MANAGING MULTIPLE AND VARYING ENERGY DEMANDS BY MEANS OF ENERGY STORAGE IN COMBATANTS WITH INTEGRATED ELECTRIC PROPULSION

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Managing multiple and varying energy demands by means of energy storage in combatants with integrated electric propulsion

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SYNOPSIS

The potential problems of managing the power flow of pulsing energy loads together with the more conventional energy loads is a challenge that needs to be addressed if the integrated electric propulsion (IEP) concept is to advance significantly.

For the all electric ship concept the primary source of energy are the main electricity generators. These feed four main types of loads: Mission essential loads needing to be available all the time, like radar: Mission important loads that must be kept working but can withstand a temporary power reduction, like the main propulsion drives: Non essential loads that can be discontinued as required, like heating; New technology loads that require pulses of energy on a irregular basis that must be provided exactly when the demand occurs.

The short-term demands for electrical energy of the combined loads can significantly exceed the available energy from the main electricity generators. In such cases a set of suitable intermediate energy store are required, together with an integrated power management system that co-ordinates all the energy flows to meet the defined performance levels.

There are several potential sources of stored energy in a combatant; these include the combatant's linear kinetic energy, the rotational energy of the main propulsion drive as well as any dedicated energy stores.

The paper describes how these energy stores can be used to meet the defined performance levels. In particular the requirement for an aircraft launch system in future all electric aircraft carriers has led to an interest in electromagnetic launch systems to replace the steam catapult. The design features of an electromagnetic launch system are described together with the options that makes it compatible with an integrated power management system.

INTRODUCTION

Today more and more commercial and naval ships are selecting full electric propulsion. Typical examples in Fig 1 are the landing platform dock ship HMS Albion, the icebreaker ship USCG Healy and the new T45 destroyers.

Fig 1. Typical ships with full electric propulsion.

Author's Biography

Eric Lewis works for ALSTOM Power Conversion Ltd. as a Power Electronics Consultant. He has worked for ALSTOM and it's former companies in many different positions for over 40 years.

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For each ship there are often different reasons for the adoption of full electric propulsion. The use of full electric propulsion has many benefits including :

- The system has a high redundancy.
- Automatic limitation of propulsion drive power, speed and overload to avoid tripping.
- Gives better performance with improved thrust, faster stops and faster turns.
- Gives an automatic fast response to the loss of a generator.
- Provides economy by matching generated power to power required.
- Gives reduced NOx emissions especially at low power levels.
- Requires lower installed power with high efficiency in all operational modes.
- Suits ships with varied operational profiles.
- More flexible vessel design to increase the ship's payload and survivability.
- Simpler engine room, with flat construction and easier layout.
- More balanced operating hours per engine gives significant reductions in planned maintenance.
- Uses technology that is understood by new technicians.
- Gives lower noise and vibrations by using fixed pitch propellers.
- Can easily adapt to the needs of future advanced electric weapons and systems.

Full electric ship propulsion is now the preferred solution for advanced ships. The electrical system for a full electric ship is shown in simplified form on Fig 2.

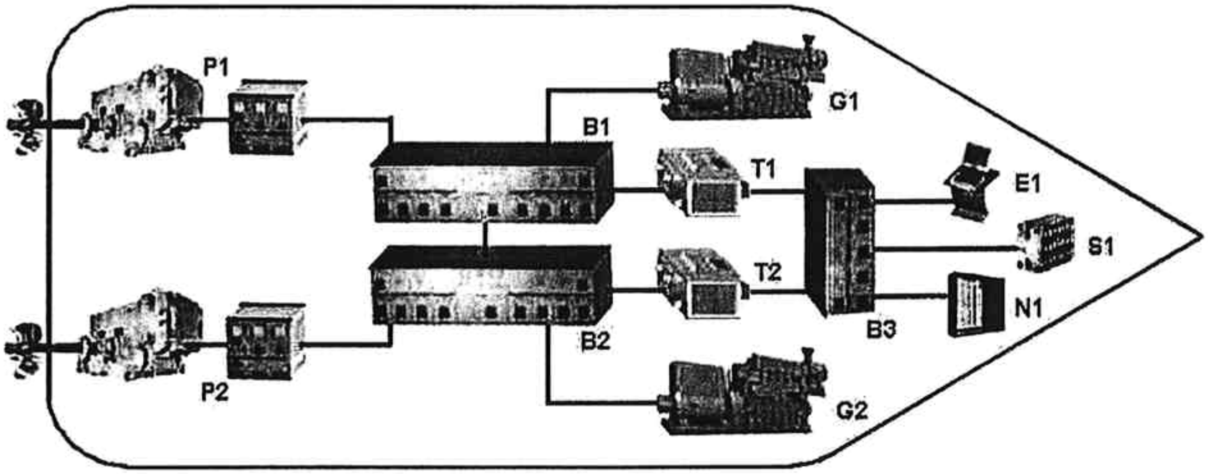
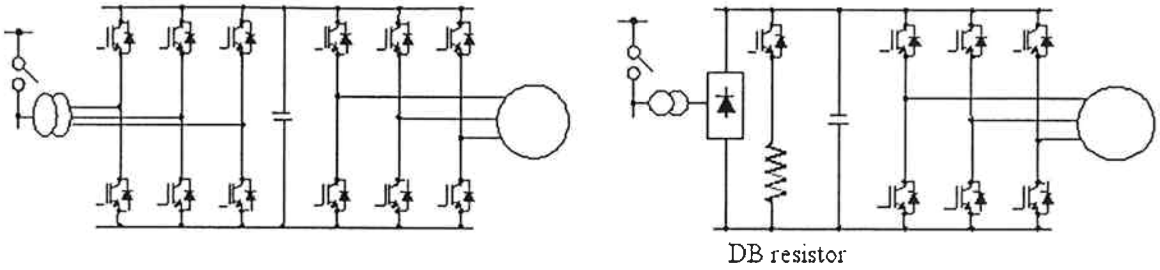


