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USE OF ENERGY STORAGE SYSTEMS IN NAVAL COMBATANTS

BY

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SYNOPSIS

The increasing trend towards electric power and propulsion systems in naval surface combatants has led to the appraisal of the use of energy storage systems to improve the combatants design, operation and effectiveness. There are a wide range of different energy storage systems that can be used, from rotary flywheels to superconducting magnetic energy stores. An ideal energy storage system would have the following key features; no moving parts, a high energy storage capacity, a small volume, a large number of full charge and deep discharge cycles, minimal maintenance, a long in-service life and the minimum of external support services. The latest generation of energy stores are now able to provide most, if not all, of these key features.

This paper includes data on the detailed performance parameters of several energy stores that are then used to illustrate the three main methods of interfacing energy stores into existing or future systems. A review of the existing linear motor launch system using Electromagnetic Kinetic Integrated Technology (EMKIT), funded by the UK Ministry of Defence (MoD) for large Unmanned Aerial Vehicles (UAVs), is presented and shows how its successful trials exceeded all design parameters. The paper shows how the different energy stores interface methods can be applied to a provide ride through support for a propulsion drive and to a future EMKIT system in order to remove its flywheel energy stores. Finally, it is shown how a similar linear motor system could form the basis for a future aircraft carrier based electromagnetic linear launch system for either large UAVs or other airframes such as the E2C Hawkeye.

Author's Biography

Eric A Lewis works for Converteam UK Ltd. as a Power Electronics Consultant. He has worked in many different positions for Converteam and its former companies such as ALSTOM Power Conversion and GEC for over 45 years on the design and application of variable speed drives for demanding applications in many industries including mining, metal processing, commercial ship systems and naval ship systems.

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in various project management positions. She is currently involved in naval projects that include the application of electromagnetic launch technologies.

INTRODUCTION

More and more commercial and naval ships are selecting full electric propulsion, and the T45 destroyer HMS Daring shown on Figure 1 is an outstanding example.

FIG.1 - NAVAL SHIP WITH FULL ELECTRIC PROPULSION

The use of full electric propulsion has many proven benefits including high redundancy and fault tolerance which in the author's opinion can be significantly increased by the appropriate selection and use of energy storage devices.

The MoD has awarded Converteam a design study to review the available energy storage devices that are viable for use in naval ships either as Commercial Off The Shelf (COTS) devices or as systems that require further development to be viable in the naval environment. The study is still on going but has already enabled the most appropriate energy storage devices to be identified and defined how they can be integrated in to the electrical systems of naval platforms.

At present lead-acid batteries are the most common method used for storing large quantities of electrical energy. Lead-acid batteries are well proven and can easily be used in series for high power applications, but they have several limitations:

- Relatively low power density;
- High weight;
- High maintenance requirements;
- The need for adequate ventilation of noxious charging and discharging gases;
- Can release hazardous chemicals if damaged.

The energy storage technologies investigated in the study are:

- Super-capacitors;
- Advanced batteries;

- Flywheels;
- Flow cells;
- Superconducting Magnetic Energy Storage (SMES).

Each type of energy store investigated is optimum for use at different discharge durations as shown on Figure 2.

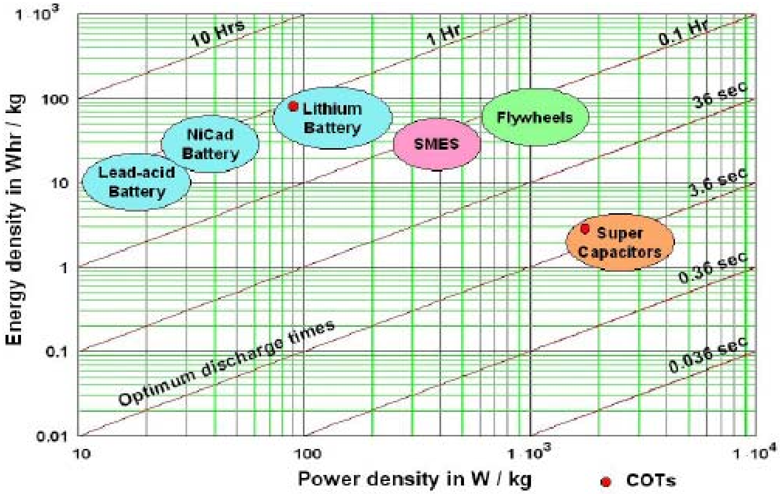

FIG.2 - ENERGY STORAGE TECHNOLOGIES

The Figure 2 shows:

- That for long term storage the optimal methods are Lithium-ion batteries, SMES or flywheels;
- That for energy storage systems requiring a rapid discharge, super-capacitors are the optimal selection;
- That the technology of Lithium-ion batteries and super-capacitors are available from COTS suppliers.

