for restoration of function even if it is partial.

To illustrate this power transfer process, consider the situation where one of the main generators, supplying one of the propulsion power trains, is taken off-line, requiring a transfer of power from the second generator that was supplying the second propulsion power train. The challenge is to determine whether power can be transferred quickly, and in a controlled manner. To analyze this scenario, a Matlab\Simulink model of an 80 MW power system for a notional destroyer was used and a simulation was performed [10]. The top-level model is shown in Fig. 10. The icons in the propulsion power train blocks represent actual components used in the model as indicated by their symbols. The red dotted line indicates the direction of power transfer. The lost generator is indicated by the crossed red lines. Prior to the start of the fault, the power system was operating in split-plant configuration where each of the main generators was supplying the corresponding propulsion load, i.e. not connected in parallel, while the auxiliary generators were supplying ship service and pulsed loads.

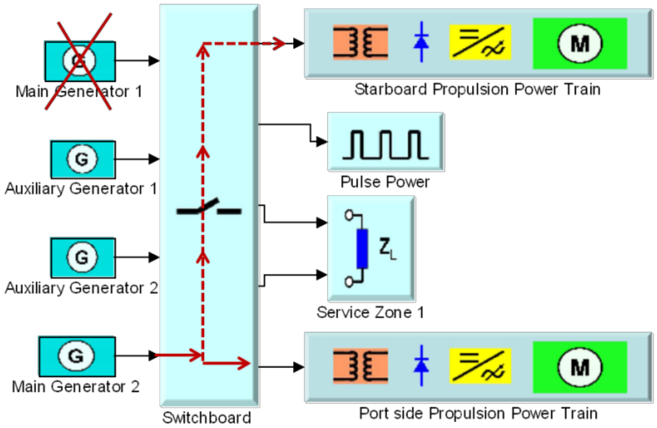

Figure 10. Power transer analysis in an 80 MW power system.

The switchboard is expanded in Fig. 11, showing the breakers' configuration and power transfer path. Breaker b61 is tripped open to initiate the loss of the generator and breaker b55 is closed 10 ms later to start the power transfer.

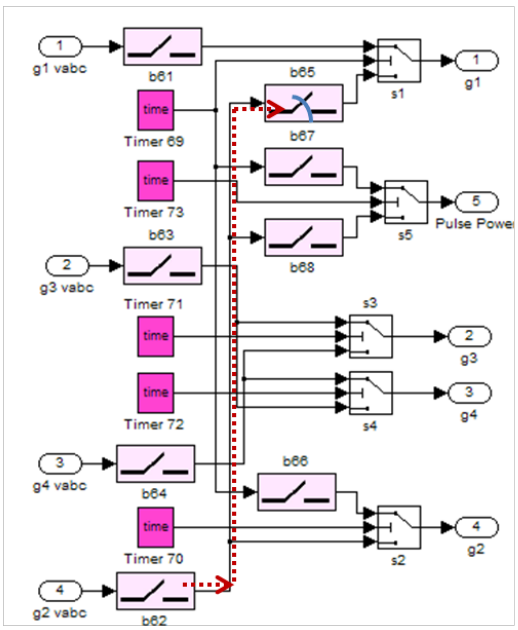

Figure 11. Switchboard model showing breakers and power transfer path.

In order to share available power equally just after the power transfer, the propulsion speed command was reduced to a value that can be supported by the available power from a single generator. This coordination between the two propulsion loads, usually performed by the ship control system, helps stabilize the ship or perhaps prevent further disruptions. The speed response of the two propulsion motors to the power transfer event is shown in Fig. 12. The current and phase voltage of the motor with lost and restored power are show in Fig. 13 and Fig. 14, respectively.

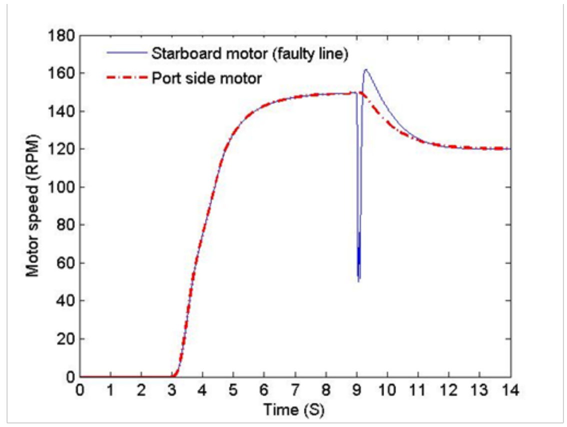

Figure 12. Propulsion motors' speeds.

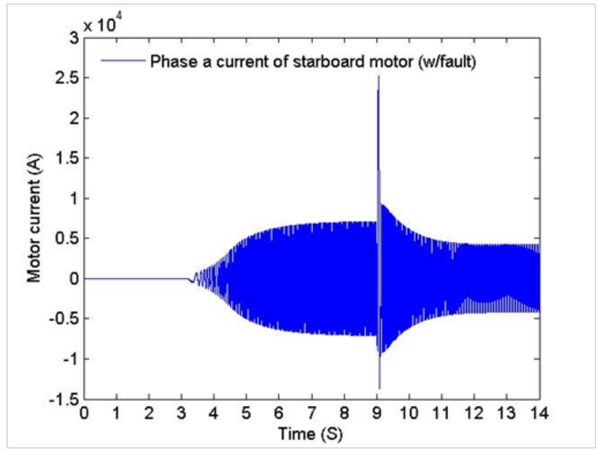

Figure 13. Propulsion motor current during power transfer event.