Fig 2. Typical system of a full electric propulsion ship.

The systems shown on Fig 2 are :

- Main medium voltage generators G1 & G2.
- Main medium voltage propulsion systems P1 & P2.
- Main medium voltage switchboards B1 & B2.
- Medium voltage to low voltage step down transformers T1 & T2.
- Low voltage switchboard B3.
- Low voltage essential loads E1, like radar.
- Low voltage non-essential loads N1, like ovens.
- Back up energy store S1. This is typically used to provide energy for short times to the essential loads.

The propulsion system can use several types of variable speed electric drives, and the most frequently used type is now the voltage source pulse width modulated (PWM) drive. For a ship with full electric propulsion it is essential for the drive system to be able to absorb energy from the propeller to enable a fast stop of the ship to be achieved. For the PWM drive system the two methods of achieving this are to either regenerate energy in to the ship's AC supply system or to dissipate the energy in resistors called the dynamic braking resistors. These two options are shown on Fig 3 based on the circuits used for commercial low voltage drive systems.


PWM with regeneration in to the AC supply

PWM with regeneration in to the DB resistor

Fig 3. The two methods of absorbing the ship energy with PWM drives.

The PWM drive system is rapidly becoming the universal drive system as it has many benefits including :

- Very dynamic torque ability.
- High immunity to AC supply disturbances.
- No significant speed limitations.
- No significant torque pulsations.
- Low AC supply harmonics.
- Low AC supply MVAR demands.
- Can cage induction motors that are inherently very robust.

For naval ships a specially developed ALSTOM drive system is used as shown on Fig 4.

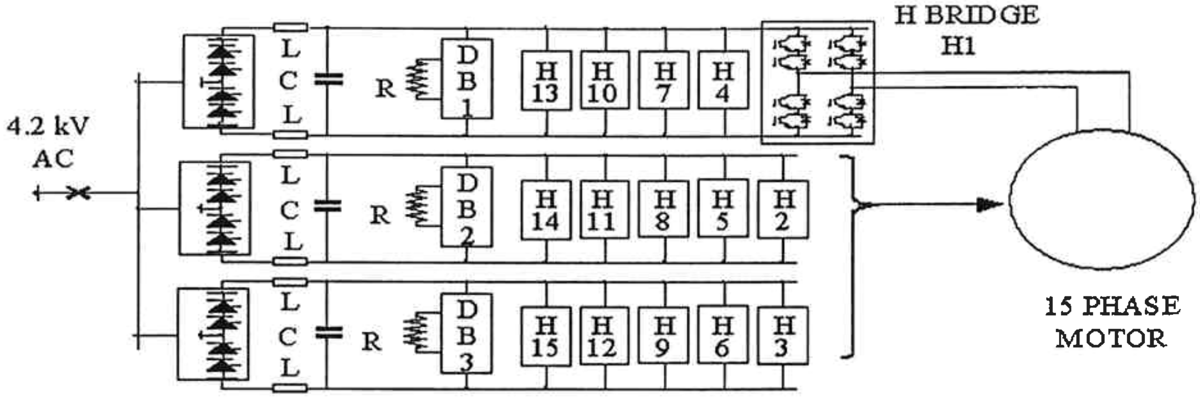


Fig 4. The ALSTOM naval drive system.

The ALSTOM naval drive system has a range of features required by naval drives including :

- Can operate on any combination of the 3 DC links and the associated motor's windings.
- Series IGBTs are used with N+1 redundancy so that any short circuit IGBT will not give an over-current event.
- The power converters are split in to 3 separate cubicles to isolate any common mode faults.
- The thyristor input converters also have N+1 redundancy and act as fast acting ACCB protection circuits.
- Does not regenerate in to the AC system and dynamic braking circuits are fitted for ship stopping.
- Has a very fast dynamic response that can be used to assist the redirection of power to future loads.

