

A Design for the Interface Between a Battery Storage and Charging Unit, and a Medium Voltage DC (MVDC) Bus, as Part of an Integrated Propulsion System (IPS) in the All Electric Ship (AES)

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Abstract

In this paper we present the design of a rechargeable battery storage device for use in an all-electric ship. The purpose of this device is to provide power of predictable quality to selected equipment. In addition a recharging unit is proposed for recharging the battery from the ship's electric bus.

1. INTRODUCTION

The MIT End-to-End Medium Voltage DC (MVDC) Integrated Propulsion System was developed in support of the U.S. Navy's "Next Generation Integrated Power System (NGIPS) Technology Development Roadmap [1]. The MIT MVDC IPS model [2] (shown in Figure 1) has the capability to simulate steady-state as well as transient propulsion plant operations. This model is being used to determine the feasibility and benefits of an electrical stored energy system to improve the Quality of Power (QOP) on the MVDC bus and also the power provided to the radar pulse load. We propose to achieve this by reducing or eliminating the transients on the bus caused by the pulse load and to also provide a predictable power source to the load. The full end-to-end MIT MVDC IPS model includes both port and starboard sides of the electrical generation and propulsion plant. Due to the complexity of the full end-to-end model and the computation time required for the full simulation, the plant was simplified for the purpose of these experiments to only one side (shown in Figure 1). This configuration is referred to as the "half plant." Figure 1 shows the MVDC bus, which is fed by the power generation system. Two loads are modeled: the (relatively constant) propulsion system, and the radar system. Prior versions of this model had the radar directly connected to the

MVDC bus (with no stored energy), but with undesirable results due to the transients produced on the bus. The present model studied employs an energy storage device that acts as a buffer between the MVDC bus and the radar pulse load.

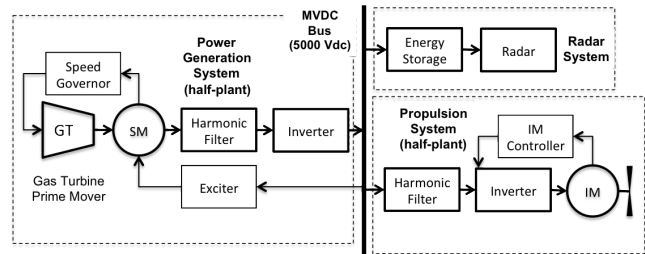


Figure 1: MIT MVDC IPS Half Plant Model Schematic (with energy storage and radar)

The QOP of the DC bus is determined by the voltage ripple and whether it is within limits specified by IEEE Std 1709 ($\pm 5\%$) [4]. Another area of interest (beside QOP on the MVDC bus) is the benefit of the pulse load being powered directly from the battery. Predictable voltage output provided by the battery can translate into more precise output from the radar transmitter, more precise beamforming, and possibly less robust and/or more inexpensive power conditioning equipment for the radar system. To maintain a charged battery system, the stored energy device is supplied by a continuous charge system from the MVDC distribution bus, where the charge rate is controlled to minimize the effect on the bus and to stay within the battery maximum charging limits. The MVDC IPS model has a 5000 Vdc (nominal) distribution bus.

There are several areas of concern with respect to the distribution of MVDC power and also the powering of pulse loads. The study in this paper attempts to address three areas of con-

cern for the MVDC IPS:

1. The QOP on the MVDC distribution bus is very important to the operation of the propulsion system and connected loads. In reference to MVDC systems QOP means compliance with specified voltage tolerances and voltage ripple [4]. A pulse load, such as the radar model referenced in this paper, if directly connected to the MVDC bus, can cause undesirable voltage transients on the bus.
2. The pulse load has mission critical functions that require QOP as well. In general, the synchronous machine (SM) generator voltage control alone is unable to track the high slew rate power requirements of the pulse load.
3. Mission vital loads such as the radar require protection from intermittent and extended loss of prime mover power due to faults or battle damage.