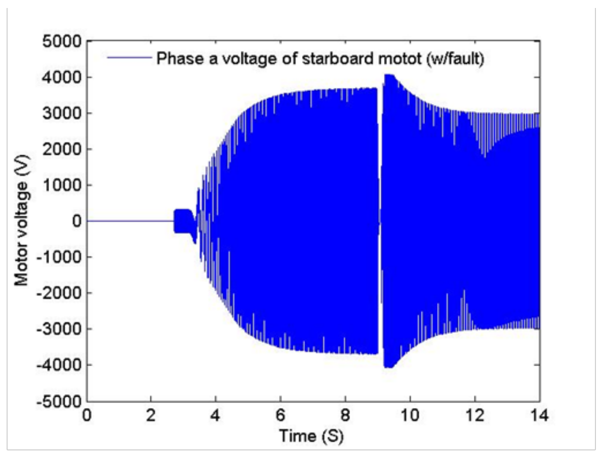

Figure 14. Propulsion motor phase voltage during power transfer event.

The results show a relatively quick restoration of power to propulsion although at a reduced power level, with large current spikes and an initial increase of both current and voltage, just after the power transfer event, before settling to their respective steady state values within few seconds. It is important to note that these results were obtained for an assumed set of parameters for most components used in the analysis such as generators, motors, transformers, and breakers' snubber parameters. A different set of parameters may produce different results, a fact that underlines the importance of using correct model parameters when such analyses are conducted.

Another example is power transfer to a large vital load such as radar. In this case the radar was connected to two different bus segments from which it could be fed. The scenario started by a loss of a generator and isolation of the corresponding bus segment that was feeding the radar load, as shown in Fig. 15, which represents the top-level Matlab\Simulink model of an 80 MW high-frequency power system used for this analysis [11]. The power transfer operation was simulated by activating the corresponding breakers with assumed time delays so that the radar received its power from the lower bus segment after the fault (Fig. 15). The radar dc bus voltage during the power transfer event is shown in Fig. 16 which indicates a brief drop in radar voltage and a stable condition afterwards. Under the conditions of this demonstration, no major disruptions in other parts of the system were observed during the power transfer event.

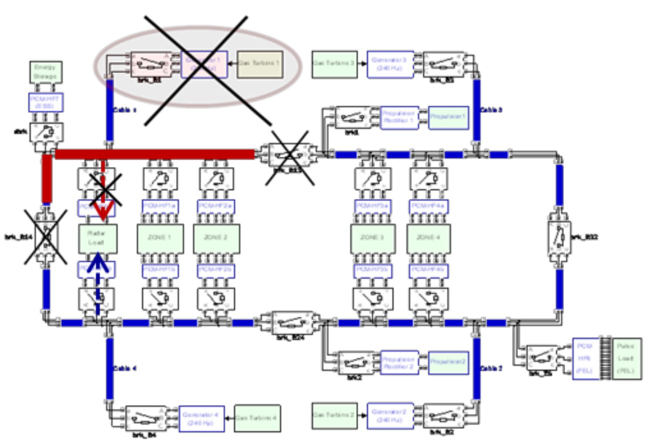

Figure 15. 80 MW Matlab\Simulink dynamic model with power transfer to radar load.

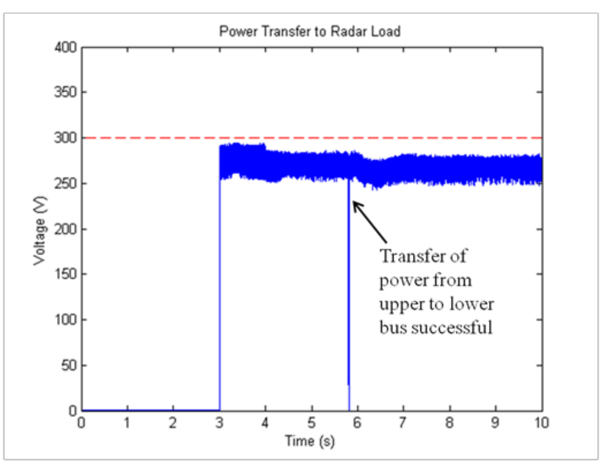

Figure 16. Radar load dc voltage before and after power transfer.

C. *Continuity of service*

Loads onboard navy ships are usually classified as vital or non-vital loads in order to differentiate between the set of loads that need continuous supply of power from those that can tolerate a temporary or permanent loss of power. Vital loads such as radar and other sensors, controllers, and computer systems, play crucial roles for the survival of the ship, and coordination among various loads in terms of priority for access to available power, for example, must be carefully addressed during the design of the power system.

Consider for example the power system shown in Fig. 17 which represents the top-level Matlab\Simulink model of an 80 MW electric ship power system that was studied earlier [12]. The model consists of 4 generator sets, several switchboards, two propulsion power trains, and a set of eight different service loads, supplied through two load center transformers and two ac busses and two dc busses. Load 4 and load 5, circled in red, are vital loads that need to be kept operational at all times.

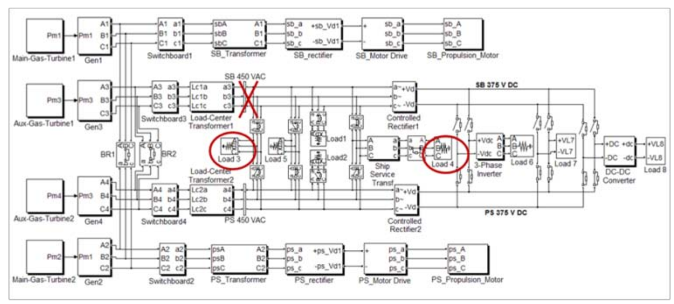

Figure 17. Early model of a notional electric ship power system.

A scenario to analyze continuity of service to a vital load was simulated using this power system model. In this scenario, while the ship was sailing at 26 knots, consuming ~ 30 MW, power to one of the 450 Vac busses was lost. This fault was simulated by opening a breaker in switchboard 3. To maintain or restore power to vital loads 3 and 4, the faulty bus was isolated by opening the breaker that connected the two auxiliary gen-sets, and power to all non-vital loads 1, 2, 6, 7, and 8 was switched-off. This was to insure that enough power from the working bus was available for all vital loads. Finally, power from the second 450 Vac bus was switched-on to vital loads 3 and 4. During this part of the exercise the different breakers were closed and opened at different time intervals, from instantaneous switching to several milliseconds intervals, in order to observe the response of the power system to the disturbance.

