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The Directed Energy Group at the Naval Postgraduate School (NPS) and the University of Texas Center for Electromechanics (UT) have collaborated to develop simulation models of electrical power systems on specified naval platforms expected to be retrofitted with laser loads. These models of ship power systems are needed to evaluate and guide the integration of pulsed laser loads onto existing ship platforms. The results of the modeling efforts provide critical information needed for the safe and effective deployment of laser systems on existing Navy combatants. They can also be an invaluable tool in the definition of a suitable energy storage system to handle the effect of the transient load.

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# Power Systems Modeling for the ONR SSL-TM Program

## ONR Grant N00014-14-1-0601

**"Laser Weapon System Integration Study"**

Final Report

Submitted to:

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# Executive Summary

Lasers are an emerging weapon system for a number of platforms, including ships. Now that they are demonstrating effectiveness, the need for optimal power system integration arises. Consequently, the Directed Energy Group at the Naval Postgraduate School (NPS) and the University of Texas Center for Electromechanics (UT) have collaborated to develop simulation models of electrical power systems on specified naval platforms expected to be retrofitted with laser loads. These models of ship power systems are needed to evaluate and guide the integration of pulsed laser loads onto existing ship platforms. The results of the modeling efforts provide critical information needed for the safe and effective deployment of laser systems on existing Navy combatants. They can also be an invaluable tool in the definition of a suitable energy storage system to handle the effect of the transient load.

To be relevant in the near term, the study focused on models needed to retrofit a DDG51 with solid state lasers having optical power levels of 30 kW, 60 kW, and 125 kW. The storage technologies considered were lead-acid batteries, lithium-ion batteries, flywheels and capacitors. Three technologies were addressed because it was not obvious which technology would be the most appropriate. Batteries are excellent energy sources but not as good as power sources. Flywheels and capacitors tend to be worse than batteries in energy density, but can be better in power density.

The key observations included:

- The modeling approach used provided significant design information for laser integration and was structured in a way that permits detailed assessments of the influence on the ship system by adding detailed, and likely classified, information concerning the attributes of specific ship loads. So the work is valuable well beyond this particular investigation.

- For the 30 kW laser, energy storage may not be necessary. This raises the larger question of the lack of engineering guidance to select which operations require storage and which operations can be addressed through advanced control of the ship power system.

- Close attention must be paid to the power electronic converters needed to interface the storage modules to the ship power system and to the load. These modules play a crucial role especially for power quality, which is crucial for effective laser operation. Furthermore, power electronics can have a major impact on the volume and weight of the storage system.

- Flywheels have a power and weight advantage over batteries for the applications studied.

- The anticipated updating of MIL-STD-1399 opens the possibility of less costly laser integration.

- Likewise, once incorporated into the ship's electrical system, the energy magazine needed to support the laser load could also assist other planned pulsed loads and can serve additional purposes, when not needed for its primary intent:

  - Function as an uninterruptible power supply (UPS) for the ship's power system in case of temporary loss of any of the normal power sources
  - Function as a power ripple leveling system when sudden loads are switched on and off the ship's power system.

- These ship models allow the study of the optimal design of the energy storage system architecture: for example, whether storage should be dedicated to the load it is meant to serve or whether it could be shared by multiple loads, or similarly whether storage should be located in close proximity to its main load or could be distributed throughout the power distribution system. Likewise the optimal granularity (number of independent sub-units making up the storage system) of the energy magazine can be evaluated by using these models.

The program was carried out successfully resulting in working computer models for the various systems considered. These models are attached herein as part of the deliverables. A description of the various models with supporting examples is given in this report to make the use of the models as transparent as possible to the potential user.

# Program Overview

## Background

High-power solid-state laser systems are being developed as advanced weapons and sensors for a variety of Department of Defense applications including naval surface combatants. These new technologies, with their still relatively low efficiencies and transient power requirements, present significant potential challenges to the electric power distribution and thermal management systems of a ship. This is particularly true for applications requiring retrofitting these new systems onto existing naval platforms with limited excess electric power generation and cooling system capacities.

Prudent design considerations suggest that the use of suitable energy storage systems in support of these large but intermittent loads seems quite likely: these "energy magazines" would provide the necessary power when needed by the loads, and then be recharged during downtime. Regarding operational specifications, the energy magazine should allow for a sustained engagement against multiple targets probably lasting several minutes. Ideally, it would charge as fast as it discharges, allowing for indefinite use as long as there is ship's fuel to expend.

The development of simulation models of ship power systems to evaluate and help guide the integration of pulsed laser loads onto existing ship platforms can be a substantial step forward in expediting a safe and effective deployment of laser systems on Navy combatants. They can also be an invaluable tool in the definition of a suitable energy storage system to handle the effect of the transient load.

The Directed Energy Group at the Naval Postgraduate School (NPS) and the University of Texas Center for Electromechanics (UT) have collaborated to develop simulation models of electrical power systems on specified naval platforms expected to contain laser loads. These new models are presented in this report and include modules for solid state laser (SSL) weapon systems at several output levels along with modules for various energy storage technologies. The new models leverage past experience of NPS and UT in jointly developing power system models of electric ships with laser weapons over the course of a collaborative effort during the last ten years [1]–[9].

Three types of energy storage methods have been investigated in the course of this research program: batteries (both lead-acid and lithium- ion), flywheels, and capacitors. Three different laser power levels likely to be employed within the next decade have also been considered: 30 kW, 60 kW, and 125 kW optical power output. All possible combinations of storage technology and laser power have been explored in the course of this cooperative program and, to date, this collaboration between NPS and UT has resulted in two Masters Theses awarded at NPS to Navy officers using the simulation models developed in the course of this latest effort [8][9].

This report summarizes the work done and includes all MATLAB/Simulink models developed as a separate attachment on a CD disk.

## Statement of Work

This program was structured according to the following tasks:

1. Collect information, develop and analyze a modularized electrical model of SSL weapon systems onboard a DDG-51 Flight IIA Class ship, including simulation modules for:
    a. 30kW SSL (LaWS)
    b. Diesel and gas turbine generators
    c. Lead acid and lithium ion batteries
    d. Capacitors and flywheels
    e. 60kW and 125kW SSLs

2. Repeat the above for an LCS Independence Class ship

3. Run representative simulations, analyze the results, and convert the analysis into a set of actionable alternatives for the Navy.

## Development of a Ship Power System Model

The approach used in carrying out the project can be summarized as follows:

- Model ship power systems
- Model alternate power supplies
- Assess attributes of various system approaches to powering lasers
- Provide effective tools to predict the performance of the various systems relative to suitable metrics.

All cases studied can be represented by the basic electrical diagram shown in Figure 1, although the internal structure of most items shown may be specific to the particular model in question.

The diagram in Figure 1 was based on analogous conceptual diagrams reported in Navy documents, particularly [10]-[12], with suitable generalizations to accommodate the various cases considered.

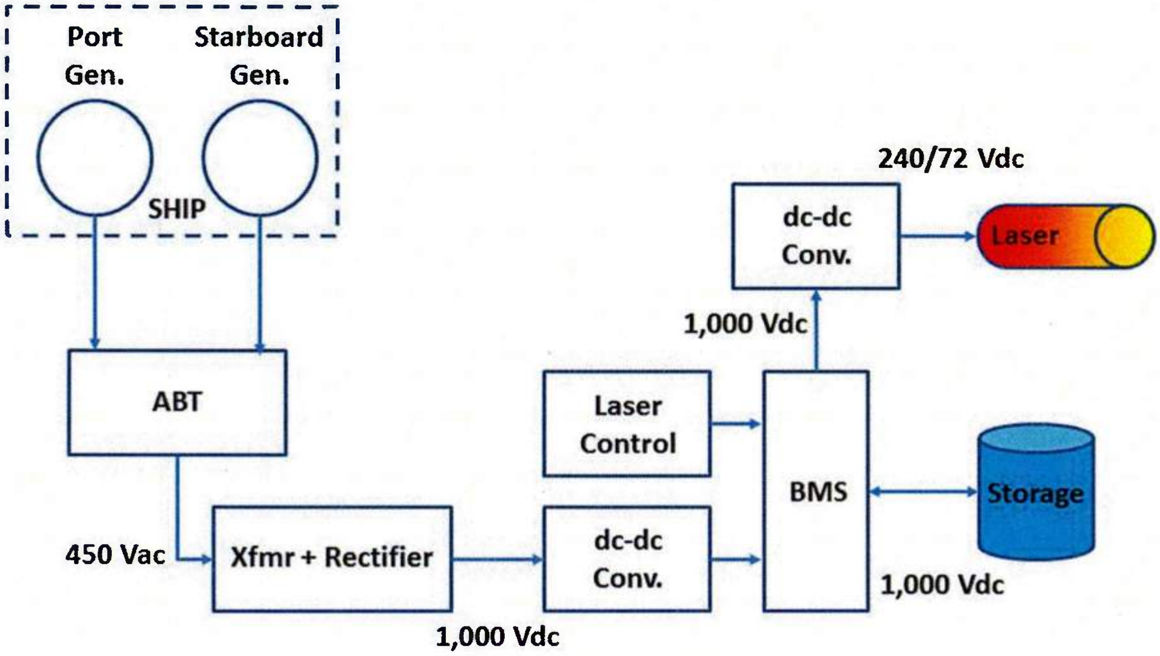


Figure 1: General conceptual electrical diagram for all models
(ABT = Automatic Bus Transfer; BMS = Battery Management System)

After the inception of the program and approximately half way through it, at the request of ONR all resources were redirected to refining the models concerned with the installation of the laser weapons as a back-fit into the existing platform of a DDG-51 Flight IIA class ship and to study in more depth than originally anticipated the performance of the laser weapon on this naval platform. Therefore, detailed models were developed for the electrical system of such destroyer class ship and the equivalent models for the LCS Independence class ship, although initiated, were left incomplete. This report, therefore, will be concerned primarily with the integration of a laser load on a DDG51 class destroyer and its expected performance.

The model of the ship proper was constructed so as to duplicate the actual distribution of electrical equipment into electrical "zones": thus, the user of the model can quickly orient himself thanks to this one-to-one mapping between model and electrical schematics (Figure 2).

For ease of use of the models, power from both the port and starboard ac busses was made available at regular intervals along the ship so that external equipment could be connected without having to change the basic electrical architecture of the ship. These power taps are evident also in Figure 2. The same ship model was used for all combinations of load and energy storage studied.

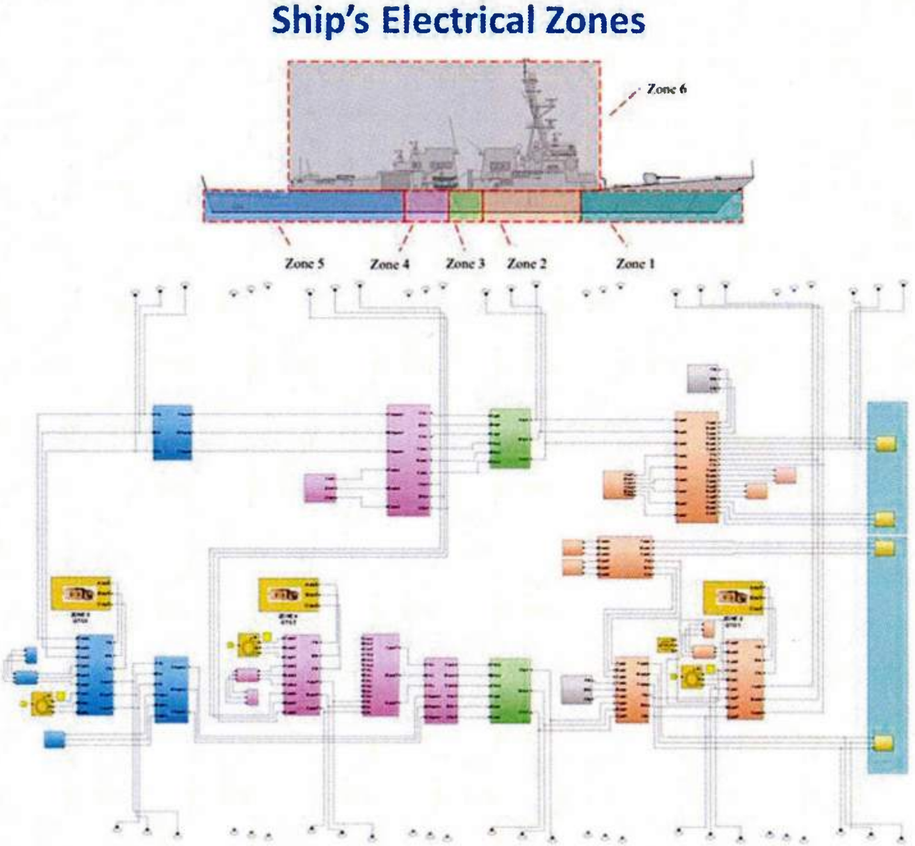


Figure 2: Internal structure of the DDG51 ship model showing the one-to-one mapping to the ship's electrical zones.

Complete technical information on all the conventional loads aboard a DDG51 destroyer could not be collected, so that conventional loads need to be fully characterized. However, the framework of the electrical system is complete and is a faithful model of the electrical system of a DDG51 class ship, constructed from actual prints of the ship. It is a simple matter of adjusting or adding the proper parameters of the conventional equipment on board in order to obtain a thorough and accurate electrical model of the ship. For example, opening the zone 2 block in Figure 2 related to Auxiliary Machinery Room 1, one gets the diagram shown in Figure 3, that shows a combination of a motor load, other miscellaneous loads, and several interconnections via circuit breakers, the whole being powered by Gas Turbine Generator no. 1.