The AC generators shown on Fig 2 provide the power for the drive systems. The generators are typically powered by either diesel or gas turbine prime movers. For specially designed diesels and basic gas turbines the typical maximum rates of change of the electrical loads are 30% load in 0 seconds or 100% load in 5 seconds to meet the classification society rules for disturbances in the AC supply system. For the latest recuperated gas turbines the corresponding typical figures are 20% load in 2 seconds or 100% load in 25 seconds. The power distribution systems for existing and future loads must be tuned in line with these response times.

The existing power management systems use a set of basic rules to ensure that power is available at all times for the essential loads of Fig 2. These rules are :

- Must at all times supply the essential loads like E1 on Fig 2.
- If the generated power is not sufficient the propulsion power is rapidly reduced to keep within the classification limits.
- Can always switch off the non essential loads to gain extra propulsion power.

The operation of these rules is shown on Fig 5 which shows the result of the generator G2 tripping with the ship at full propulsion power of 20 MW, a non propulsion load of 3 MW and both generators at their full load of 11.5 MW. The generator G1 has a very short term overload and the variable speed drives fall to zero power and then rapidly recover to use the available power. This is a simple and well proven technology.

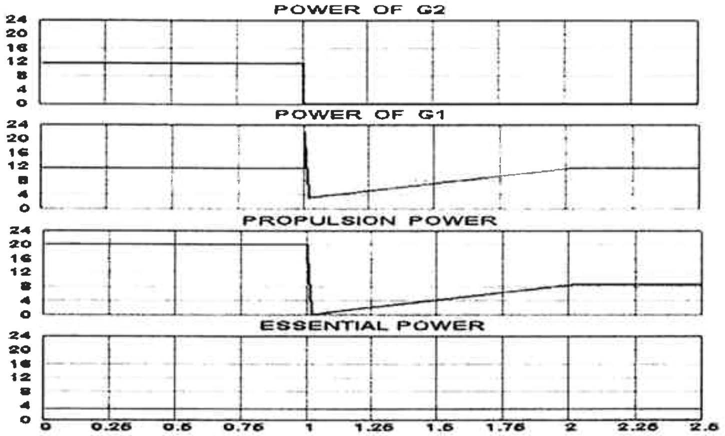


Fig 5. Response of the system to a trip of AC generator G2.

ELECTRICAL SYSTEMS FOR FUTURE COMBATANTS

The electrical systems for future combatants will have a range of new electrical systems that will need to be integrated in to the existing systems. The new systems could include rail guns and active armour. These are shown on Fig 6 where W1 is a rail gun and A1 is active armour.

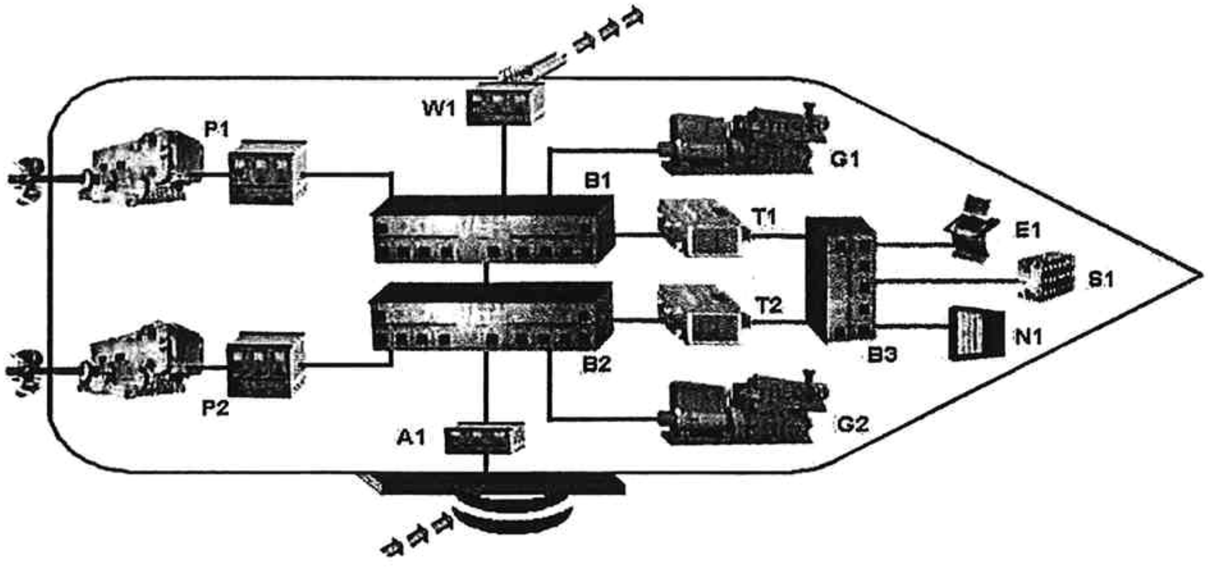


Fig 6. Future electrical systems.