In this early exercise [12], the time between initiating the fault and restoring power to vital loads 3 and 4, by closing and opening the appropriate breakers, was one millisecond. This is too fast and delay time of ~ 10 ms would have been more appropriate. The switching occurred at time t=0.95 s as can be seen in Fig. 18 and Fig. 19 which represent the voltages across vital loads 3 and 4, respectively, during the switching events. Notice that just after the power was restored to loads 3 and 4, the voltages appear to be noisier. This requires further analyses during the design of the power system to insure that sensitive loads get adequate filtering.

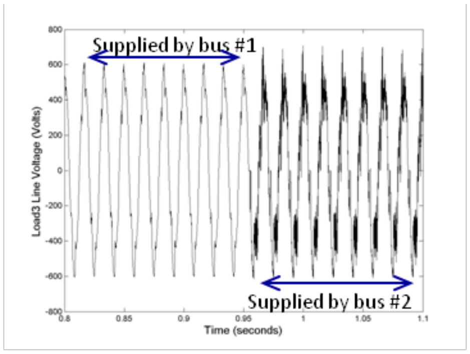

Figure 18. Line voltage across load 3 before and after the swtching event.

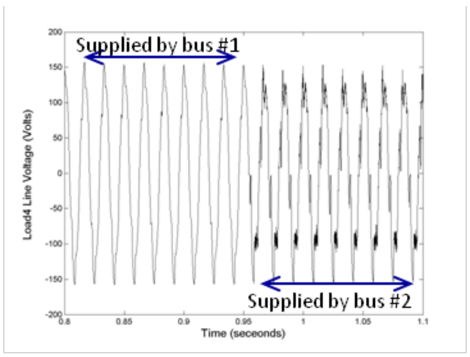

Figure 19. Line voltage across load 4 before and after the switching event.

A similar simulation with breakers' time delays set at ~ 10 ms was conducted using the power system used in the previous section, Fig. 10, which had similar service loads as the model in Fig. 17. In this simulation, load 4 was supplied by the unaffected bus, and power restoration was needed for vital load 3 only. This was achieved by taking non-vital load 2 off-line. As can be seen in Fig. 20, the restoration of power was not seamless in this case and the vital load did lose power for several milliseconds. This is due to several factors including assumed longer breakers' time delays and various circuit parameters.

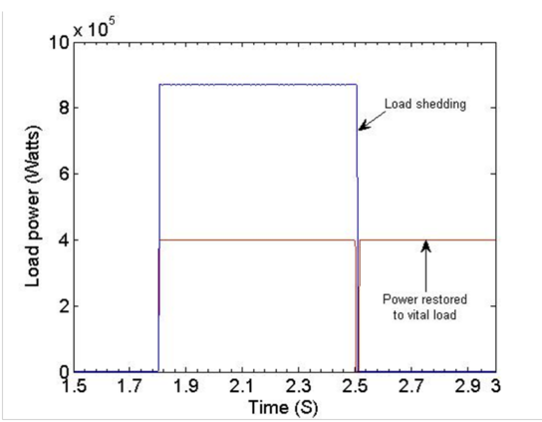

Figure 20. Continuity of service for a vital load through load shedding and power transfer.

For loads that cannot tolerate such a temporary loss of power, other approaches such as using UPS units may help alleviate the problem. However, it is not obvious that this can be achieved when switching large amount of power from one module to another. To answer this question, further simulations using actual component parameters and verified by experimental tests need to be performed.

D. Reduction of harmonic distorsions through active filtering

The intermittent nature of high-power pulsed loads onboard future naval vessels makes pulse power supplies highly inefficient subsystems, in terms of power density, even when multiple pulsed load systems share parts of their components, as was demonstrated earlier for the case of a rail gun and an FEL. To enhance the functionality of an EM rail gun power supply, the energy stored in the rotors of its high-speed rotating machines and its power electronics can be used as an active filter to reduce harmonic pollution that is present in power systems where the use of power electronics equipment is prevalent, as is the case in an all-electric navy ship.

To demonstrate the feasibility of this dual-function, a Simulink model of a propulsion power train, with an integrated pulse power supply for a rail gun system was developed [9]. The top-level of the model is shown in Fig. 21. For simplicity, only a single propulsion power train and a single generator were used. The energy storage block and an inverter were explicitly extracted out of the EM rail gun pulse power supply to clearly show their dual use.

The active filter works by injecting current into the distribution lines to eliminate or reduce harmonic currents and their detrimental effects on sensitive loads. The energy storage components are the rotors of the EM rail gun power supply, as mentioned earlier, and the dc link capacitors to which they are connected. The control block consists of a calculation block, a hysteresis control block, and an LC filter to reduce inverter switching harmonics.

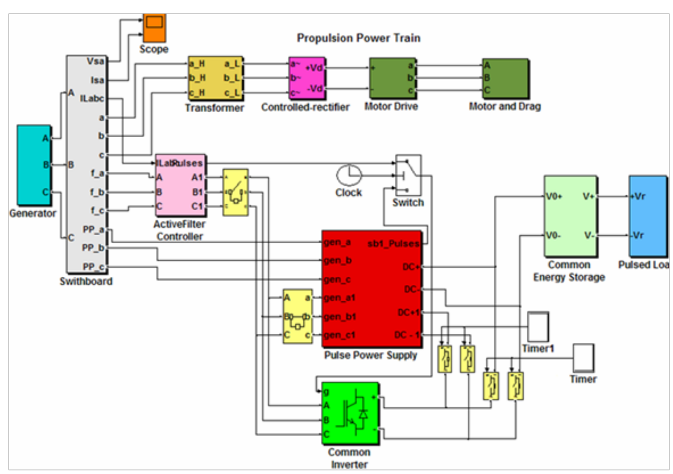

Figure 21. Circuit model for an active filter.