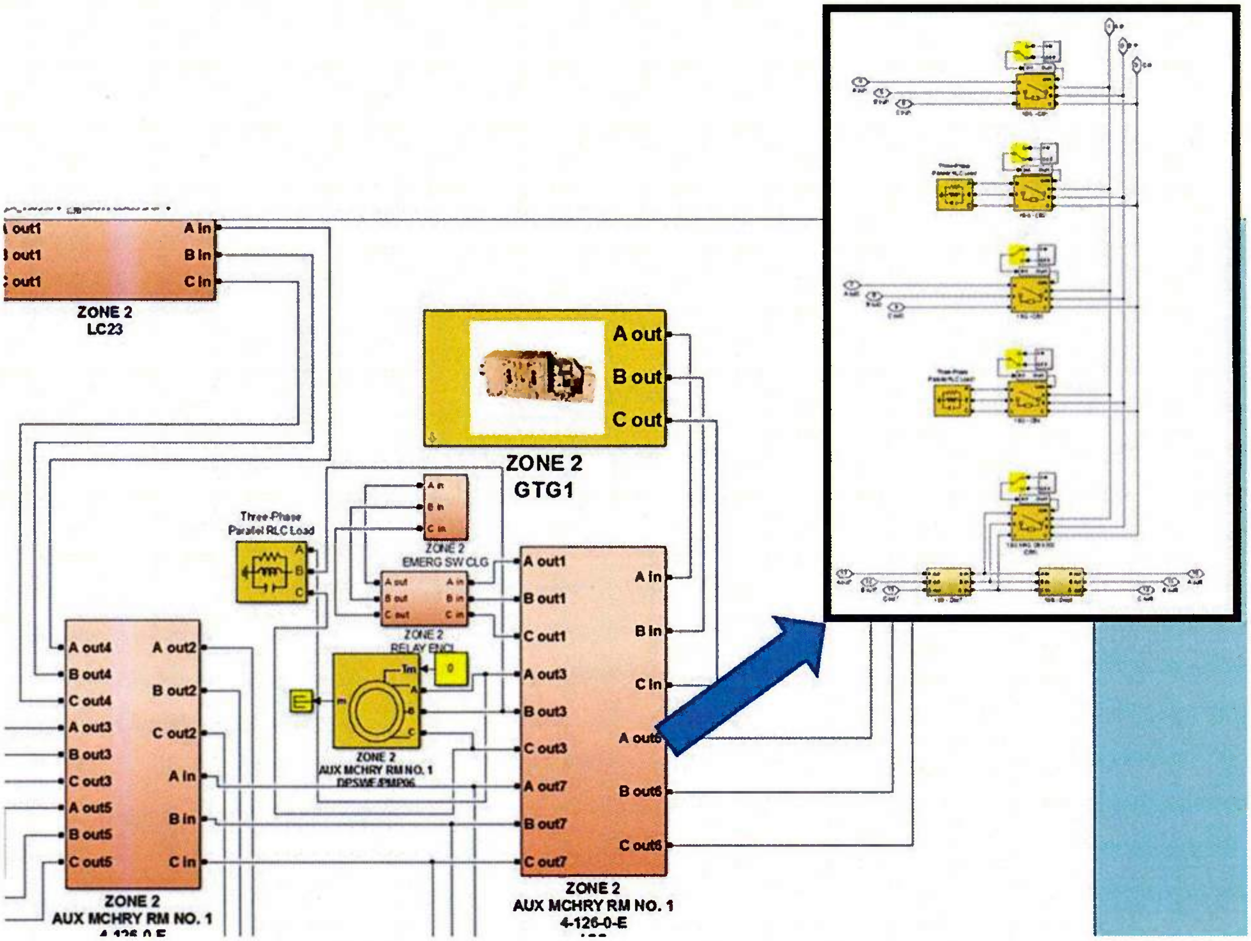


Figure 3: Internal structure of the Auxiliary Machinery Room no. 1 block in Zone 2 with gas Turbine Generator no. 1, a motor load, and other miscellaneous loads.

# Models

## Lead-Acid Battery Storage

Figure 4 shows the macroscopic diagram of the model of a DDG51 destroyer class ship retrofitted with a SSL and supported by a lead-acid battery energy storage system. The lead-acid battery model is based on the Genesis XE70 battery by Enersys (see Appendix 1). It was assumed that the laser load would be powered by both port and starboard power busses for insuring energy security. An automatic bus transfer (ABT) controller was used to insure that power to the laser was always available from one of the two busses. The incoming 450 V ac power is then transformed up in voltage and rectified resulting in a 1,000 V dc bus available for charging the battery when the laser is not powered. A battery management system (BMS) interfaces the battery energy storage to the ship power system on one side and to the laser load on the other. The BMS insures that the laser is fired only under battery power and during that time the battery is disconnected from the ship power. When the laser is not fired, the battery is disconnected from the laser and reconnected to the ship power from which it is then recharged.

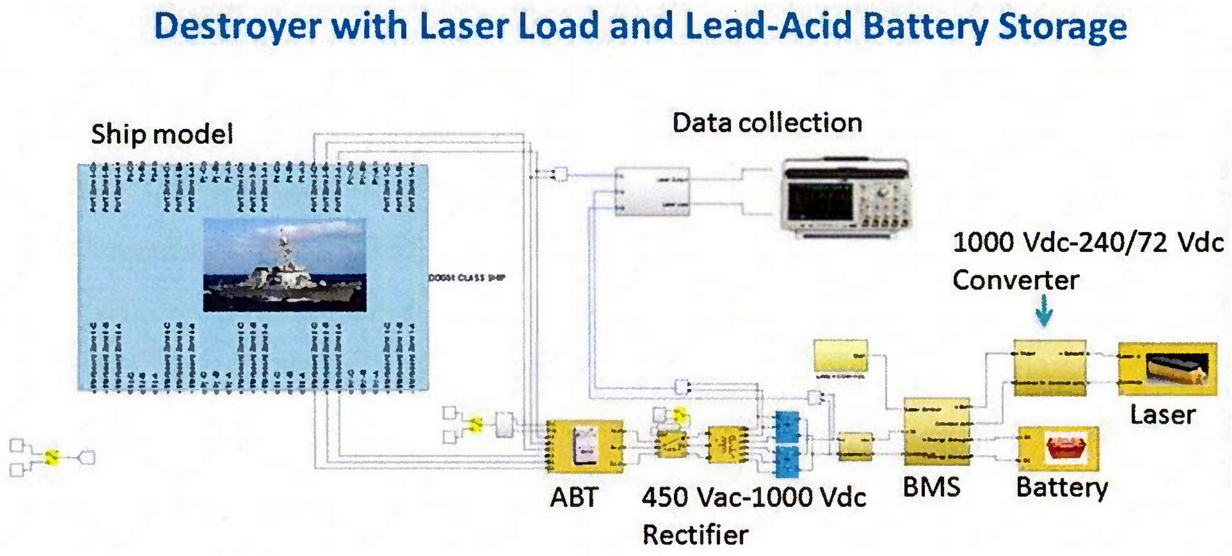


Figure 4: Diagram of destroyer class ship model with SSL and lead-acid battery energy storage (ABT = automatic bus transfer, BMS = battery management system).

The diagram is laid out essentially as in the conceptual one shown in Figure 1 except for the fact that the data collection section is shown explicitly and the dc-dc converter at the input side of the BMS is missing. The reason for this is that the battery voltage is quite flat over its normal operating range and can be easily matched by a suitable choice of the input transformer voltage ratio. In case of a need to recharge the battery after a deep discharge, the charging voltage can be varied as necessary by suitably phasing the SCRs in the ABT module. This was done to simplify the model to its minimum number of components.

### Lithium-Ion Battery Storage

The model for the system with lithium-ion battery storage is functionally identical to the one with lead-acid batteries and is reported in Figure 5. The battery used in the model is based on the VL-30 PFe cell by Saft America (see Appendix 1). The types of analyses and results obtained are similar in nature to the ones for the lead-acid cases provided allowance is made for the different battery characteristics.

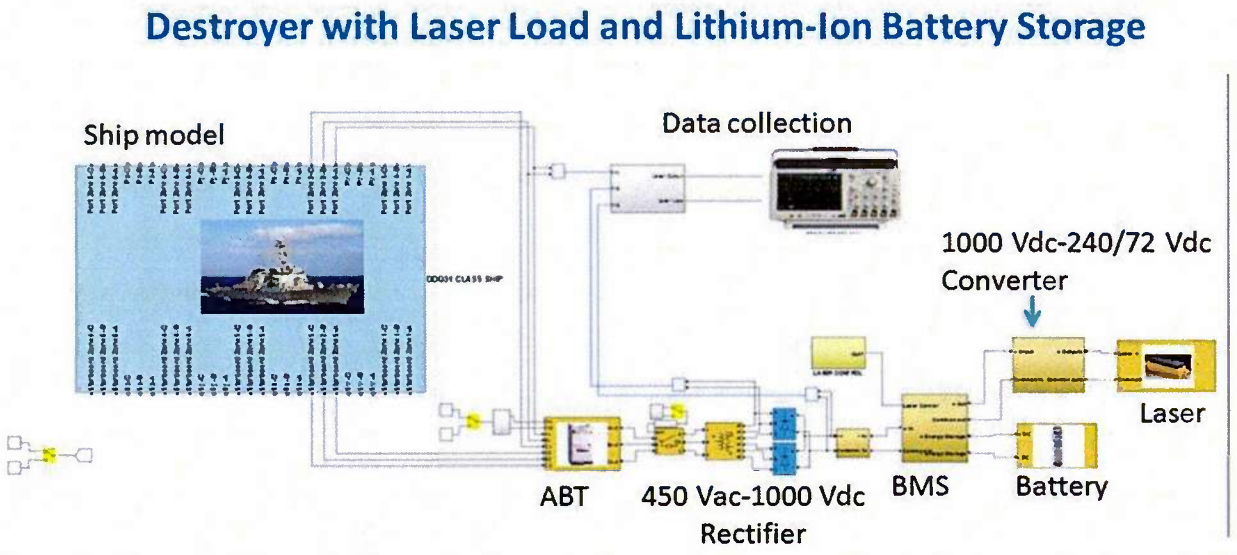


Figure 5: Diagram of destroyer class ship model with SSL and Lithium-Ion battery energy storage

### Flywheel Energy Storage System (FESS)

The overall model with flywheel energy storage looks outwardly identical to those shown in Figure 4 and Figure 5, except that the block labeled “Battery” is replaced by a block containing the model of the flywheel energy storage system. See Appendix 2 for details. Operationally, the models also work the same way via the control exercised by the BMS block: the flywheel storage is disconnected from the ship power and powers the laser when the laser is activated, whereas it is disconnected from the laser when this is not used and is instead reconnected to ship power for recharging. The electrical diagram for the flywheel energy storage is shown in Figure 6.

As in the case of the battery models, the scheme is essentially the same as that shown in Figure 1except for the addition of the data collection blocks and the absence of the dc-dc converter at the input side of the BMS. This is due to the fact that the FESS incorporates in itself a power converter through which it is interfaced to the ship power system.

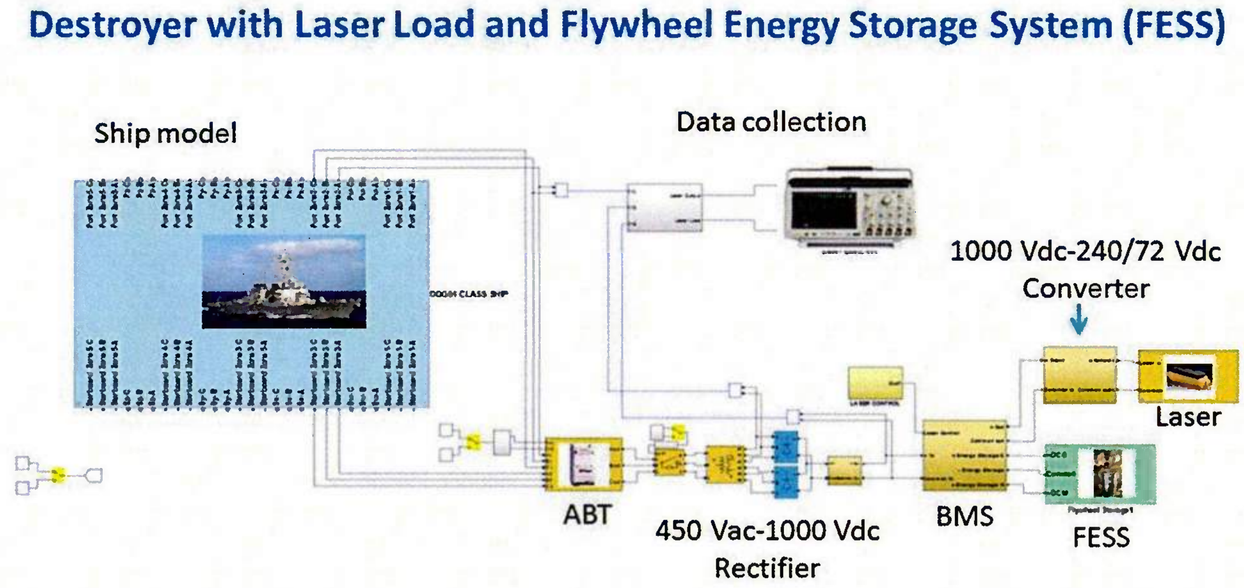


Figure 6: Diagram of destroyer class ship model with SSL and FESS

### Capacitor Energy Storage

The model using capacitors as energy storage was based on the use of capacitor BMOD0063 P125 manufactured by Maxwell Technologies (see Appendix 1). The basic model architecture is identical to that shown in Figure 1 including now the dc-dc converter between the ship's power system and the energy storage. This is required because the voltage at the capacitor storage changes considerably during the discharge phase and needs to be properly interfaced with the constant voltage provided by the ship power system (Figure 7).