There are a range of new electrical systems under development which include :

- High power rail gun weapons that have the following typical features :
  - Ship or vehicle borne.
  - Use is long range fire support with anti-armour abilities and self defense.
  - Five to ten years of development at medium power density.
  - Gun barrel is 8 meters long with a projectile speed of 2500 m/second.
  - Projectile mass is 20 k grams giving a projectile energy of 64 M Joules.
  - Pulse duration is 6 to 9 milliseconds with an output pulse power of 10 G Watts.
  - Typical gun voltage is 10 k volts at a gun current of 10^6 Amps.
  - System efficiency is approximately 40% giving an input energy per shot of 160 M Joules.
  - Firing rate is 6 rounds per minute, which lasts for a firing burst of 3 minutes.
  - Average power is 13.3 M Watts taken over 1 minute.
  - A typical development rail gun is shown in Fig 7.

- High power laser weapons that have the following typical features :
  - Ship, air or vehicle borne.
  - Main use is self-defense.
  - Near term development.
  - Pulse duration is 10 milliseconds with an output pulse power of 1 M Watts.
  - Input energy per shot is 200 k Joules.
  - Fire rate is 10 rounds per second, which lasts for a firing burst of 10 seconds.
  - Average power is 2 M Watts taken over one second.

- High power microwave weapons that have the following typical features :
  - Ship, air or vehicle borne.
  - Antipersonnel (non-lethal) and anti-electronics with reduced collateral damage.
  - 3 to 5 years development.
  - Pulse duration is 10 milliseconds with an output pulse power of 1 M Watts.
  - Input energy per shot is 40 k Joules.
  - Fire rate is 10 rounds per second with a continuous firing burst.
  - Average power is 0.4 M Watts taken over one second.

- Active armour that is designed to dynamically prevent damage to a ship or vehicle, there are 3 types.
  - Electromagnetic armour that 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 armour that creates an explosion in the opposite direction of incoming plasma jet, that is created by the incoming round.
  - Smart armour that uses sensors to determine nature of incoming round and select the appropriate defensive measure against that threat.

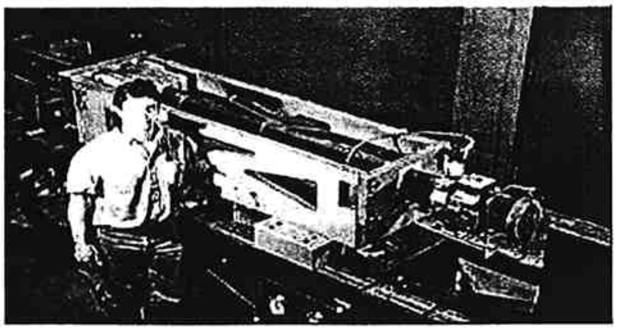


Fig 7. A typical development rail gun.

The rail gun has been selected to illustrate the future electrical power demands that could occur as it has the highest power demand. The example shown in Fig 8 shows the power demand of two rail guns each firing sets of 6 rounds on a random duty profile that averages a 25 % usage in a 10 minute period. The top graph of Fig 8. is the result of using an energy store with 1 second storage while the bottom graph is the result of using an energy store with a 20 second storage. This data shows that a long term energy store is essential to minimize the AC supply effects.