In this example, the propulsion power train was consuming ~ 11 MW with a nominal bus voltage of 13.8 kV. The results of the analysis are shown in Fig. 22 and Fig. 23, where the total harmonic distortion in the current and voltage were reduced from 28.5% to 8.2% and from 6.7% to 4.2%, respectively. The high frequencies in the signals resulted from using only a single inverter, thereby requiring high switching frequencies (>30 kHz). Using additional inverters, from the eight available from the pulse power supply, should reduce the required switching frequency and improve signal quality.

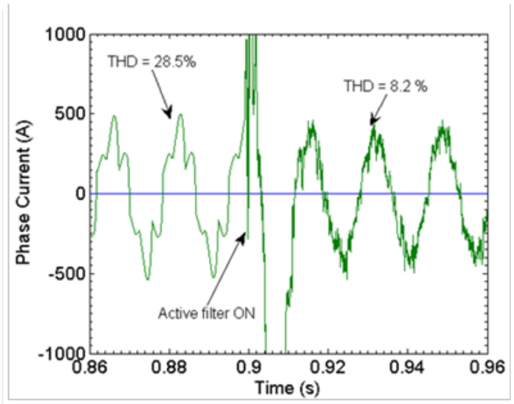

Figure 22. Current with an without active filtering.

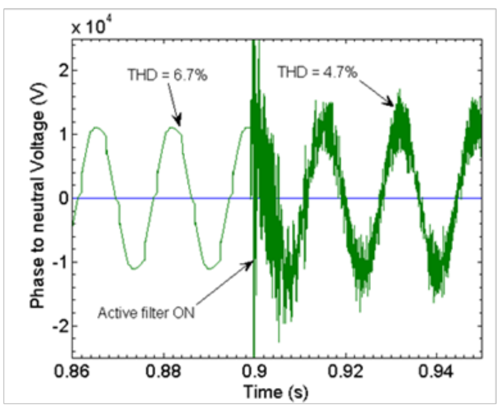

Figure 23. Bus voltage with an without active filtering.

IV. Effects of High-Power Pulsed Loads

As discussed in previous sections, advanced high power pulsed loads require power levels from hundreds of kilowatts to gigawatts. These loads must be fed from the installed electric power, possibly directly for loads requiring power-levels within the capacity of installed power or indirectly, through energy storage, for loads requiring much higher power than installed power, such as EM rail gun systems. Consequently, there are concerns about a potentially detrimental interaction between these pulsed loads and the power system. This concern would be legitimate if the high power pulsed loads were kept connected to the power system during the firing cycle. If, however, the pulsed loads can be effectively isolated from the ship power grid during the firing cycle, then, the only interaction between the power system and the loads would be during the charging of an intermediate energy storage system. This is a relatively slow process that, in principle, should not cause, or be subjected to, harmful transients.

For the case discussed in section III-A, i.e. power sharing through the use of a common energy store, the effect of charging and firing the EM gun and FEL systems on bus voltage is shown in Fig. 24. The results show that the charging cycle causes bus voltage to sag for few cycles but recovers afterwards while the power system remains undisturbed during the actual firing of the EM gun and FEL pulses. This is because prior to firing the high-power pulses the EM gun power supply was disconnected from the ship power grid and energy storage was used to provide the required power.

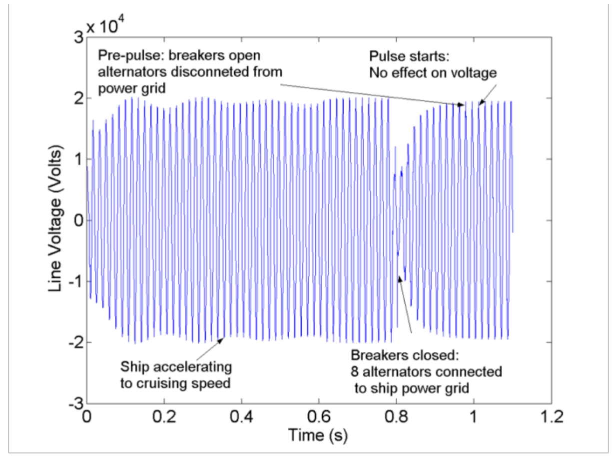

Figure 24. Effect of charging the EM gun and firing of high-power EM gun and FEL shots on bus voltage.

Several other analyses dealing with integration of high power pulsed load were conducted [8-9].

A. *Effects of pulsed loads on stability*

Analytical solutions to stability problems of dynamical systems are usually limited to small systems. Large dynamical systems such as the power system of an all-electric ship require numerical approaches to assess their stability characteristics. The general approach is to conduct numerical simulations of specific operational conditions that can create perturbations in the power system, then infer from the dynamic response if the system remains stable or becomes unstable. Pulsed loads can create such perturbations in an all-electric ship power system and therefore are a potential source of instability.

This report is limited to presenting some numerical results describing the dynamic response of an electric power system to pulsed loads. Definitions of stability terms and methods of analyses are not discussed here and can be found in textbooks such as [13] and other standard definitions [14].

One approach to stability assessment is to consider parameters defined by power quality standards such as in [15] and [16]. If these parameters, such as frequency deviations, harmonic distortion, and voltage variations (e.g., sag, swell, and fliker), remain within an acceptable range, as defined by the standards, during a pulsed power operation, then the system can be considered to be stable. Consider for example a simple capacitor-based energy storage system feeding a pulsed load as described in Fig. 25. The total stored energy is 300 MJ and a single pulse consumes 100 MJ [17]. In this analysis the minimum charging time for which power quality is maintained within the standards was calculated for two different architectures. These are, a conventional 60 Hz medium voltage ac distribution architecture (MVAC) and a medium voltage dc distribution architecture (MVDC). The results for two different operating modes, ring battle mode (RB) and split-plant battle mode (SPB) are summarized in Table IV, and depicted in Fig. 26. The results show that the MVDC power system can charge the energy storage system faster than the MVAC power system while complying with the specified power quality standards.