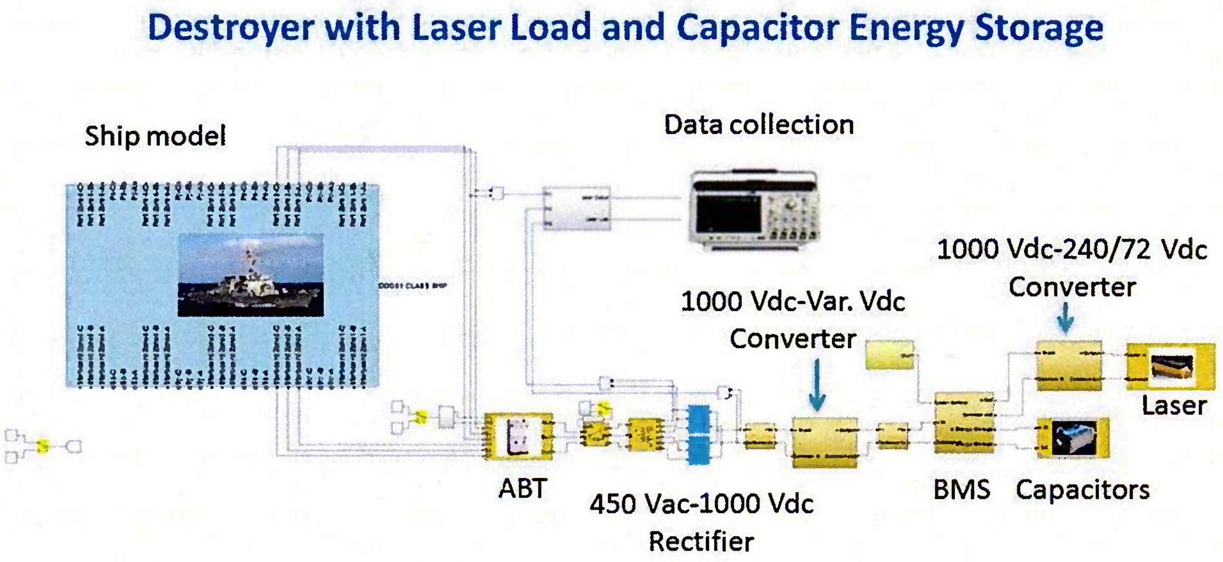


Figure 7: Diagram of destroyer class ship model with SSL and capacitor energy storage

## Laser Load

Two types of lasers with two levels of laser voltage were considered in these models: IPG Photonics laser (72 VDC) and Northrop Grumman laser (240 VDC) (see Appendix 1).

Three laser optical powers were also considered at each voltage: 30 kW, 60 kW, and 125 kW. All lasers were assumed to have a 20% wall-plug efficiency: e.g., 125 kW optical output power requires 625 kW of supplied power.

The laser duty cycle in the models is user configurable using a graphical user interface (GUI) (see Appendix 2).

# Simulation Results

## General Considerations

In the mode of operation described previously, namely that the load is powered only by the energy storage module, which in turn is recharged by the ship power system when the laser is not firing, the critical parameters are the following ones:

1. The laser power rating
2. The laser duty cycle
3. The capacity of the available energy storage
4. The charge-discharge characteristics of the energy storage
5. The length of the engagement.

These parameters give rise to a variety of scenarios that need to be studied to assess the viability of a system design and to be able to optimize it with respect to some performance or invested asset metric.

Additionally, among the many results of this study, one of the most interesting and perhaps unanticipated ones has been that close attention must be paid to the power electronic converters needed to interface the storage modules to the ship power system and to the load. These modules play a crucial role especially for issues of power quality, which can be very important in SSL systems. Furthermore, power electronics can have a major impact on the volume and weight of the storage system.

Figure 8 gives a typical trace of laser voltage versus time for a six second pulse from a 125 kW laser. The leading edge of the pulse is affected by an overshoot which, if perhaps not excessive, is nevertheless undesirable for a SSL that performs best under nearly ideal dc power conditions. Trying to limit the overshoot with filters may be counterproductive for the pulse rise-time, which is also important. This is a design issue that the model has highlighted and which points to the necessity of further detailed work in this area.

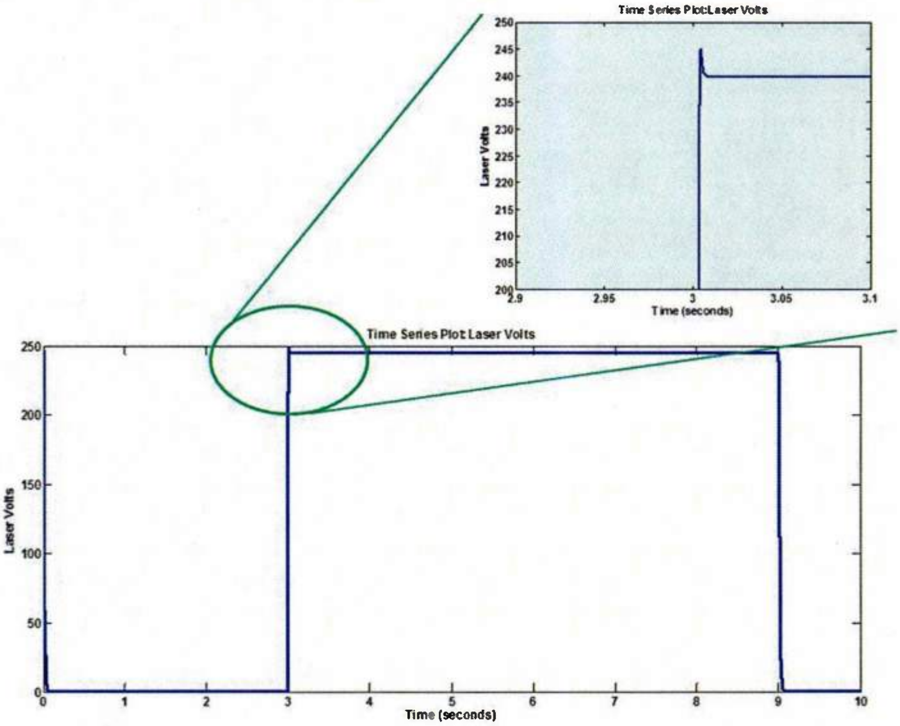
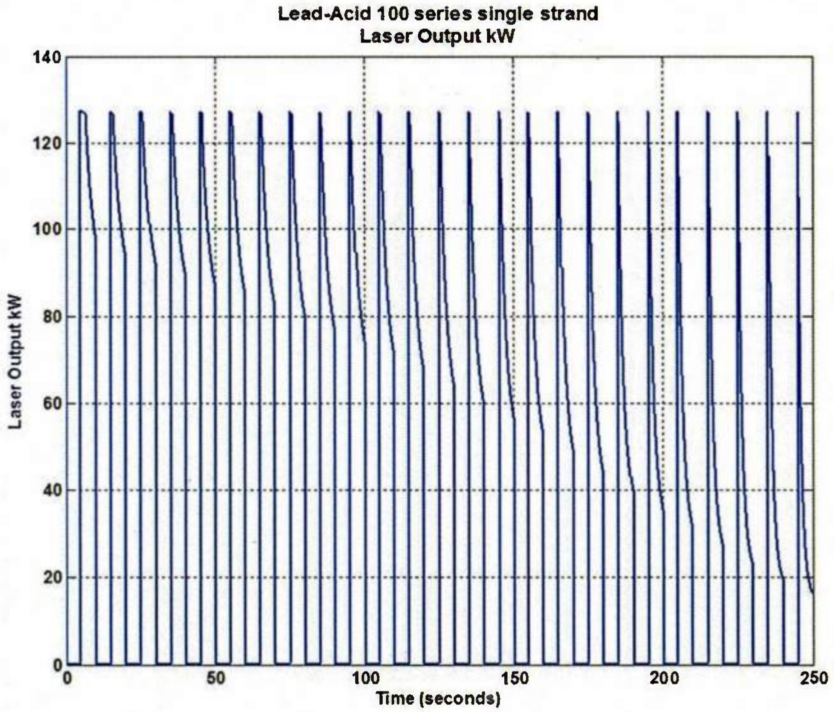


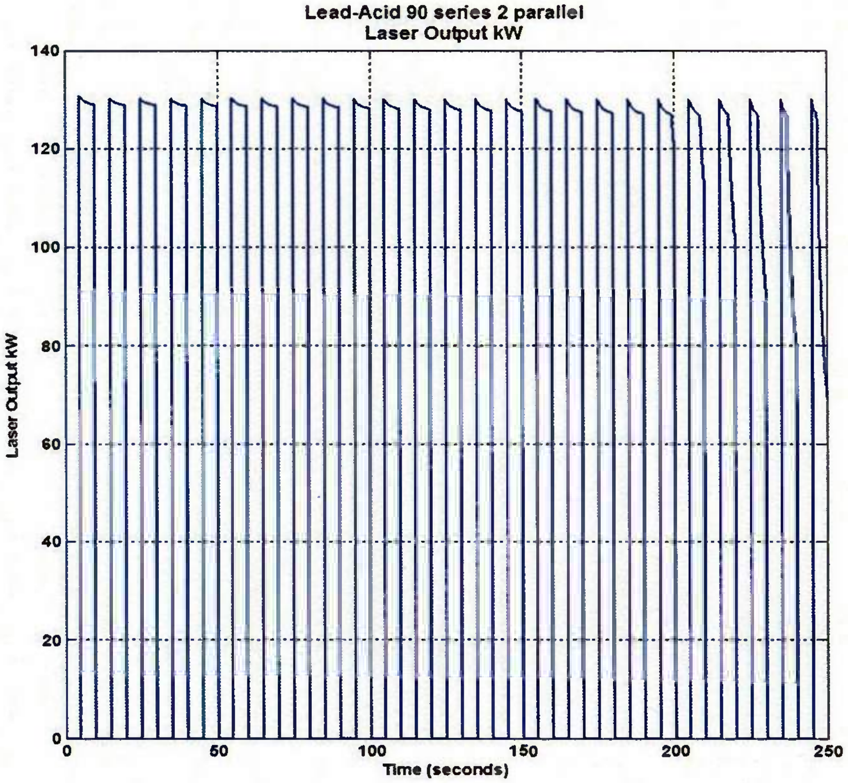
Figure 8: Details of the voltage waveform output to a 125 kW laser during a 6 second laser shot.

## Lead-Acid Battery Storage Results

The particular type of lead-acid battery used in our models (see Appendix 1) and the desired 1,000 V dc bus lead to the selection of a string of 100 such batteries in series as the basic storage unit. More than one unit can be used in parallel depending on the current required by the load. As mentioned previously, the number of possible scenarios that can be studied can quickly become very large (easily in the hundreds) based on the selection of the variables and controllable parameters of the problem. Obviously, only a few cases will be highlighted here to document the capability of the models.

A typical example of the simulation results in this case is reported in Figure 9 that shows the case of a 125 kW laser first powered by one string of 100 lead-acid batteries and fired for 5 seconds at 50% duty cycle for an extended period of time. It is clear from the plot of laser power that the system has trouble keeping the laser output steady almost from the very start when the battery is close to fully charged, because of insufficient current capacity. The addition of a second string, even with a reduced number of cells in series, provides sufficient capacity for the system to work until about 180 seconds, when the state of charge (SOC) of the battery has decayed to less than 35%.