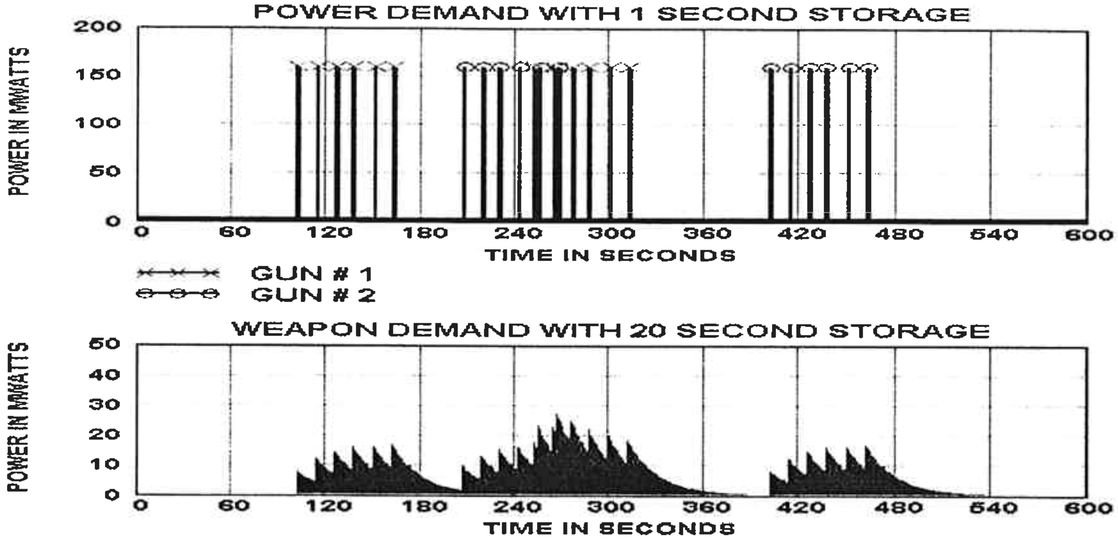
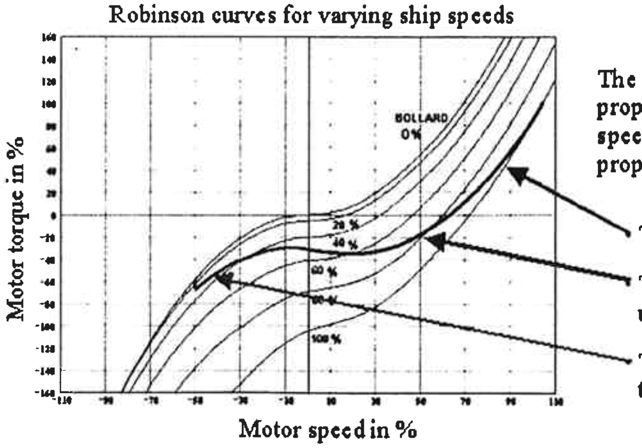


Fig 8. Rail gun power demands.

SOURCES OF ENERGY IN COMBATANTS

The primary sources of electrical energy are the AC generators shown on Fig 6. In addition there are two other energy stores that exist in present full electrical propulsion systems. These are the kinetic energy stored in the combatants linear motion and the rotational energy stored in the propulsion motor, shafting and propellers.

- Combatants linear motion energy store.
  - For a destroyer this is typically a store of 1000 M Joules
  - For an aircraft carrier this is typically a store of 5000 M Joules.
  - The available maximum regeneration power is limited by the propeller Robinson curves, shown on Fig 9.
  - For a destroyer this is typically a maximum regeneration power of only 10 M Watts.
  - For an aircraft carrier this is typically a maximum regeneration power of only 20 M Watts.
  - The maximum available power is typically only 25% of the full propulsion drive rating.
  - There is also a significant delay in getting the regeneration power.
  - This is not a very useful energy store.



The Robinson curves show the propeller's torque when the propeller speed is varied for a set of different constant ship speeds. The arrows show a typical trajectory when the propeller is reversing from full ship speed.

This is the motoring power reducing to zero.

The is the available regeneration power that could be used by other loads.

This is where the AC power is reapplied for stopping the ship.

Fig 9. Typical Robinson curve data.

- Combatant's propulsion rotational energy store.
  - Due to the low inertia involved the energy stored is small at typically 10 M Joules per motor and shaft.
  - It is also not an easily used source of energy, as PWM drives with a diode bridge input, as shown on Fig 10, do not regenerate in to the AC network.
  - If a future system is linked to the DC link of the PWM drive, as shown on Fig 10, then the drive rotational energy can be supplied on a 10 millisecond response time scale.
  - This is also not a very useful energy store, and the same applies to the ALSTOM naval propulsion drive shown on Fig 4.

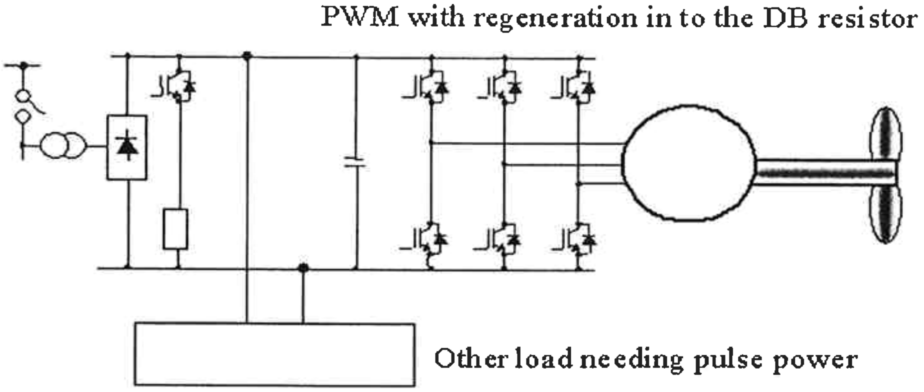


Fig 10. Using drive regeneration energy.