The battery stored energy device has the following benefits that serve to address the problem areas discussed above:

1. The battery and charger arrangement isolates the pulse transient from the distribution bus so other loads on the system have cleaner power.
2. It provides a very low impedance, predictable power source to the radar.
3. It acts as an uninterruptible power supply for the pulse load and could be used for other vital loads such as the fire control computer system.

Although a battery is used for this study, the concept of continuous charging can be applied to any electrical charge energy storage device. The controls will need to be modified to adapt to the characteristics of the device. There are three important factors for use of stored energy with the radar pulse load studied: capacity 30-50Ah at 3000 - 4000 Vdc (nominal), 450 - 750A max discharge rate, and 300 - 500A max charging rate. These guidelines are for the total stored energy battery pack (or capacitor bank, if used).

The MVDC bus has multiple criteria for QOP. IEEE Std 1709 [4] specifies values for maximum withstand voltages (both short duration and lightning impulse) and also for voltage ripple (5% rms). Of course, both phenomena should be minimized or avoided if possible.

2. CAUSES OF MVDC POOR QOP

There are two main causes of voltage ripple and peak transients on the MVDC bus. The first is inherent in the system due to rectification. The second is due to pulse or other irregular loads, such as the radar load studied here. These two are, of course, not the only causes of poor QOP on an MVDC bus, but are the main ones encountered in this study.

2.1. SWITCHING POWER ELECTRONICS

The rectification of 3 ϕ AC power and the propulsion Induction Motor (IM) hysteresis current controller cause switching noise on the MVDC distribution bus. Rectification noise is fairly predictable and can usually be satisfactorily filtered by implementing notch filters at the harmonics of the AC generating frequency. The propulsion motor is a torque reference controlled IM that has its speed set by a hysteresis current control inverter. This controller generates an AC current waveform at the frequency desired to set the speed of the IM. The noise produced by the irregular switching in the controller is not predictable and is difficult to filter. For high power systems, rotating electrical generation machinery and the conversion of AC power to DC will likely be used well into the future. So MVDC distribution systems will need to handle the switching noise on the distribution bus. The stored energy device is a possible solution to overcome switching noise for many load applications. The MVDC IPS model was used to explore the noise on the distribution bus due to switching power electronics. In Figure 2 it can be seen that at 1.13×10^6 Nm torque command (which corresponds to 25 knots ship speed - which is at the limit of the model's propulsion system rating), the noise on the bus is outside the 5% rms specification. The voltage fluctuation is approximately 5.6% rms. The filtering of this noise (from switching power electronics) is being addressed in other research.

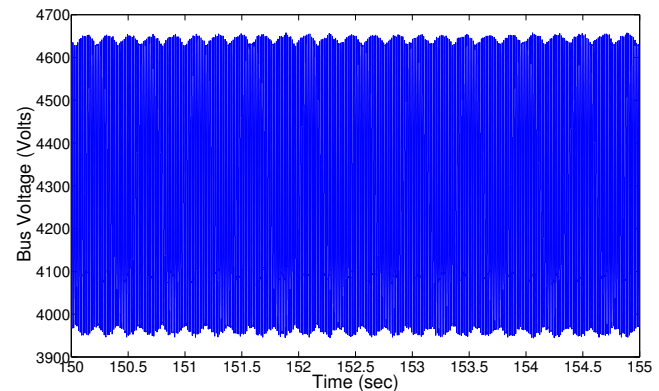


Figure 2: MVDC Bus Voltage - IM at 1.13×10^6 Nm. (Reference MVDC Bus Voltage is approximately 4.3kV with droop-control feature)

2.2. BUS CONNECTED PULSE LOADS

The SM and the gas turbine (GT) prime mover have large inertias that make it impossible for the mechanical power to follow high slew rate loads. The system relies on the DC voltage controller which acts through the rotor excitation. The DC voltage controller has its own dynamics; the control circuit requires low pass filtering at the sensor inputs and the rotor

has inductive reactance which limit the controller's ability to satisfactorily respond to high power, high slew rate loads. If a high power pulse load is connected directly to the MVDC distribution bus, the nearly instantaneous power draw will exceed the ability of the DC voltage controller to react, and will cause a transients, both on the rising and the falling slope of the power profile. This can be seen in the plot in Figure 3 which is the response to the radar load shown in Figure 4. The simulation was performed with the propulsion load discussed in Section 2.1. removed to observe the noise caused by the radar pulse load only.