(Figure 9: see caption below)

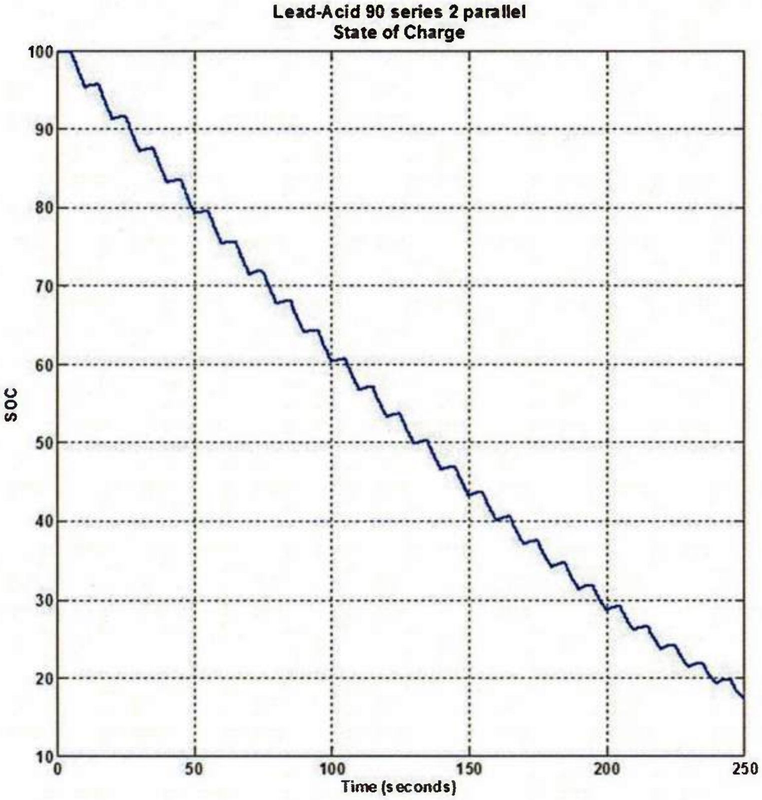
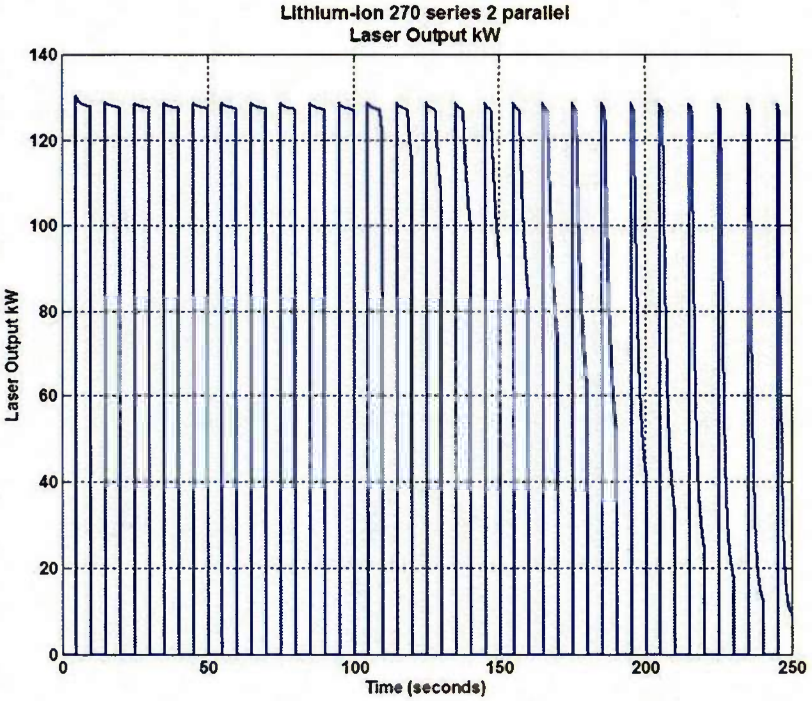


Figure 9: 125 kW laser with a repetitive 5 second pulse, 50% duty cycle.
- Upper Trace: Laser power versus time with one string of 100 lead-acid batteries
- Middle Trace: Laser power with two strings of 90 lead-acid cells in series
- Lower Trace: Battery's state of charge (SOC) versus time for 90 series 2 parallel case

The above results were obtained assuming that the battery recharges take place at constant voltage.

## Lithium-Ion Battery Storage Results

The models with lithium-ion battery storage use 270 battery cells per string to provide the necessary 1000 V at the output of the battery module, based on the battery type used (see Appendix 1). Here also, the number of cells in series and strings in parallel can be varied as needed. Plots similar to the ones shown in Figure 9 can be obtained also in this case (Figure 10).



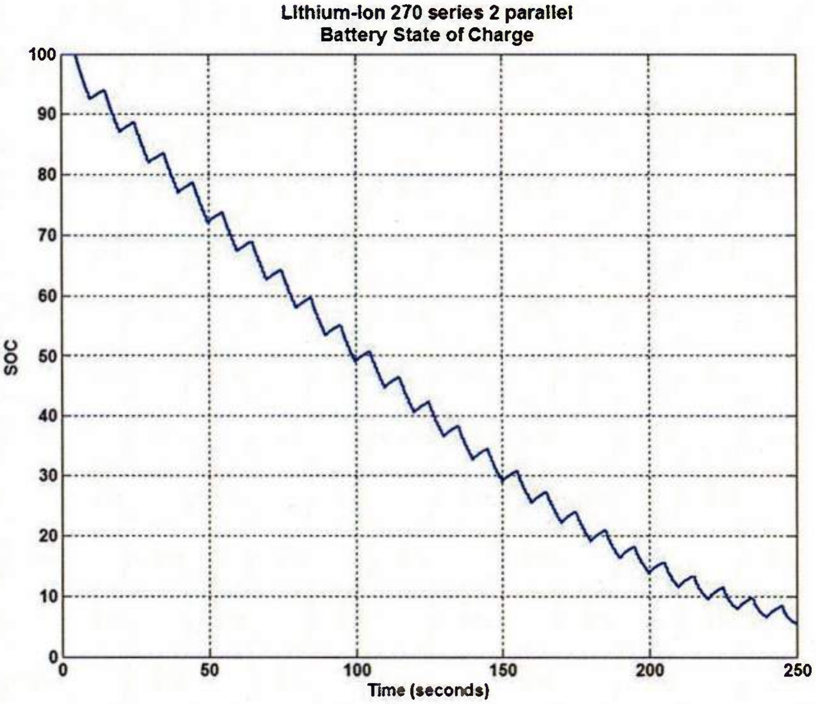


Figure 10: Identical system with identical conditions as in Figure 9 except realized with 2 strings of 270 Lithium-Ion batteries in series

## FESS Results

The flywheel model was based on typical design data generated at UT over the course of their long flywheel development programs. Flywheels possess some unique characteristics for the energy magazine: rather than the recharge rate being limited by chemical processes, as in a battery, the flywheel recharge rate is only limited by the design of the motor/generator, the power electronic interface, and the supplied power. Although each specific case must be examined in its own right, a typical recharge rate for flywheel energy storage is on the order of minutes.

As was done for the case of batteries, simulations of varying duty cycles and pulse lengths have been performed. A 1% per second recharge rate has been assumed, so that the loss in rotational speed over time can be calculated. This is an approximate average based upon flywheels designs at UT. Since the kinetic energy of a rotating mass is proportional to the square of its rotational speed, in theory, 75% of the flywheel's energy will be depleted at 50% of its maximum rotational speed. Although there is no operational restriction in slowing a flywheel to zero RPM, it will be considered depleted once the rotational speed reaches approximately 50% of its rated speed.

The design of a suitable flywheel energy storage system introduces a whole new array of variables that can be optimized. Table 1shows one such array that was considered for the 125 kW laser case.

Table 1: Various Flywheel designs tested for the 125 kW laser

| Power (MW) | Max Speed (RPM) | Radius (m) | Length (m) | Inertia (kg*m$^2$) | Energy Stored (MJ) |
|---|---|---|---|---|---|
| 17 | 3000 | 0.96 | 0.11 | 1127.5 | 55.6 |
| | 6000 | 0.48 | 0.22 | 140.9 | 27.8 |
| | 12000 | 0.24 | 0.44 | 17.6 | 13.9 |
| 8.5 | 3000 | 0.96 | 0.06 | 563.7 | 27.8 |
| | 6000 | 0.48 | 0.11 | 70.5 | 13.9 |
| | 12000 | 0.24 | 0.22 | 8.8 | 7.0 |
| 4 | 3000 | 0.96 | 0.03 | 281.9 | 13.9 |
| | 6000 | 0.48 | 0.06 | 35.2 | 7.0 |
| | 12000 | 0.24 | 0.11 | 4.4 | 3.5 |

The largest flywheel considered, 17 MW at 3000 RPM, was more than sufficient to meet the power needs, but would place a large load on the ship's service electrical plant during recharge. The 4MW flywheel was inadequate. In the simulations for smaller power lasers, other flywheels with less power can be used, but for the 125 kW laser either the 8.5 MW flywheel at 3000 rpm or the 17 MW flywheel at 6000 RPM has enough energy to supply 60, 6-second laser shots at a 50% duty cycle before depletion, and is comparable to the lead acid and lithium-ion battery storage. Figure 11 shows the typical behavior of a flywheel system under operation with a 125 kW laser load.

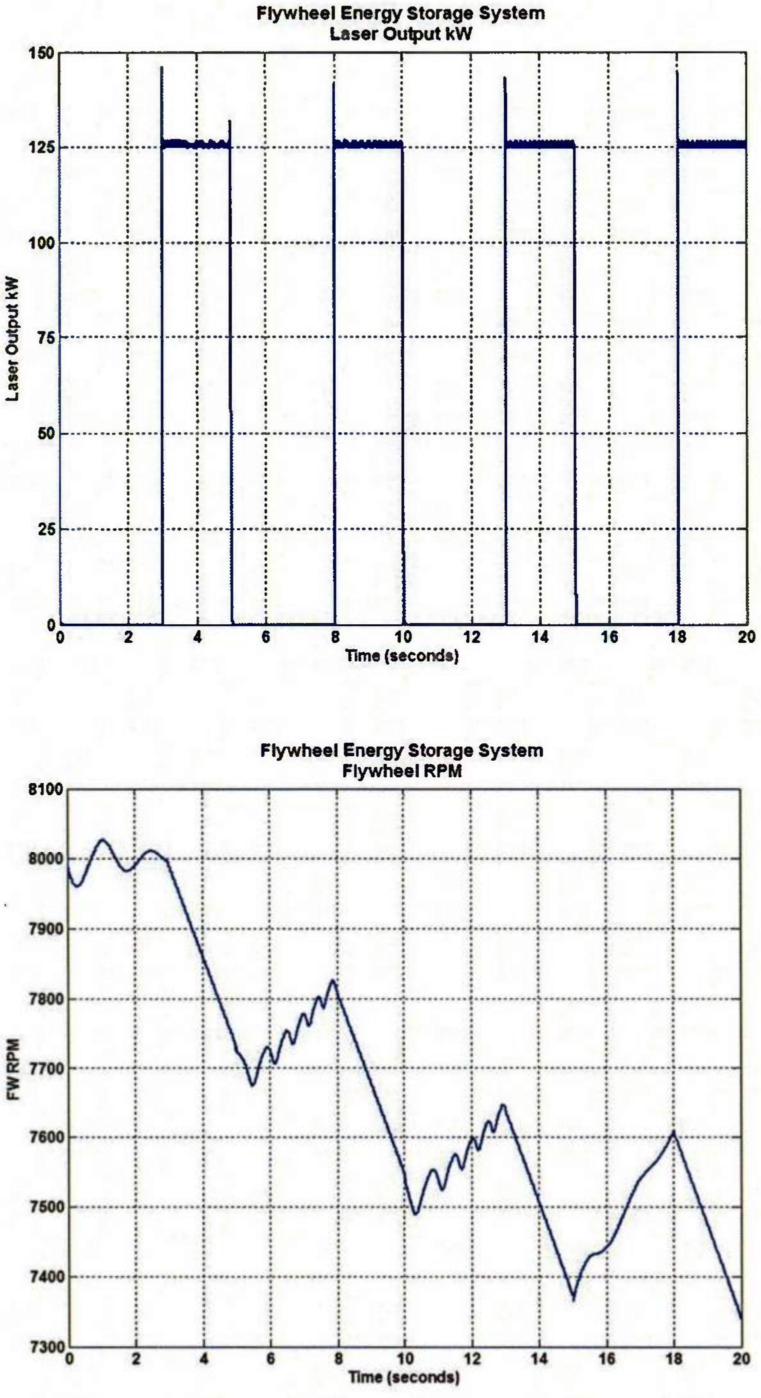


Figure 11: Typical flywheel speed during discharge-recharge cycles for a 125 kW laser at 40% duty cycle

Notice the larger than usual voltage overshoot for the case of a FESS. This is due to the fact that, in this case, the system has two converters in cascade: the first one being the one intrinsic to the FESS and the second being the output dc-dc converter powering the load (this latter one is in reality itself made of two converter sections in series, as explained in Appendix 2).

### Capacitor Storage Results

The simulations with this model are the same as those with the battery and flywheel storage. The major consideration here is that the voltage across the capacitor bank can change considerably during operation and be below the desired 1,000 V dc bus or even above, depending on the system design. This demands the interface with the power provided by the ship via an additional dc-dc converter that was absent in either the battery or flywheel case.

One interesting result obtained is that the capacitor storage may actually operate at an average voltage lower than the nominal bus voltage if the recharge time is not sufficient. Figure 12 shows the case where the capacitor voltage drops from the initial 1,000 V dc to a lower ~850 V dc average voltage after a few laser pulses, thus behaving as a lower energy storage system than it would be normally capable of (in this case about 72% of rated energy). This is due to insufficient recharge time for the laser power needed and the duty cycle imposed. However, if the parameters of the problem are properly matched, it may still be possible to support full laser operation for an extended time even at this reduced level of average stored energy. Figure 12 also shows the energy lost in heat at the laser in the last trace.