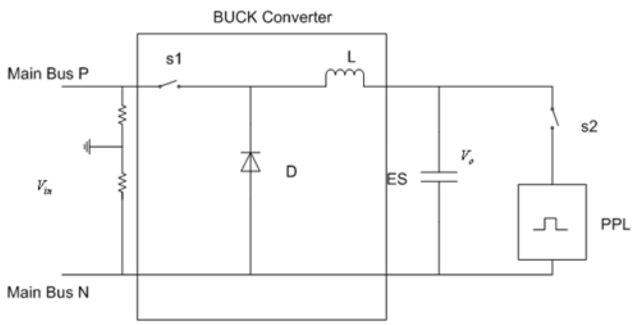

Figure 25. Model of a 300 MJ capacitor-based energy storage system.

Table IV.

	Charging time	
	RB Mode	SPB Mode
MVAC	35.72s	69.32s
MVDC	33.85s	59.99s

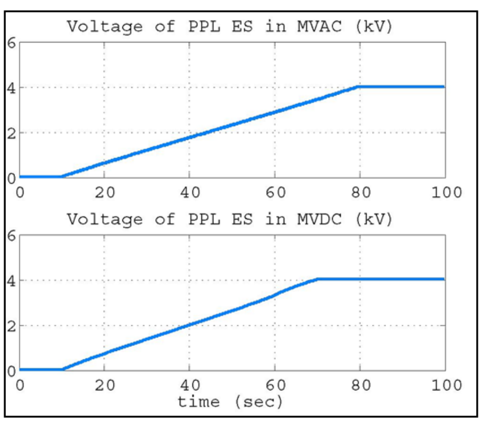

Figure 26. Voltage during charging in split-plant battle mode.

Further discussions on pulsed load related issues addressed by the ESRDC can be found in [17], [18], and [19].

B. Effects of pulsed loads on power quality

The integration of large dynamic loads into a shipboard power system must ensure that the power quality (PQ) of the electrical distribution system is controlled to appropriate standards such as [16], [20], [21], and [22], so that sensitive loads supplied by the same bus will continue to operate without degradation [23].

Assessing the potential power quality impact of pulsed power loads on an integrated ship power system requires the use of either hardware test setups or simulation models that consider all of the major components of the ship power system. This is necessary because the tightly-coupled nature of a ship power system raises the potential for PQ disturbances originating in one zone to affect electrical buses in other zones on the ship. This potential was demonstrated in 2005 when the Naval Combat Survivability (NCS) test-bed was used to determine the system impact of pulsed power loads on a laboratory-scale Integrated Fight Through Power (IFTP) system [24]. Figure 27 shows the test setup employed in the study. The test results showed that the charging circuit for a 200 kJ pulsed power load fed from the IFTP's ac distribution bus resulted in small disturbances on the port dc longitudinal bus, but not at the output of the in-zone, dc-ac inverter (i.e., 450 Vac Type I power load center bus).

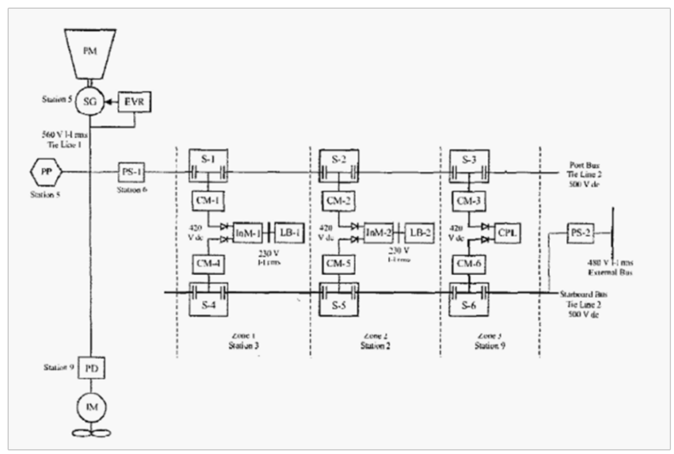

Figure 27. Naval Combat Survivability Test Bed.

A large-scale, ship power system simulation performed in 2007 on a Real-time Digital Simulator (RTDS) assessed the worst-case PQ impact of a pulsed power load on the ship power [17]. Figure 28 shows the functional topology of the RTDS medium voltage ac (MVAC) notional ship model employed in the study. The charging circuit for the pulsed power load was modeled as a six-pulse, switched power supply fed from the MVAC generation bus. In order to stress the ship power system, the pulsed power load model was set to apply a three-pulse burst of 100 MJ charging pulses to the supply bus with one-second spacing between pulses. Maintaining a constant 100 MJ pulse energy, different combinations of pulse magnitude and duration were employed (e.g., 30 MW pulse for 3.33 sec., 15 MW pulse for 6.667 sec.).

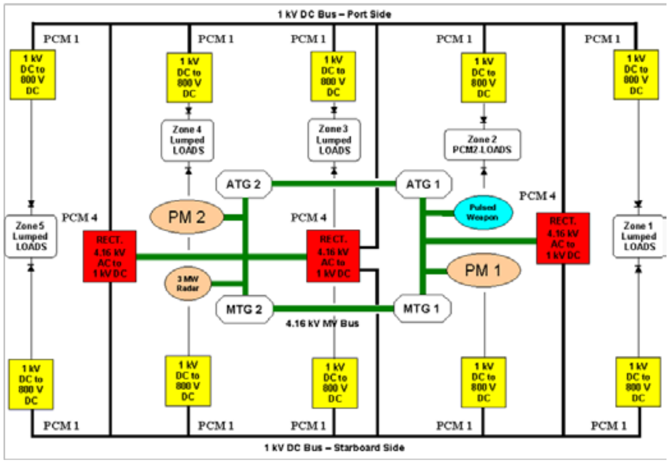

Figure 28. Topology of the RTDS MVAC Notional Ship Model.

The PQ performance indices looked at in the study included frequency deviation of the main gas turbine generators (MTGs), the total voltage harmonic distortion (VTHD) at the point of pulsed power load connection to the bus, and voltage deviation of the port and starboard longitudinal dc buses. The results of the study are shown in Fig. 29, Fig. 30, and Fig. 31. Figure 29 shows main generators MTG1 and MTG2 frequency deviation during the pulse burst with the ring bus configured for split-plant operation.