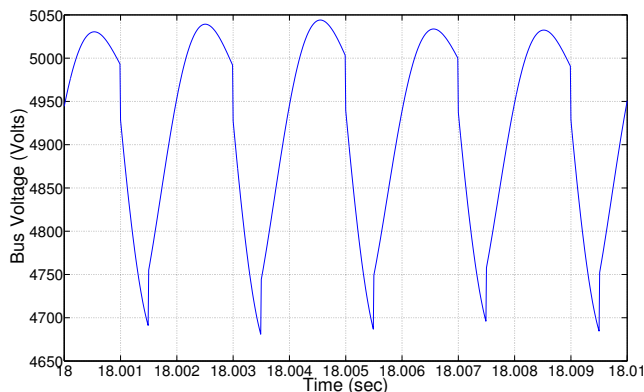


Figure 3: MVDC Bus Voltage with Radar Load Only (Voltage less than 5kV nominal reflects droop-control)

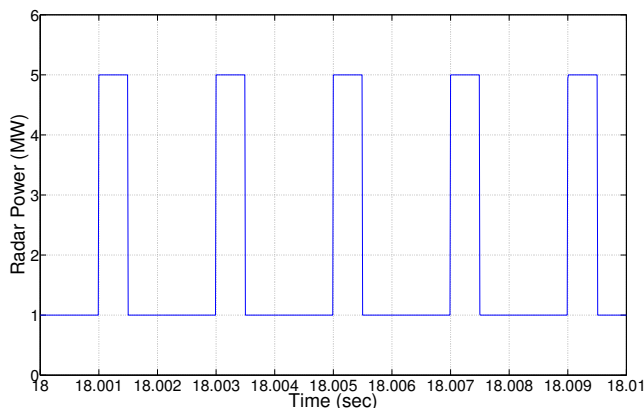


Figure 4: Radar Pulse Load

3. APPROACH

Several options were considered to address the problems discussed in Section 1.:

1. Connection of the pulse load directly to the distribution bus.
2. Connection of the pulse load directly to the distribution bus with a battery stored energy device in parallel.
3. A battery stored energy device powering the pulse load independent of the distribution bus; using multiple battery packs. One battery pack is on service supplying the load while the others are recharging.
4. Pulse load isolated from MVDC bus by stored energy device that is connected to a continuous charging circuit.

The first two methods had the disadvantage of exposing the MVDC bus to the transient of the pulse load. The transient was effectively reproduced on the bus in the second method by the dc-dc converter supplying the radar power bus. The third method had a disadvantage of requiring switching between battery packs. This poses a problem by inducing a transient on the bus which powers the radar as one battery pack that is at its depleted voltage is replaced by a pack that is at its fully charged voltage. The fourth and present method is to isolate the pulse load completely from the MVDC distribution bus, powering it solely from the battery energy storage device (ESD). The charging system is commanded to maintain a reference state of charge (90%) of the battery. As the battery gets depleted from supplying the pulse load, and the SOC drops below 90%, the battery charging current source will respond by supplying a charge current that exceeds the discharge rate of the battery to bring the SOC back to the reference value.

4. RADAR MODELING

The IPS needs to maintain QOP in the presence of pulse loads while simultaneously delivering propulsion power. A modern phased array radar is designed such that one radar system can perform both a surface/air surveillance scan and also dedicated contact tracking. This is achieved through the array elements being powered in relative phases from one another to reinforce the electromagnetic energy in one direction and attenuate it in another. The system may operate in many different modes at different power levels. Power levels can range from low power that is associated with a general surveillance scan all the way up to maximum power when the system is tracking multiple contacts in high resolution. The mode, and consequently the power level of the radar is determined by the fire control system algorithms based on the contact environment. For this study, a radar pulse load model was approximated to simulate a pulse load [3]. The pulse load changes the power level from low power (1MW) to high power (5MW) at a period of 2ms and 25% duty cycle, which are reasonable characteristic parameters of a modern phased array radar [3].