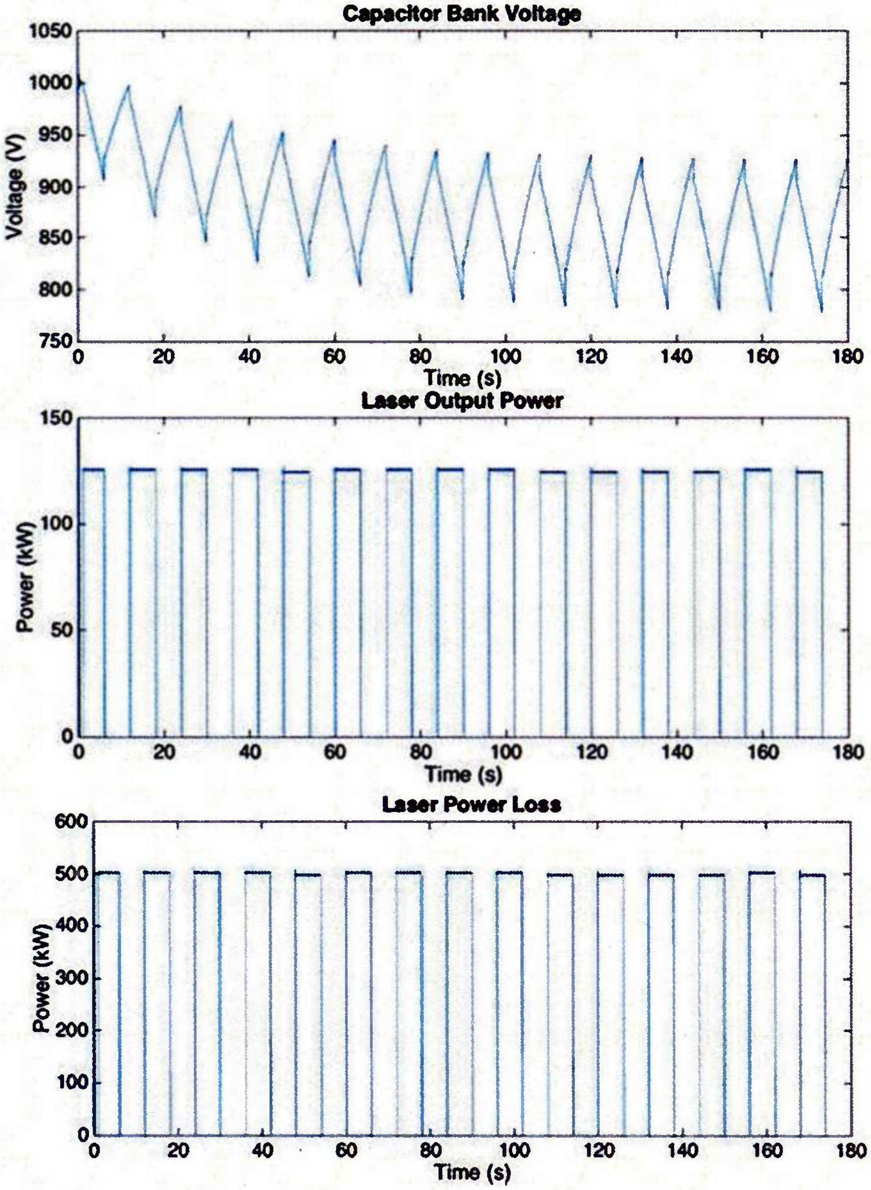


Figure 12: Operation of capacitor storage at lower than nominal bus voltage but still sufficient to support the load

## System Level and Comparative Results

Since the full destroyer power system has been incorporated in all the models developed (Figure 2), it is possible to conduct studies of the effect of the pulse load with energy storage on the ship's power system. It will also be noted from Figure 2 through Figure 7 that the user of the models has the option of drawing power at different locations along the ship's power busses, both port and starboard, by simply reconnecting the load at any of the terminals provided. Several studies of ship's power quality can then be conducted. A typical waveform is shown in Figure 13. Notice some slight ripples on the sinusoidal waveform when the laser is off and the battery is being recharged by ship power. These ripples are not a numerical artifact of the model; they are a real physical effect due to non-linear electronic feedback from the power converters. To minimize the effects on other ship electronic systems, these fluctuations must comply with MIL-STD-1399, until or unless it is modified.

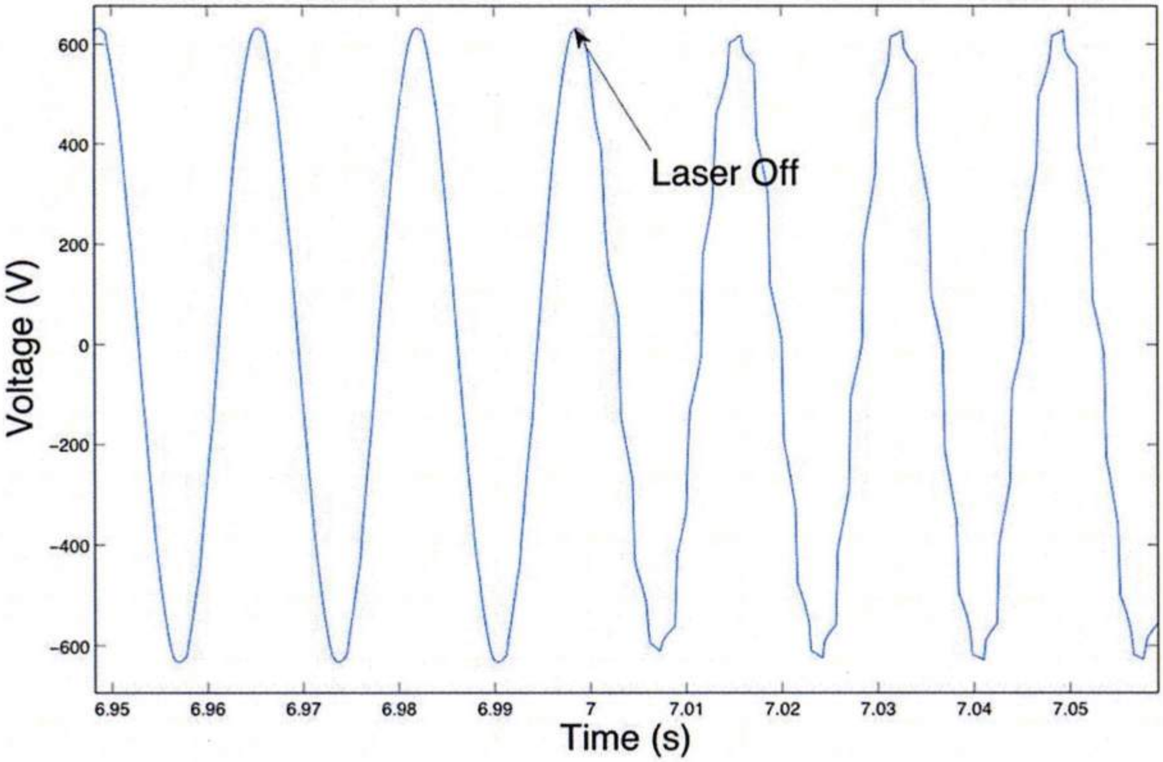
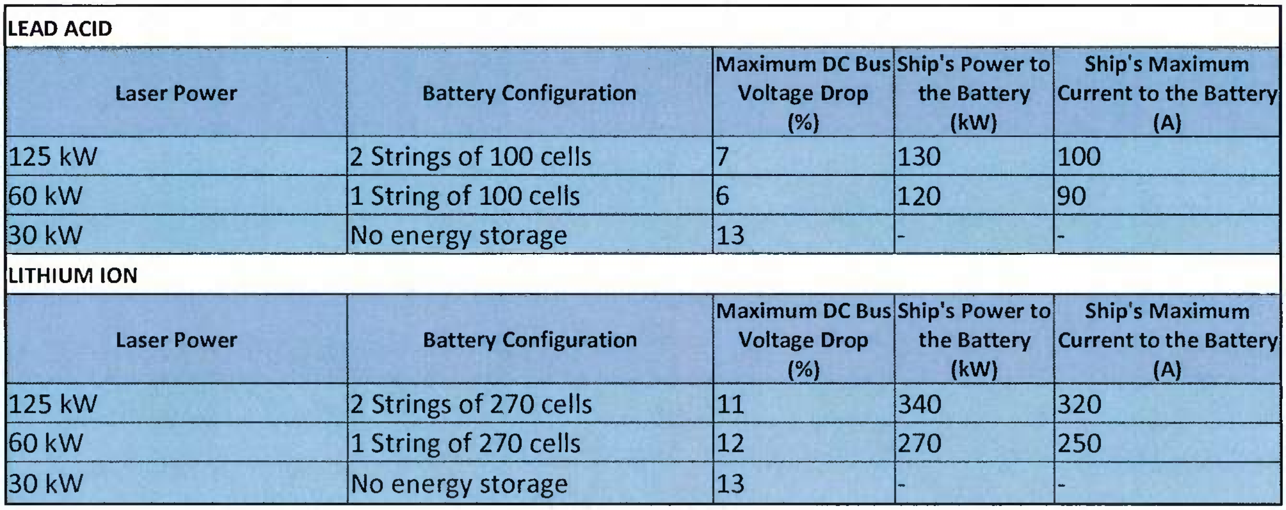


Figure 13: Example of ship's power at the time of transition from laser on to laser off

Along the same line, for example, some results regarding the ability of the system to maintain a stable dc bus are reported in Table 2 where the data were obtained comparing the options of the two types of battery storage considered in this study.

Table 2: Comparative changes in dc bus voltage level for some combinations of batteries and laser loads



| LEAD ACID | | | | |
|---|---|---|---|---|
| Laser Power | Battery Configuration | Maximum DC Bus Voltage Drop (%) | Ship's Power to the Battery (kW) | Ship's Maximum Current to the Battery (A) |
| 125 kW | 2 Strings of 100 cells | 7 | 130 | 100 |
| 60 kW | 1 String of 100 cells | 6 | 120 | 90 |
| 30 kW | No energy storage | 13 | - | - |
| LITHIUM ION | | | | |
| Laser Power | Battery Configuration | Maximum DC Bus Voltage Drop (%) | Ship's Power to the Battery (kW) | Ship's Maximum Current to the Battery (A) |
| 125 kW | 2 Strings of 270 cells | 11 | 340 | 320 |
| 60 kW | 1 String of 270 cells | 12 | 270 | 250 |
| 30 kW | No energy storage | 13 | - | - |

A number of considerations can be made from this data set. For example, one could determine whether the battery charging current and power is acceptable, or whether the dc bus voltage drop is tolerable, or whether it is worthwhile to even consider energy storage for the 30 kW laser, if the expected bus sag is only 13% without any storage as shown in the table. These are examples of useful information that can be derived from the models.

The models are most useful in comparing various alternatives in regard to providing the needed power to the expected loads. For example, the results of a very preliminary study of this type comparing the two battery storage options are reported in Figure 14.

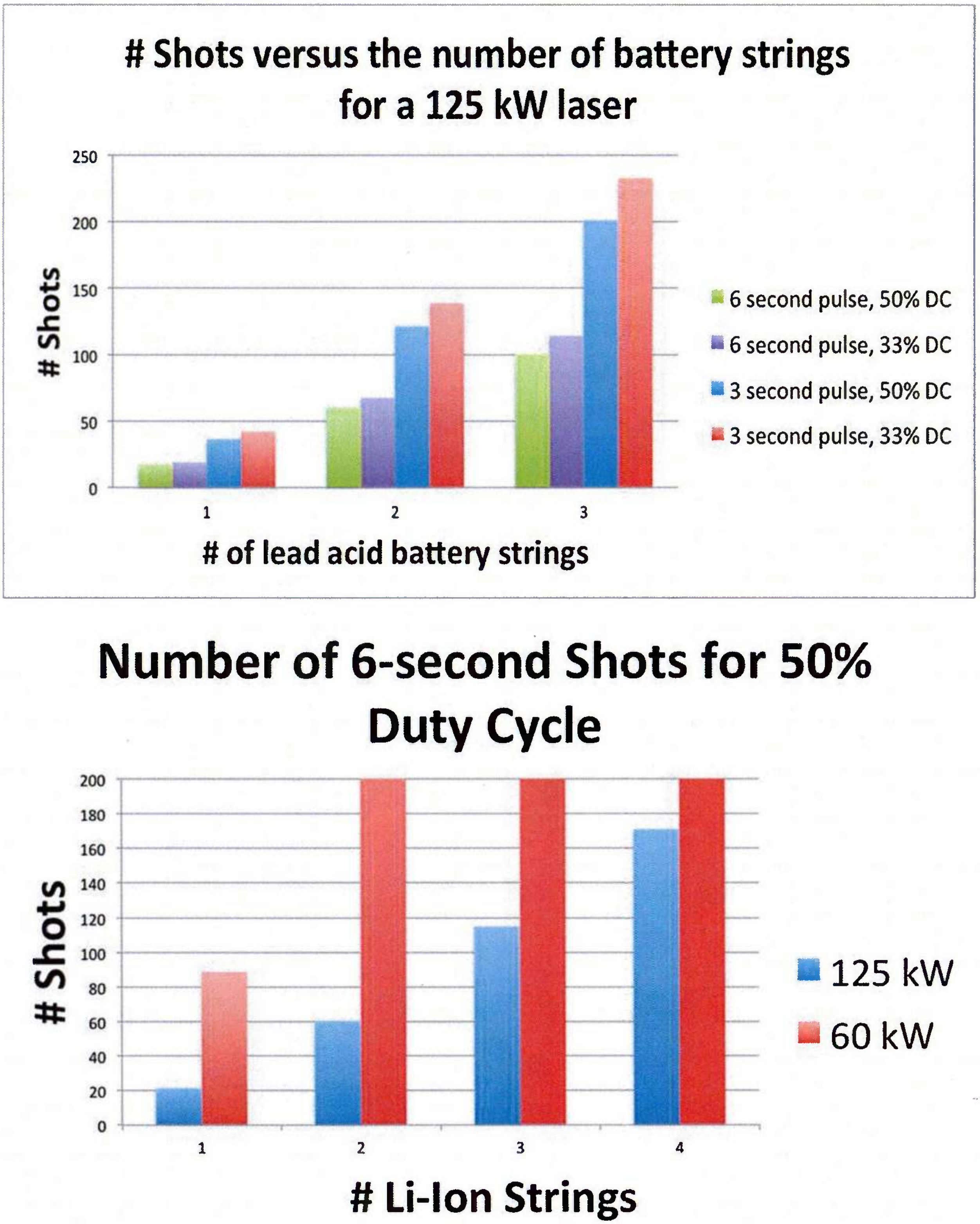
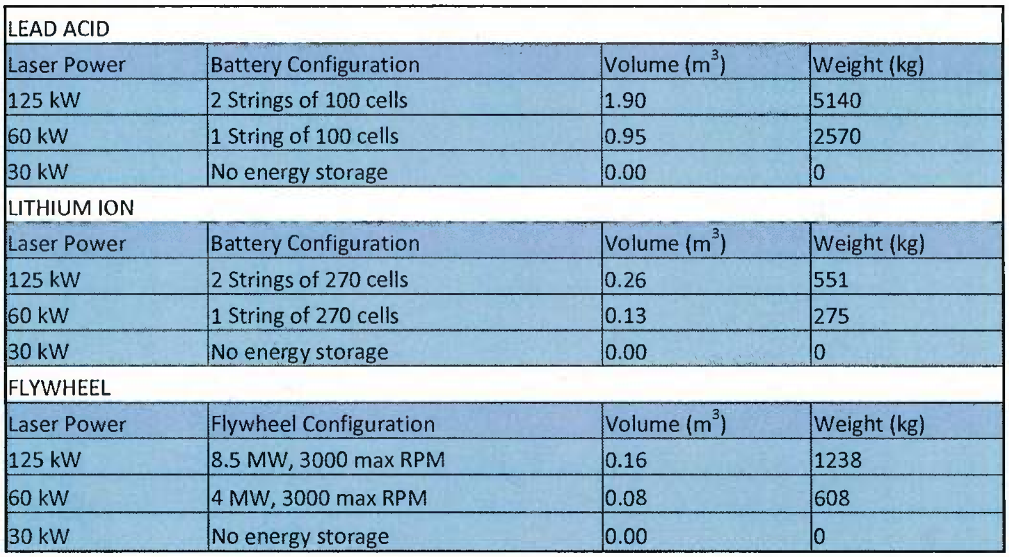