When selecting an energy storage device for a given application it is essential to understand the specific technical features required which can vary very significantly between different applications. Two of the main applications defined in the MoD contract are for Zonal Energy Storage (ZES) and Pulse Power Energy Storage (PPES).

ZES AND PPES ENERGY STORE APPLICATION DATA

For ZES applications the typical requirements are for power of 1 to 8 MW delivered in a time of 0.5 to 300 seconds, which requires energy storage of 0.5 to 2400 MJ as illustrated on Figure 3.

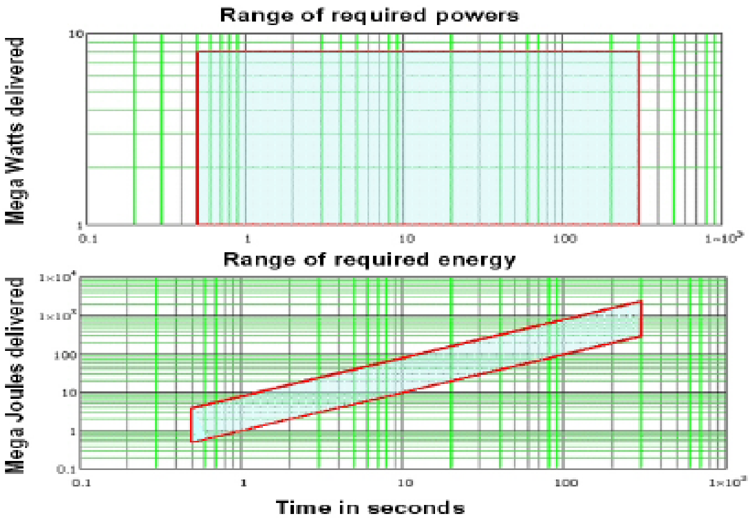

FIG.3 - TYPICAL ZES ENERGY STORAGE PARAMETERS

The main ZES application requirement is to store energy very efficiently for long periods. The discharge of the energy does not take place on a regular basis and for most applications is released in a period measured in many seconds. When a naval ship is in an operational state that permits running on a single main prime mover, a ZES store of this type could be used to support the ships services and propulsion if a loss of the single prime mover occurs. With the appropriate design a ZES store could support all the vital ship services plus a limited degree of propulsion power until an alternative prime mover becomes available. This would avoid a black ship, avoid running unnecessary prime movers and maximise the fuel economy during this operational mode.

The PPES operational requirements are very different and require an energy storage system that can discharge its energy in less than a few seconds, is able to be charged and discharged on a very frequent basis and still has a long in service life. There are some PPES applications that will always require a specially designed energy store for extreme application requirements, for example a rail gun system. There are other PPES energy store applications that are less demanding with parameters shown in Table 1.

TABLE 1 - *Typical PPES Energy Storage Parameters*

	Discharge time in seconds	Discharge Energy in MJ	Stored Energy in MJ)	Repeat time in seconds
Rating 1	0.5	2	4	60
Rating 2	2.5	6	12	60
Rating 3	2.5	17.5	35	60
Rating 3	2.5	35	70	60

The data shown in Table 1 is typical of PPES ratings used for launching various sizes of airframes from small unmanned aerial vehicles (UAVs) up to full size combat aircraft from naval platforms. When reviewing the type of energy store to be used for a given application it is essential to understand the operating profiles of the different energy store types that are available.

ADVANCED BATTERIES

There are a range of advanced batteries that have been developed in recent years and the Lithium-ion type offers a high energy density and is ideal for ZES applications. The operating profile of a Lithium-ion battery is shown on Figure 4.