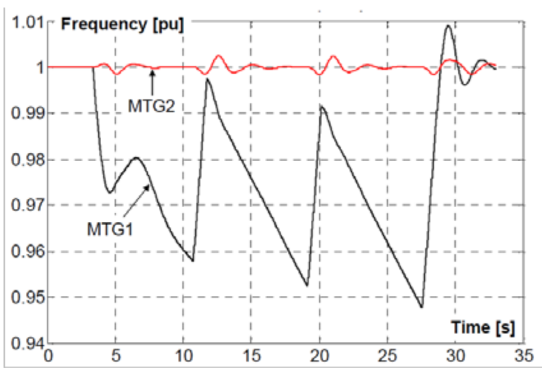

Figure 29. Main generator frequency deviation.

The largest frequency deviation of MTG1 following the application of the pulse sequence reached just over 5%. According to the current standards (i.e. +/- 4% frequency transient tolerance; MIL-STD-1399) this would be unacceptable for a continuing sequence of disturbances. However, this study concluded that the concept of flexible thresholds appeared as a reasonable option for the design of future shipboard power systems. The authors of the study suggested that the prevailing frequency deviation limits of the time could probably be extended much higher, for example closer to (10…15)%, provided the generators and other equipment on the ac bus are compatible with such distortions. The rotating machines on the ac side of the shipboard power system would then need to be rated to operate under higher harmonic distortion.

Due to the split-plant bus topology of this case the pulses did not cause a severe frequency deviation on MTG2. However, this result clearly demonstrated that even in the open bus arrangement the cross-coupling through the dc zonal distribution (DC ZED) system resulted in a measurable response of the generator on the alternate ac bus.

Figure 30 shows the total distortion of the voltage before, during, and after one pulse. The distortion varies from less than 2% before the pulse to around 10% during the pulse and back to 2% after the pulse. These results revealed that in order to keep within the maximum total harmonic distortion limit of the government standards (i.e., +/- 5%), the pulse power level would have to be reduced, or some form of harmonic filtering would need to be applied.

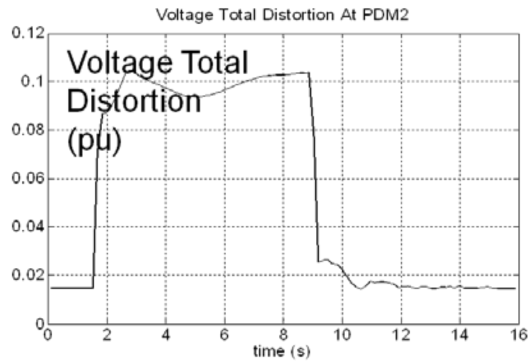

Figure 30. Total voltage harmonic distortion.

Finally, Fig. 31 shows the predicted voltage variations before, during and after the charging pulse for both the ac side (MTG1 and MTG2) and the dc side. It can be seen that the voltage variations remained within the limits established by the standards, i.e., +/- 8%. Other conditions which might result in higher reactive power demands during the pulse would have to be investigated in order to assess all possible adverse conditions regarding voltage variations. Once again, the propagation of the disturbance to the other longitudinal dc bus via the DC ZED configuration is shown in the port 1 kV dc bus curve.

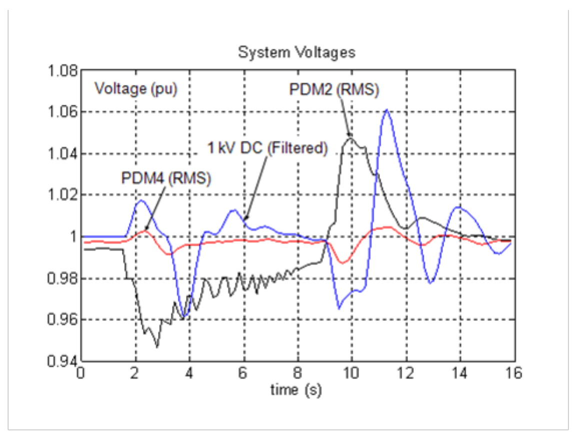

Figure 31. Variation of voltages at the point of common coupling of the pulsed load, the terminals of MTG2, and the 1 kV bus.

User equipment interface requirements for ship ac power systems are provided in subsection 5.2 of MIL-Std-1399, Section 300A. Subsection 5.2.7.2 specifically addresses the ramp loading limit of pulsed loads in specifying that “Ramp loading shall be limited to an average rate of 2,000 kVA per second. No step shall be greater than that specified for pulsed loads (see 5.2.7)"[20]. The load step limit in subsection 5.2.7 for Type I, 60 Hz power is 70 kVA. This 2 MVA per second ramp rate limit for pulsed loads does not speak directly to the power quality implications of operating large dynamic loads in shipboard power systems, but, it does establish a historical baseline for ac ship power systems against which desired pulsed power load ramp rates should be compared.

V. ENERGY STORAGE INTEGRATION

Energy storage is necessary onboard modern all-electric navy ships for effective management of power. It plays several roles that are crucial for the safety and proper operation of the ship. Its integration with the power system has raised several issues that include type, size, location, control, and interface with the power system and the loads. Pertinent characteristics are discussed in the following sections.

A. Need of energy storage for high-power pulsed loads

High-power pulsed loads that need power levels higher than the installed power require energy storage. A long range rail gun system is an example of such a load. Because power is used for very short time intervals, i.e. short pulses, the energy involved is small enough that it can be stored onboard navy ships. Yet, the demand for stored energy increases with demands to improve mission performance and ship survivability.

B. Minimum level of energy storage

The minimum level of energy storage is dictated by its intended use. Four major categories can be identified and are listed below in an approximately descending scale of energy storage level:

1. High-power pulsed loads: As indicated earlier, these loads place a high demand on installed power onboard; typically, the firing rate, pulsed power level, and pulse length, determine the minimum level of stored energy.