Figure 14: Some comparative performance of lead-acid and lithium-ion batteries

The models can also been used to compare the various energy storage methods in regard to their size and weight. Table 3 shows the results of one such analysis.

Table 3: Weight and volume requirements for some configurations of energy magazines for various laser power levels. These are the minimum configurations required to deliver approximately sixty 6-second shots at a 50% duty cycle. Note: the flywheel volume and weight is for the rotor only.



| LEAD ACID | | | |
|---|---|---|---|
| Laser Power | Battery Configuration | Volume ($m^3$) | Weight (kg) |
| 125 kW | 2 Strings of 100 cells | 1.90 | 5140 |
| 60 kW | 1 String of 100 cells | 0.95 | 2570 |
| 30 kW | No energy storage | 0.00 | 0 |
| LITHIUM ION | | | |
| Laser Power | Battery Configuration | Volume ($m^3$) | Weight (kg) |
| 125 kW | 2 Strings of 270 cells | 0.26 | 551 |
| 60 kW | 1 String of 270 cells | 0.13 | 275 |
| 30 kW | No energy storage | 0.00 | 0 |
| FLYWHEEL | | | |
| Laser Power | Flywheel Configuration | Volume ($m^3$) | Weight (kg) |
| 125 kW | 8.5 MW, 3000 max RPM | 0.16 | 1238 |
| 60 kW | 4 MW, 3000 max RPM | 0.08 | 608 |
| 30 kW | No energy storage | 0.00 | 0 |

These results and the ones shown throughout this report are shown to highlight the usefulness of the models more than actual definitive objective data on which decisions can be based regarding the relative suitability of one storage system with respect to another: more comprehensive studies are needed for such determination, but the models here developed can be a very useful tool in investigations of this type.

## Conclusions

In a joint research effort, UT and NPS have developed simulation tools to model the integration of laser loads on naval systems. In particular, the following has been achieved:

1. One ship power system completed (DDG51 destroyer class) with a second one under development (LCS Independence class)
2. Three SSL power levels have been considered: 30, 60, and 125 kW
3. Four storage technologies modeled: lead-acid batteries, lithium-ion batteries, flywheel energy storage system, and capacitor energy storage.

Using these simulation tools, preliminary studies have been performed and typical results for a variety of laser powers, laser duty cycles, and energy storage technologies have been presented herein. It has been shown that the models developed can be used effectively as predictive tools for evaluating the performance of the various systems relative to suitable performance and other metrics.

Once it is incorporated into the ship's electrical system, the energy magazine could also support other planned pulsed loads and can serve the following additional purposes, when not needed for its primary intent of powering pulsed loads:

1. Function as an uninterruptible power supply (UPS) for the ship's power system in case of temporary loss of any of the normal power sources
2. Function as a power ripple leveling when sudden loads are switched on and off the ship's power system.

The effectiveness in carrying out these additional functions can also be studied via the models developed jointly by UT and NPS.

Finally, these ship models allow also the study of the optimal design of the energy storage system architecture: for example, whether storage should be dedicated to the load it is meant to serve or whether it could be shared by multiple loads, or similarly whether storage should be located in close proximity to its main load or could be distributed throughout the power distribution system. Likewise the optimal granularity (number of independent sub-units making up the storage system) of the energy magazine can be evaluated by using these models. An even more fundamental question that could be addressed is at what power level is energy storage needed if one incorporates an advanced control system to use the ship power system optimally.

# Appendix 1: Component Data

genesis™
XE
PURELEAD
RANGE SUMMARY

The Genesis™ XE thin plate pure lead battery excels in demanding environmental and cycling applications such as:

☐ Alternative energy applications, e.g. solar and wind power

☐ Hybrid electric vehicles (HEV)

**Specifications**

**Battery Design**

☐ 12V pure lead-tin VRLA AGM battery

☐ UL94 V-0 flame retardant case and cover

☐ M6 female no-maintenance terminals, 3/8-16 female terminals for XE95

☐ Can be installed in any orientation except inverted

☐ Rugged construction (optional metal jacket, except for XE60 and XE95)

☐ Approved for shipping as non-hazardous, nonspillable

**Performance Features**

☐ -40°C to 80°C (-40°F to 176°F) with metal jacket

☐ 300+ full depth of discharge cycles

☐ High rate charge and discharge

☐ 2 year shelf life at 25°C (77°F)

☐ Superior deep discharge recovery

☐ UL recognized - file No. MH12544

EnerSys
Power/Full Solutions

Publication No: US-XE-RS-004 November 2006

# Rechargeable Li-FePO$_4$ battery
## VL 30P Fe Super-Phosphate™

3.3 V high power lithium iron phosphate cell

Saft's VL 30P Fe cell is ideally suited for applications requiring high discharge, continuous or pulse power; fast re-charge; low temperature performance; long cycle and calendar life; low heat generation; and/or higher levels of safety.

Saft always supplies cells as complete energy storage systems customized as needed to meet customer specifications.

### Saft's battery systems

Individual lithium-ion cells need to be mechanically and electrically integrated into battery systems to operate properly. The battery system includes electronic devices for performance, thermal and safety management specific to each application.

### Benefits

- Excellent power density and specific power
- Electrochemistry stable under most abuse conditions
- Non-toxic, extremely stable cathode material
- Hermetically sealed cells
- Maintenance free battery
- Operates in any orientation
- No memory effect

### Key features

- High discharge, pulse and continuous power
- Fast re-charge capability
- Excellent low temperature performance
- Long cycle and calendar life
- Low heat generation
- Exceptionally high efficiency

### Typical applications

- Military hybrid electric vehicles
- Naval power for torpedoes, actuators and launchers
- Civil marine boats
- Pulse power for unmanned applications

| | |
|---|---|
| **Electrical characteristics** | |
| Minimum capacity at C rate at 3.8 V / 2.0 V & 25°C | 30 Ah |
| Nominal voltage | 3.3 V |
| Energy | 105 Wh |
| Recommended maximum discharge current at 25°C | |
| Continuous | 300 A |
| 2 s pulse | 500 A |
| 200 ms pulse | 500 A |
| Power at 25°C & 100% SOC | |
| Continuous | 1155 W |
| 2 s pulse | 1650 W |
| 200 ms pulse | 1650 W |
| Impedance at 25°C & 50% SOC at 10 C | |
| 2 s pulse | 1.2 mΩ |
| 200 ms pulse | 0.9 mΩ |
| **Physical characteristics** | |
| Diameter | 54 mm |
| Height | 215 mm |
| Mass | 1.02 kg |
| Volume | 0.508 L |
| **Cell operating conditions** | |
| Lower voltage limit for discharge | |
| Continuous (-20°C to +45°C) | 1.5 V / 2.5 V |
| Pulse (1.75 V) | 1.5 V |
| Charging method | Constant current / Constant voltage |
| Charging voltage | 4.1 V / 3.8V |
| Recommended continuous charge current at 25°C | C/1 rate |
| Fast charging modes* | |
| Operating temperature | -30°C to +60°C |
| Discharge | -30°C to +60°C |
| Charge | -30°C to +60°C |
| Storage and transportation temperature | -40°C to +60°C |

*Fast charging may impact life - contact Saft for higher currents or lower temperature

SAFT

## DATASHEET 125V HEAVY TRANSPORTATION MODULES

### FEATURES AND BENEFITS

- CAN bus digital monitoring and communications
- Highest power performance available
- Over 1,000,000 duty cycles
- Temperature and voltage monitoring
- Ultra-low resistance

### TYPICAL APPLICATIONS

- Buses
- Electric trains and trolleys
- Heavy duty transportation
- Cranes, RTGS
- Utility vehicles
- Mining equipment

### PRODUCT SPECIFICATIONS

| ELECTRICAL | BMOD0063 P125 B04/B08 |
|---|---|
| Rated Capacitance[1] | 63 F |
| Minimum Capacitance, initial[1] | 63 F |
| Maximum ESR $_{DC}$ initial[1] | 18 mΩ |
| Rated Voltage | 125 V |
| Absolute Maximum Voltage[1,5] | 136 V |
| Maximum Continuous Current (ΔT = 15°C)[2] | 140 $A_{RMS}$ |
| Maximum Continuous Current (ΔT = 40°C)[2] | 240 $A_{RMS}$ |
| Maximum Peak Current, 1 second (non repetitive)[3] | 1,800 A |
| Leakage Current, maximum (VMS 2.0)[4] | 10 mA |
| Maximum Series Voltage | 1,500 V |
| **TEMPERATURE** | |
| Operating Temperature (Ambient temperature) | |
| Minimum | -40°C |
| Maximum | 65°C |
| Storage Temperature (Stored uncharged) | |
| Minimum | -40°C |
| Maximum | 70°C |

Maxwell TECHNOLOGIES
Enabling Energy's Future®

# Appendix 2: Model Details

## General Information

The MATLAB/Simulink models developed in the course of this project were developed and run on a desktop personal computer with Microsoft Windows 7 operating system and 3.16 GHz of clock speed. The latest MATLAB/Simulink version and modules used are described below:

```
-------------------------------------------------------------------------------------------------
MATLAB Version: 8.2.0.701 (R2013b)
MATLAB License Number: 875352
Operating System: Microsoft Windows 7 Version 6.1 (Build 7601: Service Pack 1)
Java Version: Java 1.7.0_11-b21 with Oracle Corporation Java HotSpot(TM) 64-Bit Server VM
mixed mode
-------------------------------------------------------------------------------------------------
MATLAB                                Version 8.2        (R2013b)
Simulink                              Version 8.2        (R2013b)
Bioinformatics Toolbox                Version 4.3.1      (R2013b)
Control System Toolbox                Version 9.6        (R2013b)
Curve Fitting Toolbox                 Version 3.4        (R2013b)
DSP System Toolbox                    Version 8.5        (R2013b)
Data Acquisition Toolbox              Version 3.4        (R2013b)
Image Processing Toolbox              Version 8.3        (R2013b)
Instrument Control Toolbox            Version 3.4        (R2013b)
MATLAB Coder                          Version 2.5        (R2013b)
MATLAB Compiler                       Version 5.0        (R2013b)
Neural Network Toolbox                Version 8.1        (R2013b)
Optimization Toolbox                  Version 6.4        (R2013b)
Parallel Computing Toolbox            Version 6.3        (R2013b)
Signal Processing Toolbox             Version 6.20       (R2013b)
SimMechanics                          Version 4.3        (R2013b)
```

| | | |
|---|---|---|
| SimPowerSystems | Version 6.0 | (R2013b) |
| Simscape | Version 3.10 | (R2013b) |
| Simulink Coder | Version 8.5 | (R2013b) |
| Simulink Control Design | Version 3.8 | (R2013b) |
| Stateflow | Version 8.2 | (R2013b) |
| Statistics Toolbox | Version 8.3 | (R2013b) |
| Symbolic Math Toolbox | Version 5.11 | (R2013b) |
| System Identification Toolbox | Version 8.3 | (R2013b) |
| Wavelet Toolbox | Version 4.12 | (R2013b) |

---

Four basic models have been developed, one for each energy storage technology considered, all with similar functionalities:

| | |
|---|---|
| DDG51_Laser_LA_R1.slx | Model of DDG51 ship with laser and lead-acid battery storage |
| DDG51_Laser_LI_R1.slx | Model of DDG51 ship with laser and lithium-ion battery storage |
| DDG51_Laser_FW_R1.slx | Model of DDG51 ship with laser and flywheel energy storage |
| DDG51_Laser_CAP_R1.slx | Model of DDG51 ship with laser and capacitor energy storage |