For future combatants there are a wide range of alternative energy stores that can be used :
- Flywheel energy stores.
- Battery energy stores.
- Capacitor energy stores.
- Fuel cell energy stores.
- Super conducting magnetic energy stores (SMES).

The flywheel energy store is available now in a very wide range of designs and is able to meet all the future requirements. The Fig 11 compares the different solutions, and this shows that flywheel energy stores have the optimum combination of energy, power output and size. At present flywheel energy stores are the preferred store for use with rail gun weapons.

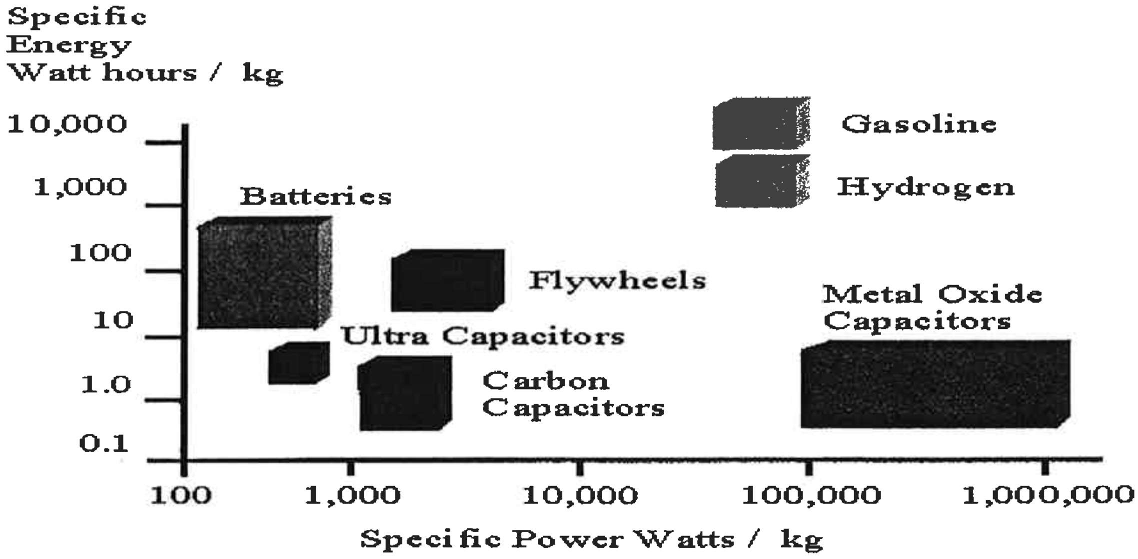


Fig 11. Comparison of energy stores.

The Fig 12 shows a large flywheel energy store made by the University of Texas–CEM that is rated at 2 M Watt, 480 M Joules at 15 000 rpm. This store can deliver 2 M Watts for up to 3 minutes. For future combatants it is possible to maximize efficiency by operating on only one prime mover and AC generator when the combatant is at medium speeds in a non threat situation. The flywheel energy store shown on Fig 12 could be used to provide all the ships services if a trip happens when running on one generator until another prime mover is started.