The Lithium-ion battery works by moving and storing lithium ions from the anode to the cathode during battery discharging and in the reverse during battery charging. Most batteries of this type use a graphite anode and lithium oxide $LiCoO_2$ for the cathode, but there are several variants including a Lithium-titanate battery that uses a high surface area nano lithium titanate oxide based cathode material and a Lithium-iron-phosphate battery that uses a safer $LiFePO_4$ cathode material.

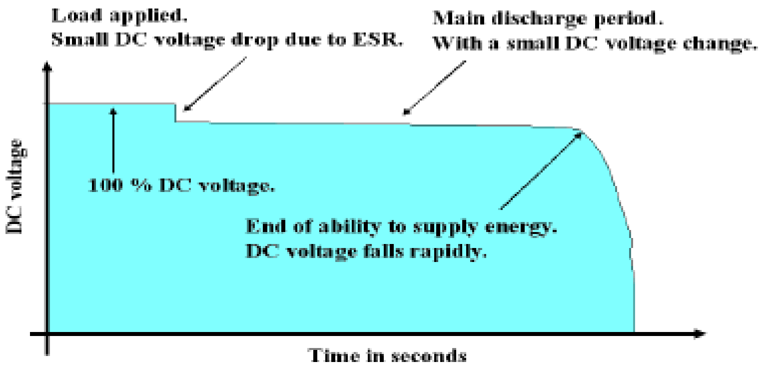

FIG.4 - OPERATING PROFILE OF A LITHIUM-ION BATTERY

The typical operating voltage of an individual battery is 3.5 volts DC and for a high power system many batteries are connected in series.

The charging and discharging of Lithium-ion batteries must be accurately controlled due to the following limitations based on typical battery voltages:

- The charging voltage is 4.1 +/- 0.05 volts DC per battery;
- Charging at 4.0 volts DC per battery will reduce the capacity by 10% but will increase the service life;
- Once charged a trickle charge must be avoided as this can cause metallic lithium to form in the battery;
- To avoid problems can either recharge when volts fall to 4.0 volts per battery or float charge at 4.0 volts;
- The normal discharge voltage range is 3.8 to 3.2 volts DC per battery;

- The discharge is stopped at 2.5 volts DC per battery to preserve the battery’s operational life;

- Must not discharge below 1.5 volts DC as they will become unusable due to internal short circuits developing;

- Charging above 4.30 volts DC per battery will cause plating of metallic lithium on the anode and the cathode material will become an oxidizing agent and release oxygen. The overcharging will eventually cause the battery to heat up and if left unattended could vent flames. This problem does not occur with the Lithium-iron-phosphate batteries, which have been specifically designed to replace industrial lead-acid batteries.

In selecting the type of Lithium-ion battery to be used in a specific application the consequences of damage to a battery or a battery module must be considered.

For certain types of Lithium-ion batteries the effect of an object damaging the battery’s casing, especially by puncturing, is to release an exothermic reaction with consequent high temperatures and flames.

This can be avoided by selecting certain types of Lithium-ion batteries. The Lithium-Iron-Phosphate technology was specifically designed to have a damage tolerant battery, which are now used to replace lead-acid batteries in several transport related applications.

The outline of a typical Lithium-ion battery and a battery module are shown on Figure 5 and the properties of one battery are detailed in Table 2.

FIG.5 - TYPICAL LITHIUM-ION BATTERY AND A MODULE

TABLE 2 - *Typical Properties of a Lithium-ion Battery*

Charge voltage (max)	4.1 Volts
Nominal operating voltage	3.6 Volts
Discharge voltage (min)	2.5 Volts
Maximum continuous current	300 Amps
Capacity	30 Amp hours
Cycle life	>100,000 Cycles
Specific energy	97 Watt hours/kg
Weight	1.1 kg
Volume	0.0051 m^3

To fully utilise the capabilities of one Lithium-ion battery a specially designed charger must be used with very accurate control of the battery voltages. For high power systems a large number of batteries are used in series for example a design using 1200 volts DC to charge the batteries will require 292 batteries in series.