These models contain the full representation of the electrical system of the DDG51 ship and tend to run rather slowly. If a much faster simulation is desired concentrating the attention on the pulsed load side of the system, it is possible to replace the ship model with a simple equivalent three-phase generator as the source. These reduced models have also been included for convenience and are labeled as follows:

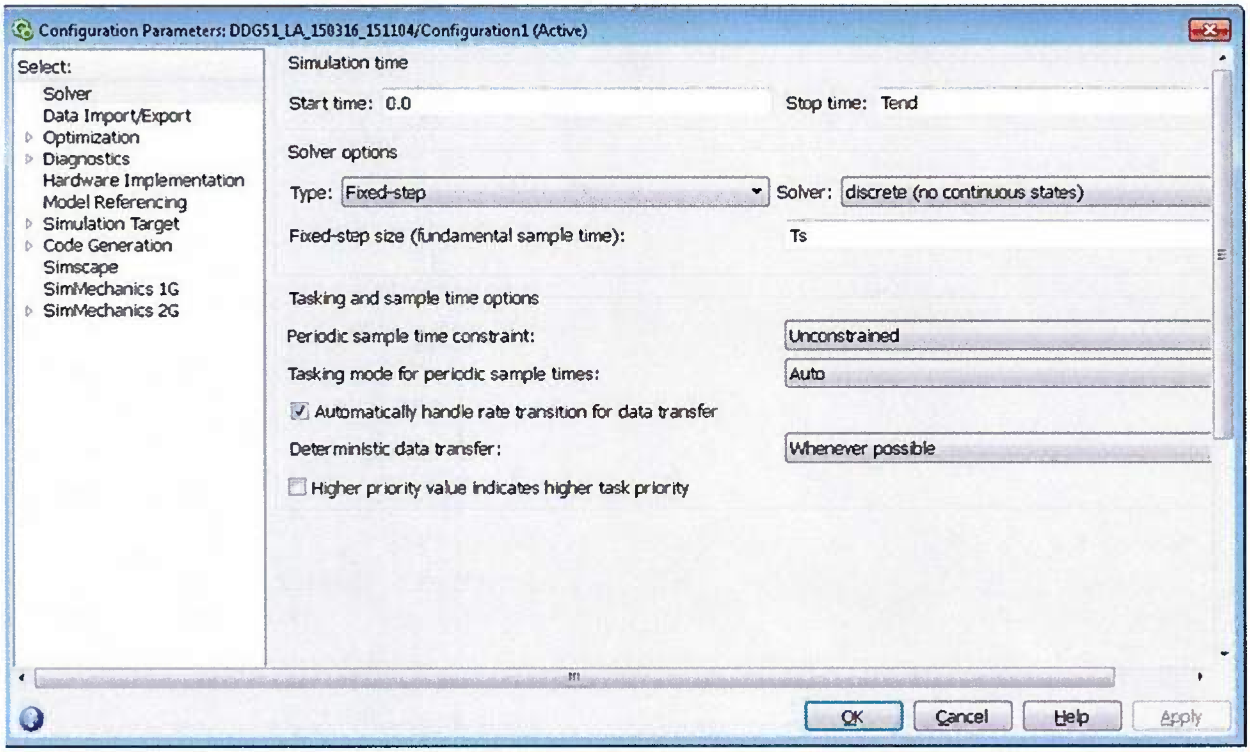
| | |
|---|---|
| EqGen_Laser_LA_R1.slx | Model with generator, laser, and lead-acid battery storage |
| EqGen_Laser_LI_R1.slx | Model with generator, laser, and lithium-ion battery storage |
| EqGen_Laser_FW_R1.slx | Model with generator, laser, and flywheel energy storage |
| EqGen_Laser_CAP_R1.slx | Model with generator, laser, and capacitor energy storage |

The following data files are associated with each of the above:

| | |
|---|---|
| DDG51_Inputs_Battery_R1 | to load data for running the lead-acid or lithium-ion models |
| DDG51_Inputs_Flywheel_R1 | to load data for running the flywheel model |
| DDG51_Inputs_Capacitor_R1 | to load data for running the capacitor model |

These data files have to be run at least once before the corresponding model. The data files are well documented with a descriptive comment line for each variable. Some of the data in them can be changed as desired, while some parameters should not be modified unless absolutely necessary (this is also well indicated in the files). Once run, the data file may not be used again until a change is desired in some of the changeable parameters, which, however, can also be changed directly from the MATLAB command line without altering and re-running the data file.

The basic configuration parameters used in the simulations is shown in Figure 15. Although other configurations are possible, it was found that the set of parameters shown worked well.



Configuration Parameters: DDG51_LA_150316_151104/Configuration1 (Active)

Simulation time

Start time: 0.0

Stop time: Tend

Solver options

Type: Fixed-step

Solver: discrete (no continuous states)

Fixed-step size (fundamental sample time): Ts

Tasking and sample time options

Periodic sample time constraint: Unconstrained

Tasking mode for periodic sample times: Auto

☑ Automatically handle rate transition for data transfer

Deterministic data transfer: Whenever possible

☐ Higher priority value indicates higher task priority

Figure 15: Suggested simulation configuration parameters

The overall model schematics have already been shown in Figure 4 through Figure 7. In what follows, a presentation of the key items needed to run a successful simulation will be given along with a brief explanation of the special blocks used in the models. This will be done using the Lead-Acid battery model as reference for common items, while the other three models will be invoked only in the description of blocks that are specific to them. **Error! Reference source not found.**

Regarding the inner composition of the various blocks, in general the following comments apply:

a. All items germane to a particular function have been combined into one Simulink block with external input items, if any, pertaining to that block listed in a pop-up dialog box. All details about the structure of the block are available by examining the lower levels within each block by right-clicking the block and selecting the option “Look Under Mask”.

b. All blocks with a colored background either have a pop-up dialog box associated with them that must be filled out with the appropriate inputs for each run, or contain within them items with parameters or settings accessible to and modifiable by the user. The only blocks without need of any input are those with white background, which generally indicate simple measurement or signal routing blocks.

c. Three main classes and methods of data input exist in the models:
   i. Filling in all parameters in the pop-up dialog boxes of colored blocks, as explained in point (b) above
   ii. Running an initial data file, prior to a run
   iii. Setting special switches directly in the model.

   It is imperative that all inputs be provided before each run and that care be taken that no intrinsic conflict exists among the various inputs for a successful simulation.

d. Some blocks display a pictorial representation of the unit to which the block refers. In order for these pictures to display properly several .jpg files must be present in the MATLAB root directory (these files have been included in the deliverable CD). If these files are missing, the pictures will not display but this will not affect the operation of the program.

e. All variables resulting from the simulation are output on scopes or meters or to the MATLAB workspace with variable names that attempt to be mnemonic for ease of identification.

## Description of main blocks

**Automatic Bus Transfer (ABT)** Modeled as a standard ac transfer switch implemented with Silicon Controlled Rectifiers (Figure 16).

**Input Rectifier Section** Modeled as a Y-primary and Δ/Y dual winding secondary transformer followed by two diode rectifiers in parallel to achieve a 12 pulse rectification for smoother dc output. The transformer secondary ac output is adjusted to match the expected battery dc voltage as entered in the input data file.

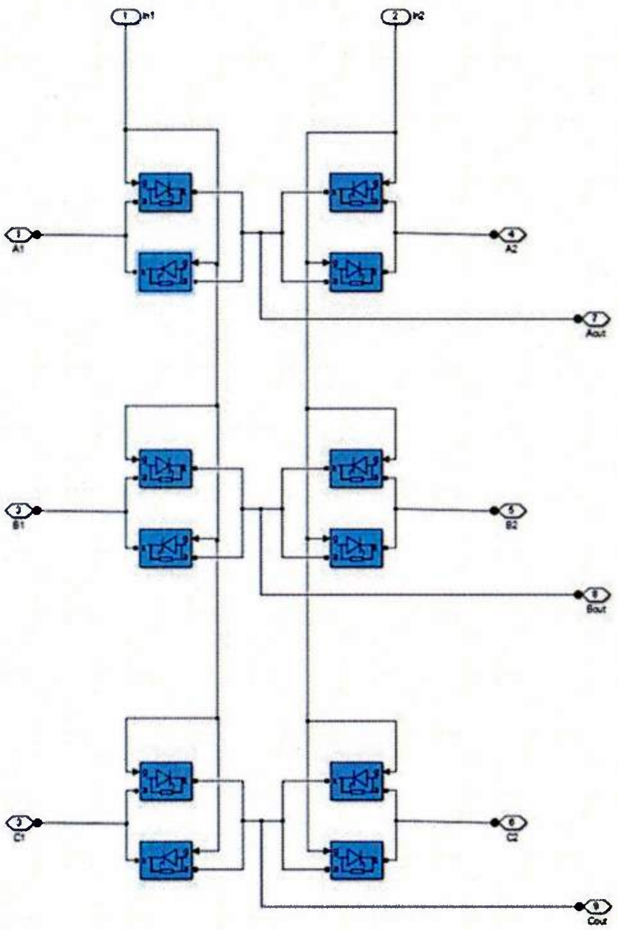
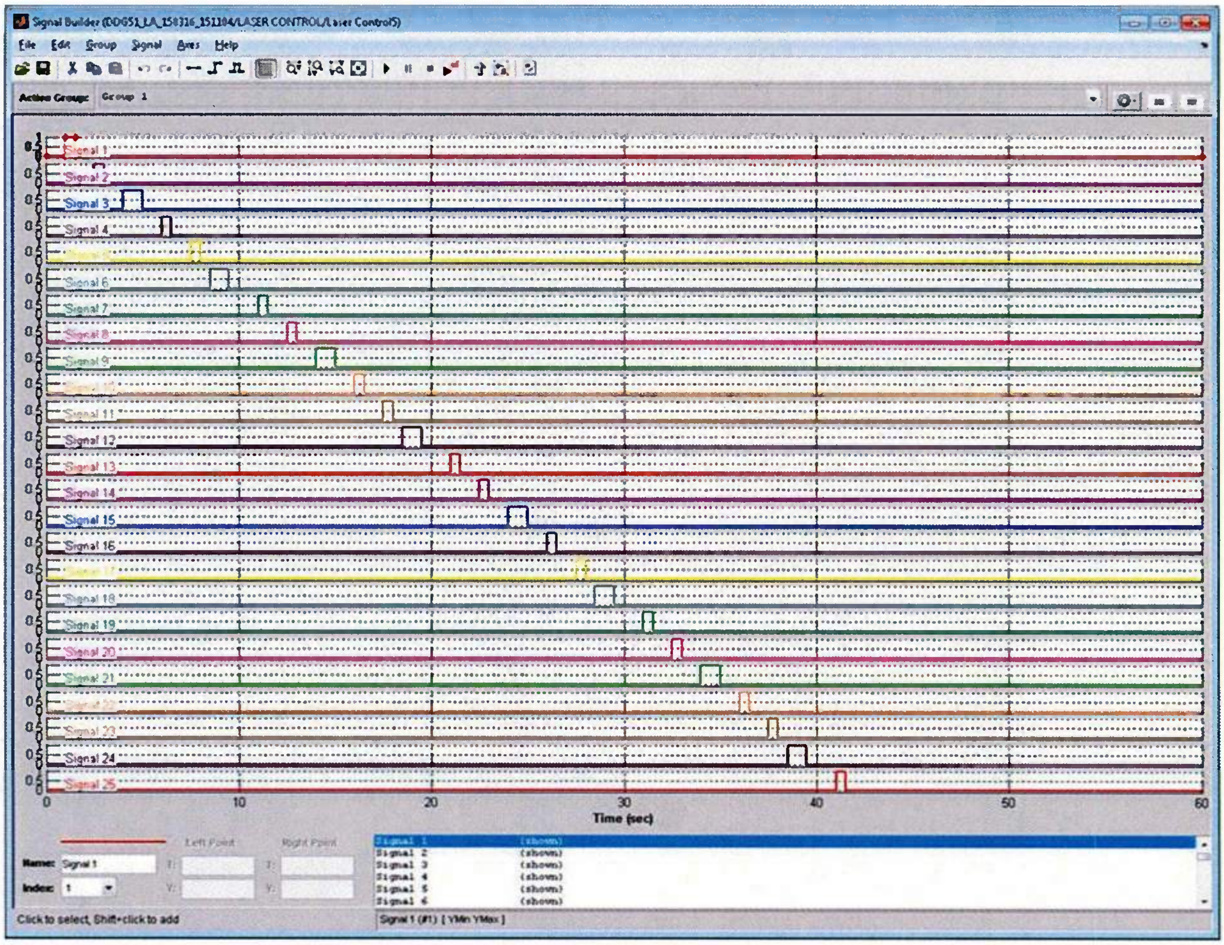


Figure 16: Internal structure of ABT block

| | |
|---|---|
| **Battery Management System (BMS)** | It is modeled as a bank of circuit breakers switching alternatively the ship power or the load across the energy storage system under the command of the Laser Control block. |
| **Laser Control** | Implemented via a graphical user interface of 25 independently defined pulses recombined serially into a single pulse train. The user can intervene directly on the pulses setting their on/off times by simply moving the pulses' transition times with the mouse along the time axis. This allows broad freedom in defining the laser pulse sequence (Figure 17). |