2. UPS: The minimum level of stored energy is determined by the power needed and the time for which it is expected to be available to support vital functions when the primary power source is not available.

3. Load leveling: The turning on and off of various loads on a ship may result in undesirable voltage oscillations in the power busses which can be mitigated if a sufficient level of auxiliary energy storage is available to support them during periods of high demand. The storage needed is determined by the amount of bus sag that can be tolerated and the length of time it is expected to last.

4. Active filtering: The minimum level of energy storage is dictated here by the maximum desired ability to suppress unwanted frequency components in the output power profile. Usually, active filtering does not require a lot of energy as compared to the previous three cases.

C. Types of energy storage

The choice of the appropriate type of energy storage to use depends on the loads' missions and the characteristics of the storage technology that are relevant for use on navy ships. Size, cost, efficiency, safety of use, and integration with the ship power system are some of these characteristics. Due to the limited space on modern all-electric navy ships size is a major factor. Two performance parameters are often used to compare storage technologies. These are specific power, given in Watts per kilogram and specific energy, given in Watt-hours per kilogram. A comparison of various storage technologies in terms of these parameters is shown in Fig. 32.

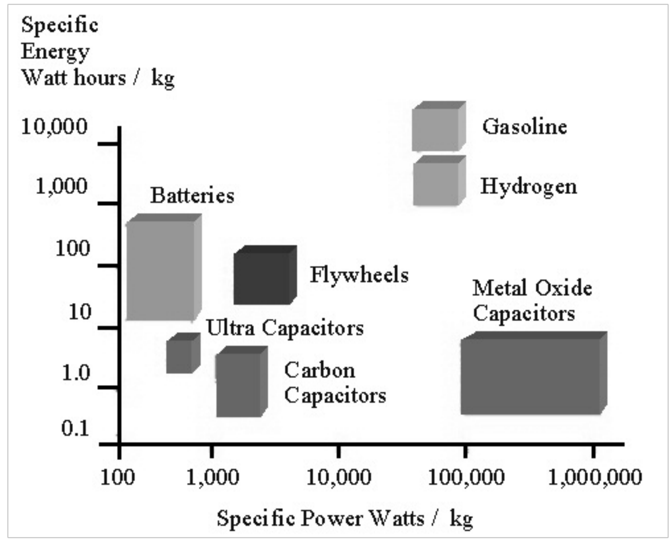

Figure 32. Comparison of energy storage technologies.

Flywheel-based energy storage systems are good candidates that balance specific power with specific energy. An example of a flywheel module for use as load-leveling and UPS unit to support efficient gas turbine operations [25] is shown in Fig. 33. A total of 8 such modules would be needed for 2.5 MW 10 minute operation. A typical integration of a flywheel energy storage system with a turbo-generator power module is depicted in Fig. 34 [25].

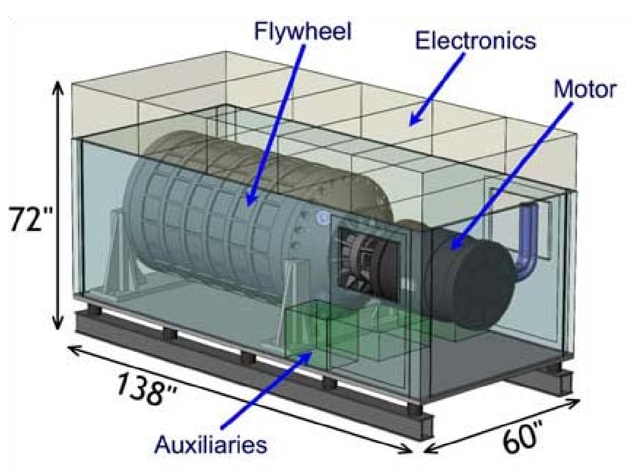

Figure 33. Example of a flywheel energy storage module.

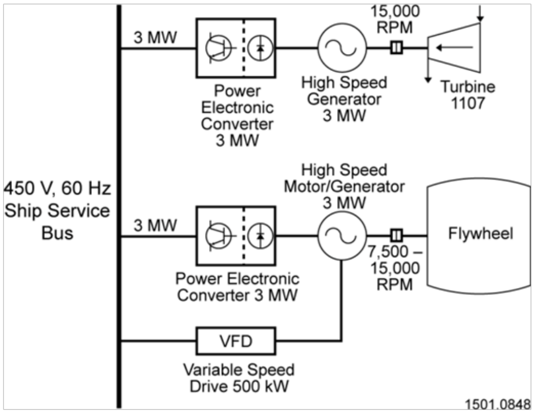

Figure 34. Integration of a flywheel energy storage system with a turbo-generator power module.

Batteries are also good candidates for energy storage and they have been used extensively on Navy ships. However, their use in multi-MW installations may present some challenges with regard to size, number of cells required, and overall reliability. Battery technology is evolving, however, and is an option to be considered.

Other storage technologies, such as capacitors and super-capacitors, are improving in performance and may be used in applications that do not require large amount of stored energy.

D. Multiple use of energy storage

In addition to its use with high power pulsed loads, energy storage can also be used in conjunction with an active filtering system, as shown earlier. Furthermore, it is often used as an uninterrupted power supply (UPS) to support vital loads. Load leveling is another function energy storage can perform when demands for additional power for short period of times arise. This function enables smaller total installed power when peak power demands occur intermittently and for short periods of time only.

Another possible function of energy storage is to improve fuel efficiency by operating in conjunction with the power system so that the prime movers can operate at their highest efficiency when the load profile changes. This function and UPS function are discussed further in the following sections.

1) fuel efficiency improvement

In current navy ships, such as DDG 51 class, multiple turbo-generators units are used so that each unit supports part of the load and operates below its rated power, which is very inefficient in terms of fuel consumption. The reason for operating under this mode is to avoid total power failure that results in a blackout, if only one power unit were operating. An option to avoid this undesirable scenario and operate efficiently is to use an energy storage system with the lowest number of power generating units that operate close to their rated power. This mode of operation saves fuel in the long run and increases the overall life of the turbo-generators by reducing their combined operating hours. The resulting integration of the flywheel with the turbo-generators is as depicted in Fig. 34 but with more power generating units, as needed. Further discussion on this topic can be found in [25].