5. ENERGY STORAGE MODELING

Much of the rapid advancement in battery technology is driven by the hybrid and electric vehicle industry. This area of research is also important to the Sea Grant College program for use in Unmanned Undersea Vehicles [6]. The battery energy storage device for this application was modeled using the SimPowerSystems[®] library battery model framework [7]. The parameters were set to use the lithium-ion battery algorithm. The model consists of 1000 cells connected in series to produce a nominal 3300 Vdc battery pack. There are five “banks” connected in parallel to allow for the required recharge rate. The SAFT[®] Super-Phosphate[™] battery [5] parameters were used. This battery has superior discharge current capacity, up to 1760A and a large capacity, 10Ah per cell. The battery parameters are as follows (per cell):

Nominal Voltage	3.3V
Rated Capacity	10Ah (33Wh)
Fully Charged Voltage	4.0V
Nominal Discharge Current	10A
Maximum Discharge Current	1750A (continuous)
Nominal Charging Current	10A
Maximum Charging Current	150A (6 min)
Internal Resistance	0.8mΩ

A battery pack is a set of battery cells that are connected in series and parallel. For example, most of the simulations use a basic battery pack that contains 1000 LiFePO₄ in series and various number of these in parallel (banks). The battery’s total energy is stored or depleted in a predictable manner as a function of the charge or discharge rate, respectively, the state of charge of the battery, the number of cycles and the temperature. Number of cycles and temperature were not modeled in this study as they have a tertiary effect and they would unnecessarily complicate the model. The battery packs would need a cooling method in practice, however, to maximize their efficiency and their lifecycle.

6. CONTINUOUS CHARGING MODEL

The continuous charging circuit is comprised of a battery storage system, a charging system, and a controller, as can be seen in Figure 5. The battery charging system is a current controlled device that has a closed loop SOC regulator. In the present Simulink[®] model, this element is a SymPowerSystems[®] controlled current source. The SOC controller regulates the battery SOC at a near-maximum value. Ninety percent was used for the simulations, but this can be optimized. The regulator must not be set too high as the battery voltage rises rapidly near full charge when charging and the battery can be permanently damaged or its life drastically shortened. The SOC regulator should be set as high as possible, minus a safety margin, to make the most use of the available stored energy, and to minimize the battery pack size for cost and weight optimization.

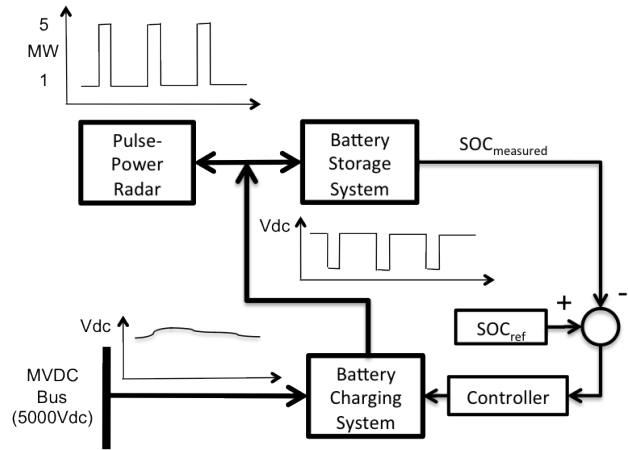


Figure 5: Continuous Charging Circuit Schematic

There are three advantages for the stored energy configuration shown:

1. The radar is isolated from the MVDC bus, eliminating unpredictable power supplied to the radar and conversely eliminating radar pulse load affecting the QOP on the MVDC bus.
2. The battery storage device is permanently connected to both the MVDC bus and the battery terminals so there is no switching required to maintain charging current to the battery storage device.
3. It eliminates the need to have multiple battery banks for alternate charge / discharge operations.