Active Group: Group 1

Name: Signal 1

Index: 1

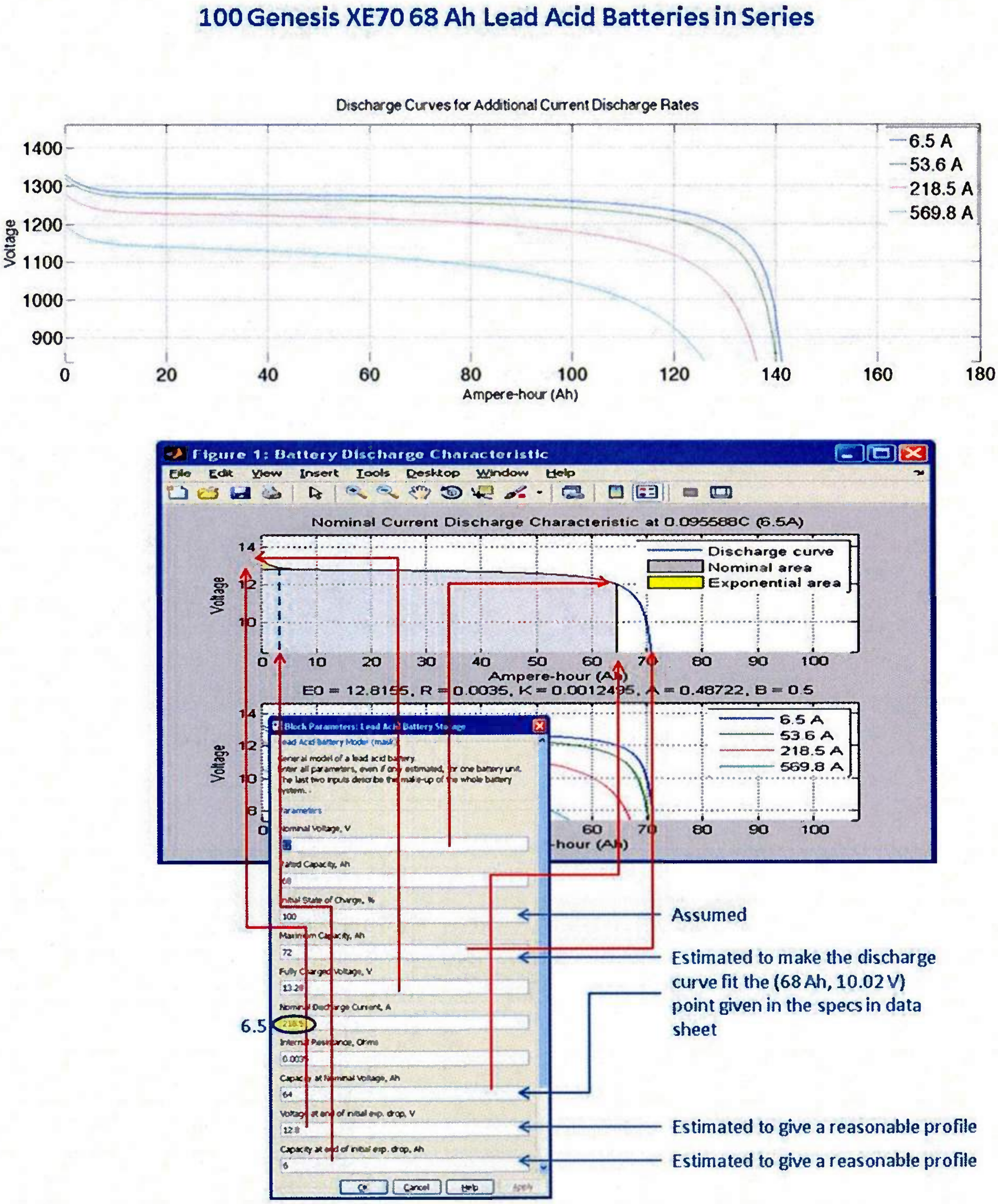
```
Signal 1          (shown)
Signal 2          (shown)
Signal 3          (shown)
Signal 4          (shown)
Signal 5          (shown)
Signal 6          (shown)
```

Figure 17: Graphical user interface for setting the laser pulse sequence

**Battery Energy Storage**

The battery energy storage block is based on a native SimpowerSystem block that represents a generic battery. The user needs only provide data in the input parameter dialog box obtained by double-clicking on the battery storage block. Normally, no additional inputs should be entered in the blocks found in the lower layers of the battery storage block.

The battery block represents the cumulative action of all individual battery cells in parallel or series combination. For example, a set of 100 lead acid batteries in series results in the overall Voltage - Ampere-hour profile shown in the top diagram of Figure 18 for various cases of discharge currents. The user must input the data for the single cell in the parameter dialog box based on the information provided by the cell manufacturer. Since this may be subject to difference in nomenclature and practice, Figure 18 also



Block Parameters: Lead Acid Battery Storage

Lead Acid Battery Model (mask)

General model of a lead acid battery.
Enter all parameters, even if only estimated, for one battery unit.
The last two inputs describe the make-up of the whole battery system.

Parameters

Nominal Voltage, V: [illegible]

Rated Capacity, Ah: 68

Initial State of Charge, %: 100

Maximum Capacity, Ah: 72

Fully Charged Voltage, V: 13.28

Nominal Discharge Current, A: 218.5

Internal Resistance, Ohms: 0.0035

Capacity at Nominal Voltage, Ah: 64

Voltage at end of initial exp. drop, V: 12.8

Capacity at end of initial exp. drop, Ah: 6

Assumed

Estimated to make the discharge curve fit the (68 Ah, 10.02 V) point given in the specs in data sheet

Estimated to give a reasonable profile

Estimated to give a reasonable profile

Figure 18: Cumulative battery energy storage characteristics (top) resulting from the example of block inputs for single Genesis XE70 battery cell (bottom)

gives a guide as to what is the physical interpretation for the various input parameters needed. The example reported is for the particular case of the Genesis XE70 battery: it can be seen that some of the parameters are not available from the data sheet and some reasonable estimates must be made.

The additional inputs in the parameter dialog box not shown in the figure are self-explanatory. Of course, what has been shown for the Genesis XE70 battery can be adapted opportunely to other battery types.

**Flywheel Energy Storage**

The FESS diagram is shown in Figure 19: it consists of a flywheel, a synchronous machine that works both as a generator and a rotor, and a bidirectional power converter that interfaces it to the ship's power system and load. Since the version of SimpowerSystem used did not support a single representation of a synchronous machine working as a generator and motor, the two functionalities had to be modeled separately with the attendant need to keep the two machines in synchronism with each other.

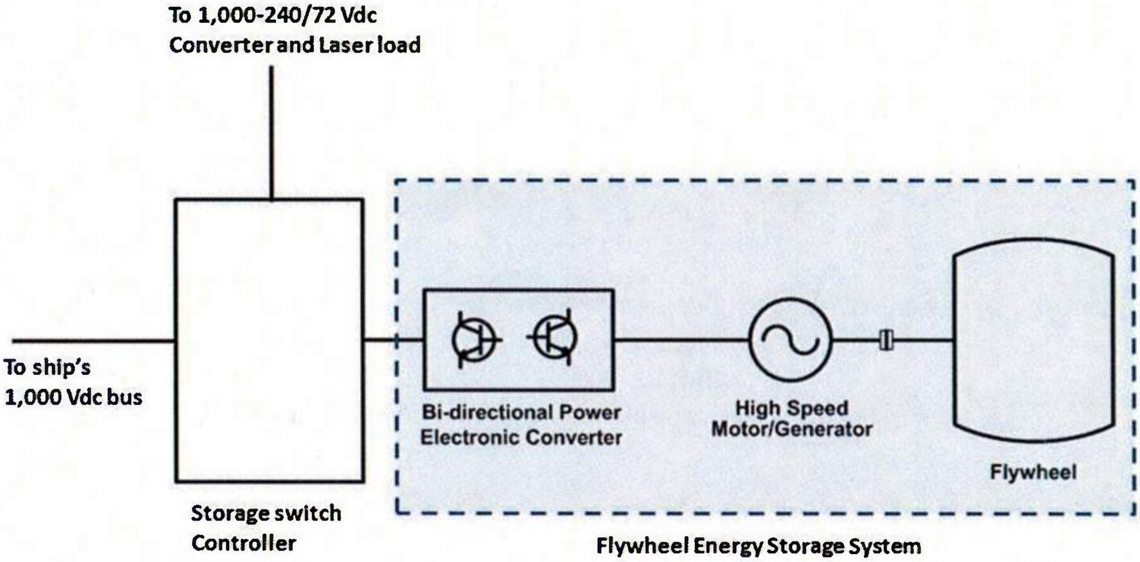
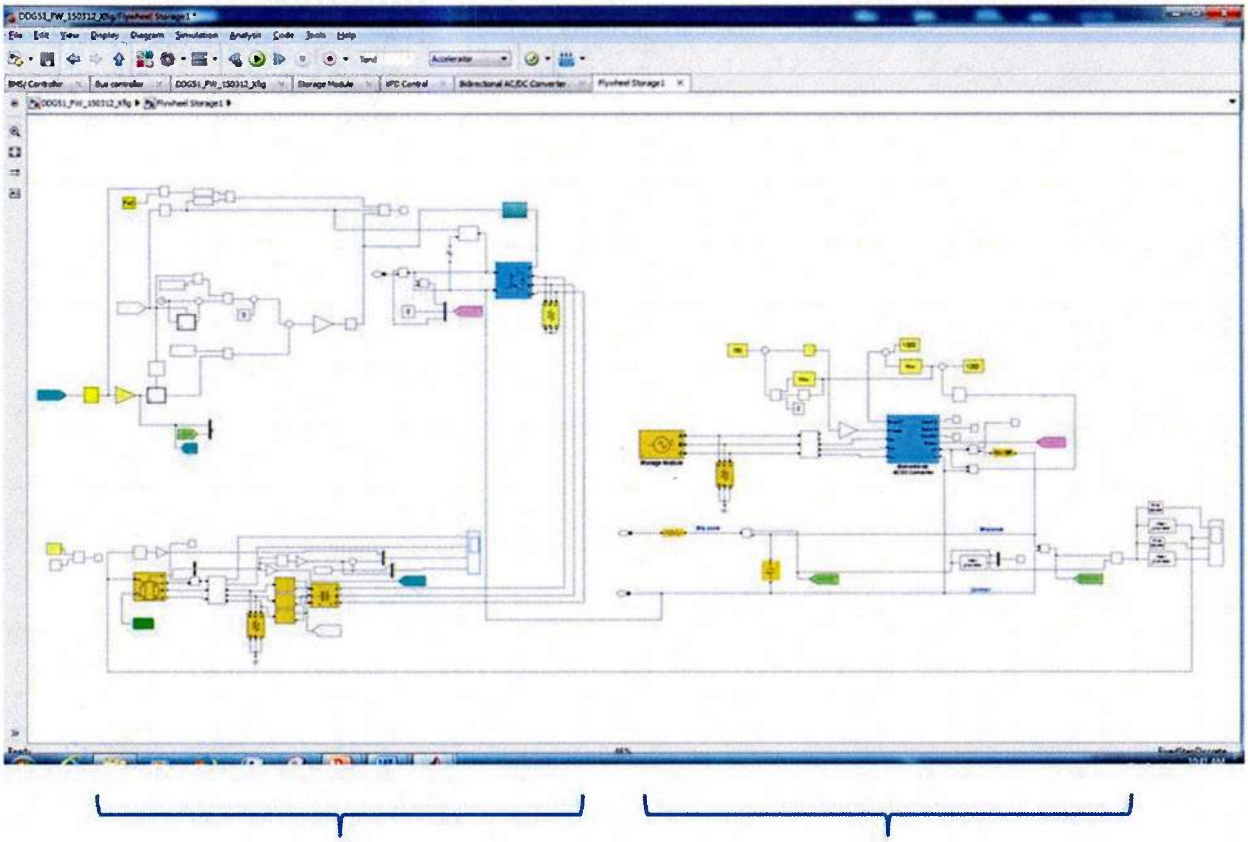


Figure 19: Schematic diagram of the FESS

This is shown in the diagram of the internal structure of the FESS block reported in Figure 20. The inputs needed for the FESS block are self-explanatory as described in the input dialog box.



Synchronous motor drive

Synchronous generator and bidirectional power converter

Figure 20: FESS block structure

**Capacitor Energy Storage** The block representing the capacitor energy storage allows for a maximum configuration of five strings in parallel, each with 20 capacitors in series. The inputs needed for the capacitor storage block are self-explanatory as described in the input dialog box.

**Output dc-dc Power Converter** This is realized as a set of two series dc-dc step down converters. The first converter is always active, whereas the second one is inserted only if the step down ratio is deemed to be too large. This block does not need any local intervention by the user, as its parameters are fully determined by the input data file.

| | |
|---|---|
| **Input dc-dc Power Converter** | This block is present only in the model with the capacitor energy storage system. It is essentially the same as the block used for the output dc-dc power converter, except for some obvious parameter adjustments. Likewise, this block does not need any local intervention by the user, as its parameters are fully determined by the input data file. |
| **Laser load** | It is represented by its equivalent impedance to the circuit. The user needs to input only laser power and rated voltage in the input parameter dialog box obtained by double-clicking on the laser load block. |
| **Measurements** | All significant simulation data are output to scopes and numerical displays for immediate use, or workspace data files for post-processing, plotting, and permanent records. |

The user has also the option of enabling or disabling the operation of manual switches distributed throughout the model by toggling the switch at the bottom left of the model. Similarly, the operation of other simple features and blocks of the model should be self-explanatory.

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[12] Gregory Nelson – SEA 05D1, "LCS Solid State Laser Ship Integration Study – Final Report", Naval Sea Systems Command Carderock Division, Aug. 24, 2012