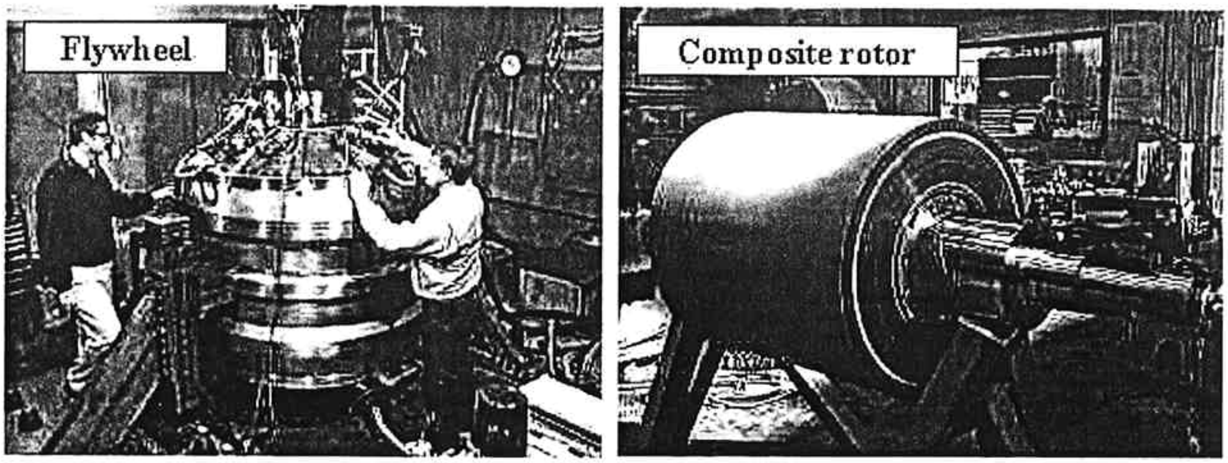
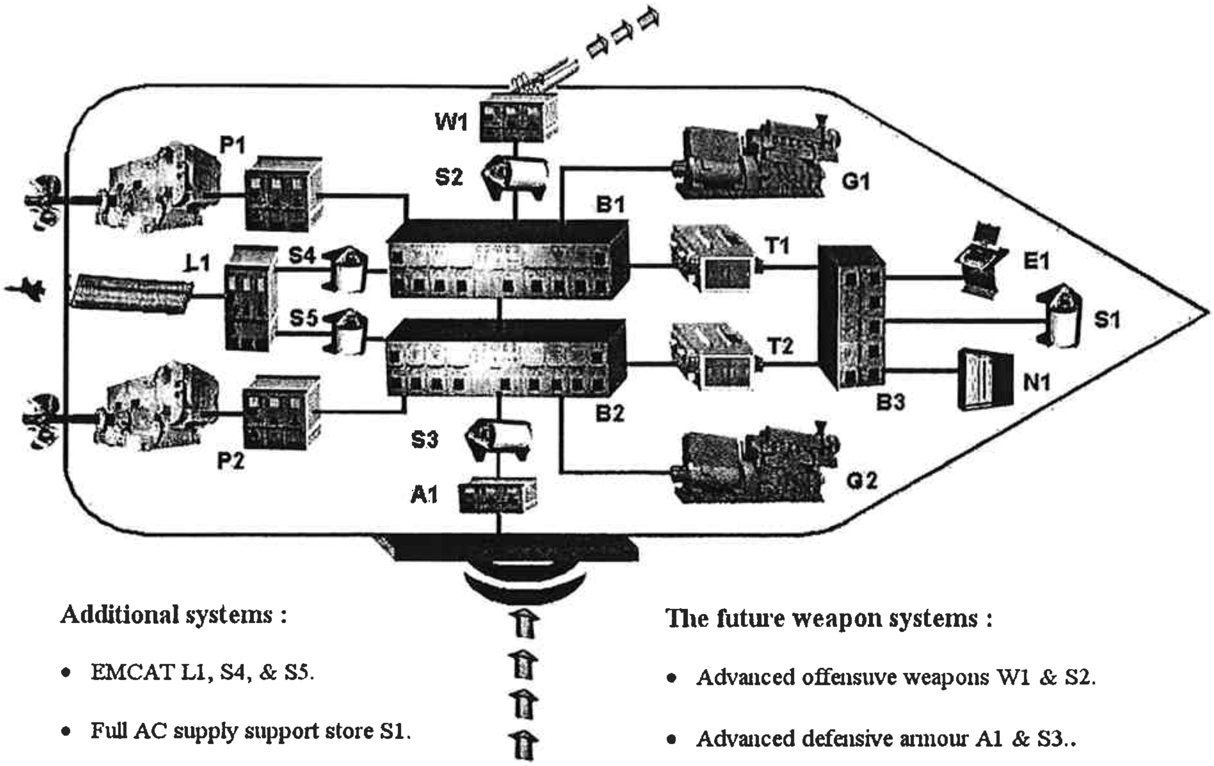


Fig 12. Large flywheel energy store.

THE INTEGRATED SYSTEM FOR FUTURE COMBATANTS

The Fig 13 shows a possible combatant with the flywheel energy stores S1 to S5 added plus an electromagnetic catapult airframe launch system (EMCAT). The flywheel store S1 is used to cover power supply transients, the energy stores S2 to S5 are to buffer energy demands.



Additional systems :

- EMCAT L1, S4, & S5.
- Full AC supply support store S1.

The future weapon systems :

- Advanced offensuve weapons W1 & S2.
- Advanced defensive armour A1 & S3..

Fig 13. A full system of a future combatant.

When the rail guns are operating for the duty cycle shown on Fig 8 the typical demands on the AC generation system are shown on Fig 14. The Fig 14 shows the operation where the energy demands are passed directly back in to the AC generating plant and the propulsion drives are operating at maximum speed and power.