2) UPS function

To demonstrate the multi-function characteristic of energy storage, a 100 MJ, 4 MW, super-capacitor energy storage system (ESS) was integrated with an 80 MW all-electric ship power system [11]. The top-level diagram of the corresponding Matlab\Simulink model is shown in Fig. 35. The energy storage system (ESS) is directly connected to the ring bus as shown highlighted in Fig. 35. In this example the ESS was used as a UPS unit supplying power to loads connected to an isolated segment of the ring bus after a loss of power.

As indicated on Fig. 35, the loss of 1 of 4 turbo-generators caused the isolation of a bus segment (between crossed breakers) resulting in a loss of power to several connected loads. The ESS was activated after a short time delay to, in effect, replace the lost generator but at a lower power level. The output power of the ESS is shown in Fig. 36, along with the total connected power of ~3.2 MW, which agree well.

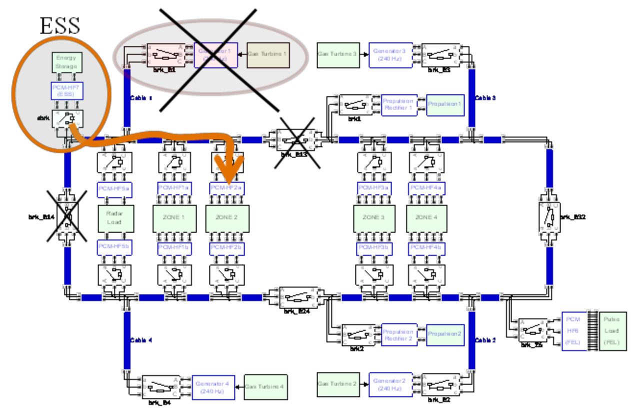

Figure 35. Integrated Energy Storage System operating as a UPS unit.

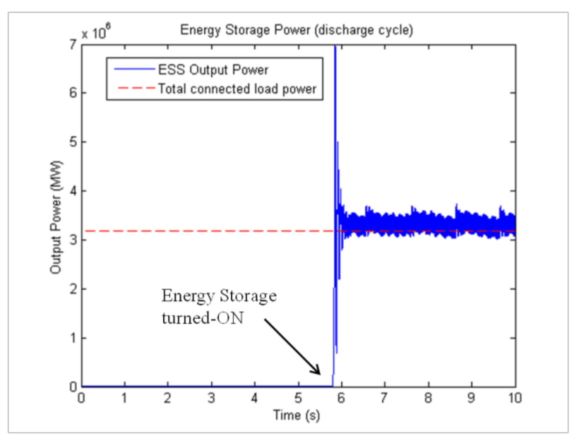

Figure 36. ESS output power and connected power.

3) Dynamic load interface

Recent development of power electronics technologies are making the application of energy storage as an interface between dynamic loads and the power system possible. High speed power control is possible through the use of flexible interface power electronics converters devices (similar to FACTS converters in ac transmission systems). These devices are able to provide high speed real power control using energy storage back-up power and, as a result, can prevent the need of load shedding or generator drop during disturbances caused by malfunctions or high power pulsed loads.

VI. LOAD-CENTRIC POWER SYSTEMS

As discussed in previous sections, the multitude of loads with mission-specific power requirements need to be coordinated so that the power system can provide the power they need and when they need it in an efficient and safe manner. An optimization of load coordination with performance metrics that reflect the need to accomplish all load missions and reduce fuel consumption will result in a power system configuration that is best suited for use in an all-electric navy ship. In other words, it is the load missions that determine the structure of the power system architecture to use for a given navy ship and the missions it has to accomplish. This load-centric approach to power system design is necessary because of the special and unconventional nature of the loads and their missions. A simplified description of various loads with representative power generation and conversion modules are shown in Fig. 37 [3].

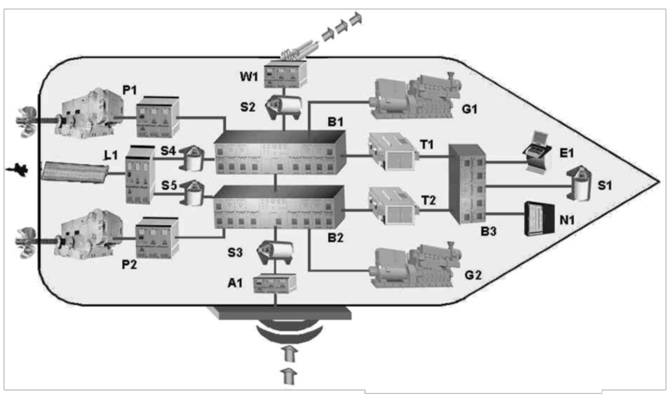

Figure 37. Example of loads on an all-electric navy ship.

In this figure, the depicted loads are as follows:

- P1, P2 : propulsion loads
- W1: high-power rail gun
- A1: active armor
- E1: radar
- L1: electromagnetic launch (EMALS)
- N1: typical ship service load
- S1-S5: energy storage modules, shown here as flywheels.
- G1, G2: Generators
- B1-B3: switchboards
- T1, T2: transformers

VII. CONCLUSION

Modern all-electric navy ships will include advanced systems that require a wide range of continuous and intermittent electric power. Some of the loads require the use of energy storage which, with proper coordination, can be used for other functions that enable the ship to perform its missions effectively and efficiently. Provisions for power transfers among the loads enable continuity of service which can be crucial for the survival of the ship. Components that are required by advanced systems but used intermittently, such as inverters and rectifiers of a rail gun system, can be used to perform other functions such as active filtering in order to improve power quality thereby reducing the need of high-power filters. In-depth considerations of load missions and their coordination enable optimum designs of power systems for all-electric navy ships.

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