7. RESULTS

For all the results shown in this section, 5 battery banks were used (5000 cell battery pack). This could be further optimized both for maximum storage capacity as well as minimum volume and weight. The important factors for optimization are both the allowable charge and discharge current specifications, the internal resistance of the pack, the pack voltage (number of cells in series), and energy capacity. As can be seen in Figure 7, the battery is initialized with 97% SOC. As the radar load (Figure 6) depletes the battery, the charge controller will maintain the battery at a commanded 90% (note the approximate 1% steady state error shown due to proportional-only control). The plot shown in Figure 8 shows the battery voltage as the battery supplies the pulse load. The battery current is shown in Figure 9. The MVDC bus voltage is shown in Figure 10. This is the voltage at steady state and as can be seen, it has very small variance and meets the specification for voltage ripple [4]. There is no detectable affect on QOP from the charging circuit. As discussed, the charging circuit has a second order smoothing function applied to the

current command signal to filter the charging demand from the MVDC bus.

The radar power load for this simulation is the same as shown in Figure 4. The bus voltage for the continuous charging scheme can be seen magnified in Figure 10. Note that there is no detectable transient on the bus from the charging circuit as designed. The bus sees only the slow varying demand from the charging circuit which can be carefully controlled to draw power from the bus smoothly. In the present implementation, the current command is passed through a second order transfer function to produce a zero slope entry for any step change in current command. The time constant of the controller can be set larger than the SM voltage controller so the MVDC bus will not experience a pulse transient. Also, the presence of the stored energy device allows margin to recover from a significant increase in the power of the pulse load. Presently, the charging circuit controller uses a simple proportional controller, so there is some steady-state error in the battery SOC output but this is not a critical parameter in our application. This can be corrected with integral control if precision is required. Figure 7 shows the battery SOC during the full simulation. It settles to the commanded 90% minus the steady-state error. Figure 8 shows the battery voltage during the simulation. The transients on the battery bus can be absorbed by the charging circuit control because it is current and SOC controlled. The charging circuit can maintain a smooth “average” current output in which the battery will be charging during the low power cycle of the radar, and then discharging (minus the charging circuit current) in the high power cycle of the radar. Figure 9 shows the battery current during the full simulation. Since the duty cycle of the pulse is 25% it is somewhat easy to see from this plot the energy balance that is maintaining the battery SOC (300A input to the battery for $\frac{3}{4}$ of the cycle and 900A output for $\frac{1}{4}$ of the cycle).