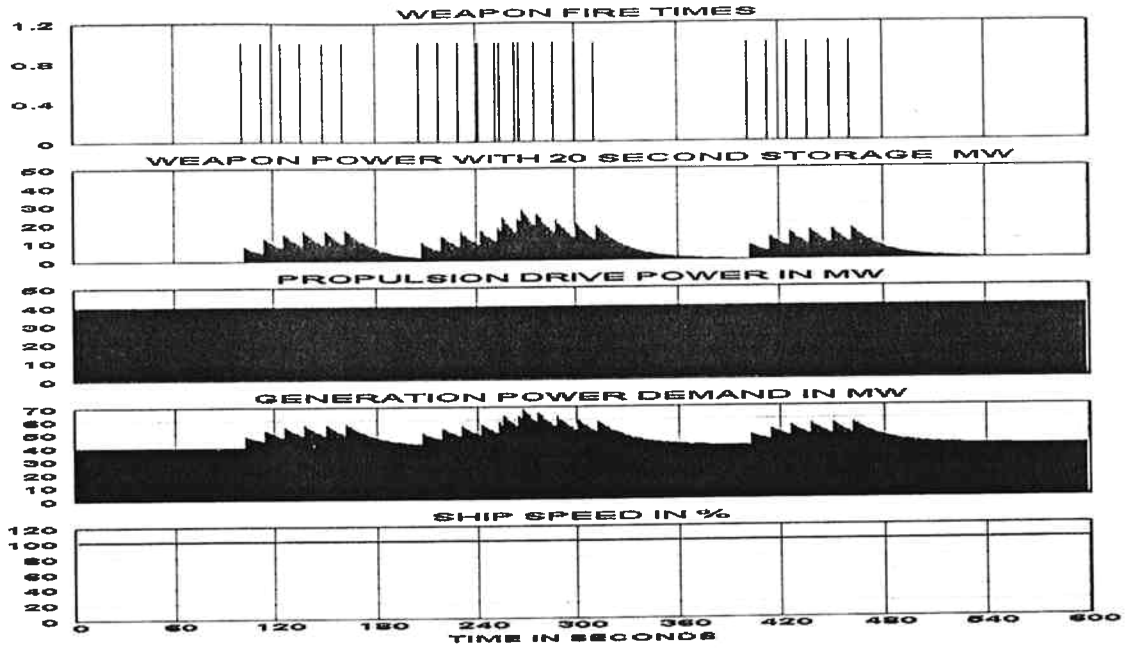


Fig 14. Typical power demands with propulsion at full speed.

This shows that a significant extra 160 % overload power demand exists from the nominal full propulsion power of 40 M Watts and that the AC system will need to have a fast response to the varying AC supply demands. The Fig 14 is using a 20 second time constant energy store for the rail gun weapons. This method of control will need significant overload ability in the generating system together with fast acting voltage control regulators. If the fast response of the propulsion drive is used then it is possible to use the combatants linear inertia energy store to further smooth out the demands on the AC generation system, see Fig 15.

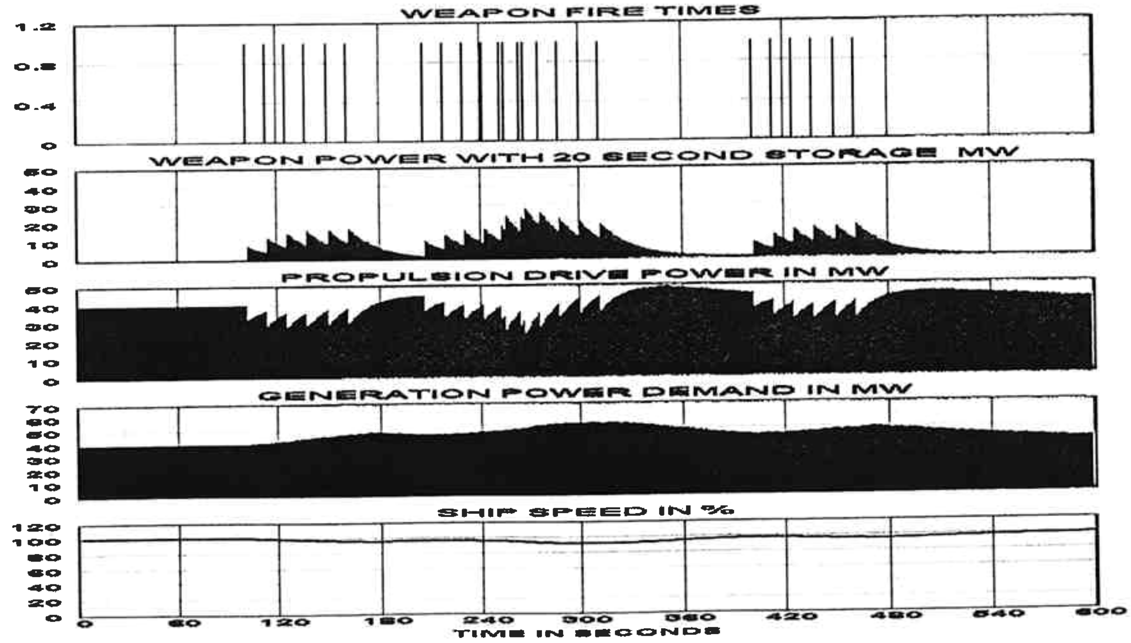


Fig 15 . Smoothing energy demands using the ships inertia and the propulsion drives.