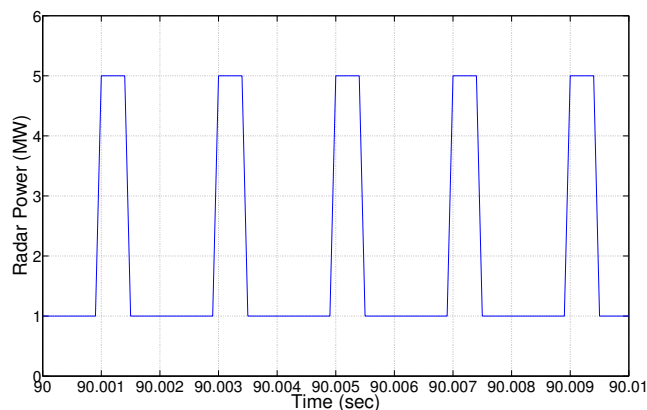


Figure 6: Radar Power in Continuous Charging Scheme

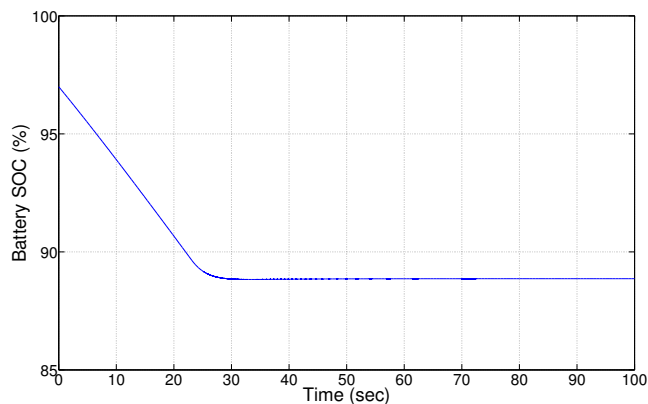


Figure 7: Battery SOC in Continuous Charging Scheme

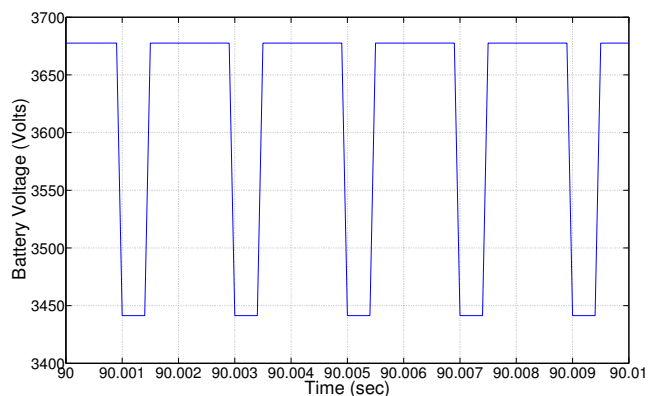


Figure 8: Battery Voltage in Continuous Charging Scheme

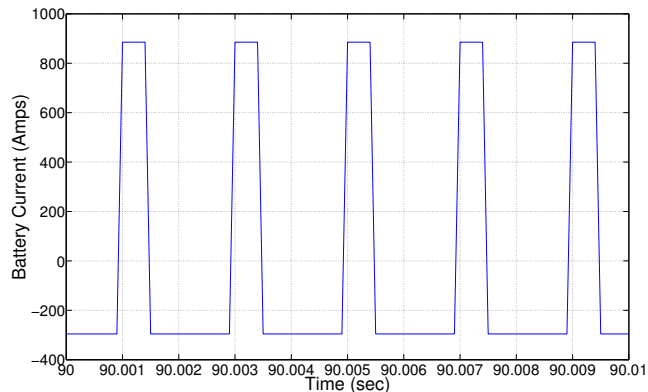


Figure 9: Battery Current in Continuous Charging Scheme

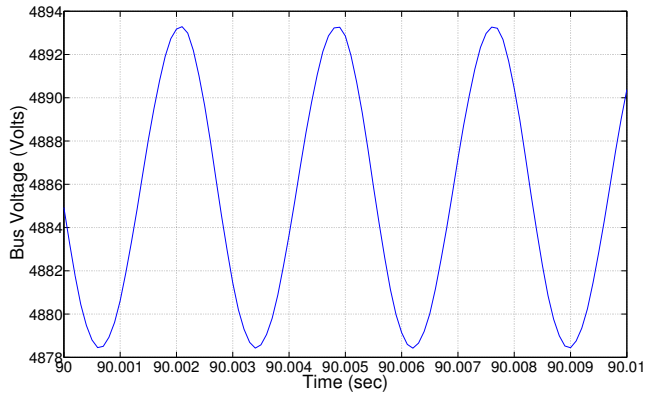


Figure 10: MVDC IPS Bus Voltage in Continuous Charging Scheme (magnified)

8. CONCLUSIONS

The continuous charging scheme has been shown to be a beneficial configuration in simulation. All of the concerns listed in Section 1. are addressed and the benefits listed in Section 6. are realized. The MVDC IPS bus is protected from radar pulse load transients, the radar itself experiences a higher QOP and the system does not need to be switched; it can be continuously operated. The system can also work well for backup power in the event of a loss of ship's power. Some areas for further investigation are to design a current controlled charging circuit using a dc-dc boost converter, improve the charge controller to optimize available stored energy and to maximize battery lifecycle and optimize the battery pack size.

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