For such systems it is essential to use a battery control and monitoring system that provides four essential features:

- Balancing the voltage on all the batteries within a high tolerance. There are a number of technical options used by different manufactures including passive resistors to active bypass circuits;

- Monitoring of the mean battery voltages to set the optimal voltage charging profile;

- Monitoring of individual batteries to provide overall protection and detection of any faulty battery;

- A disconnecting means to avoid either over charging or over discharging the batteries.

A number of Lithium-ion battery suppliers can now provide these facilities to enable high power systems to be developed, but a development project will be required to enable the benefits of the technology to be utilised in ZES applications. The exception is a range of Lithium-iron-phosphate COTS batteries with a fully integrated COTS control system for voltages up to 1000 volts DC which also have the increased safety of the Lithium-iron-phosphate technology.

SUPER-CAPACITORS

Super-capacitors are now available in an easily used COTS module that can be directly connected in series to build high power systems. The operating profile of a super-capacitor is shown on Figure 6.

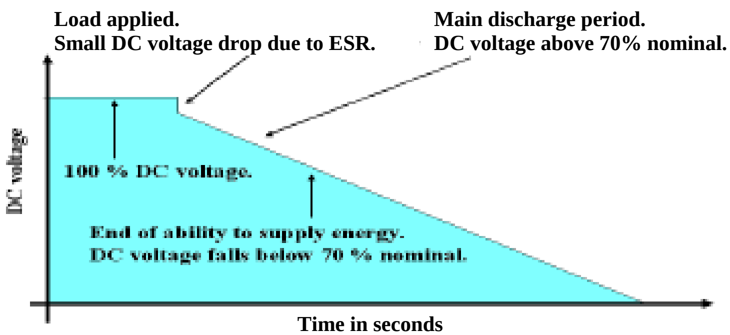

FIG.6 - OPERATING PROFILE OF A SUPER-CAPACITOR

The typical operating voltage of an individual super-capacitor is 2.7 volts DC and for the COTS module shown on Figure 7, which uses 18 super-capacitors connected in series, the operating voltage is 48.6 volts DC.

The control of charging and discharging of super-capacitors is easily implemented as there is a well defined charging voltage and the super-capacitors can be discharged to zero voltage with no adverse affects on the super-capacitors.

The ability to fully discharge a set of super-capacitors makes it very easy and safe to replace a defective module.

FIG.7 - SUPER-CAPACITOR COTS MODULE

The characteristics of the COTS module are defined in Table 3 and the module contains the required battery balancing and monitoring circuits that are connected to a separate monitoring system.

TABLE 3 - *Typical Properties of a COTS Super-Capacitor Module*

Rated capacitance	165 Farads
Nominal operating voltage	48.6 Volts
Nominal current	150 Amps
Stored energy	190 k Joules
Equivalent Series Resistance (ESR)	7 m Ohms
Cycle life	1,000,000 Cycles
Weight	14.2 kg
Volume	0.012 m^3

Super-capacitors are ideal for PPES applications as their life exceeds 1 million cycles including deep discharge, and they are equally viable for ZES applications when only a short storage time measured in seconds is required.

One ZES application that is ideal for super-capacitors is to support the combatant's AC and DC bus sections, for a few seconds, while a fault is being cleared on the combatant's main power generation bus.

One ZES could also replace a significant number of distributed Uninterruptible Power Supply (UPS) units, which are commonly used to support mission critical systems including radar and still be survivable on a zonal basis.

It is also possible that the very large PPES that will be required for future dedicated applications could also be used to provide support facilities to assist other systems in continuing to operate during power system disturbances.

Most importantly these benefits are available in fully standardised COTS modules that avoid any development costs when super-capacitors are used in either ZES or PPES applications.

FLYWHEELS

There are a number of COTS flywheels available, but without exception, they were developed for slow energy release commercial applications and use magnetic bearings and vacuum technology to store energy efficiently.

Unfortunately the COTS designs are not suitable for use on naval platforms as they are unable to withstand the following:

- 2g vertical, 1.5g horizontal in addition to the static gravity load;
- 10° pitch + 5º trim giving a total of 15º;
- 30º list;
- Single 45º roll for short periods;
- 15g vertical and 10g horizontal for equipment on shock mounts for shock rated combatants.

Flywheels provide the optimum storage for many ZES and PPES applications but they require significant development costs. The author believes that the development of flywheels for naval applications is being funded by the US navy.

For the 2009 season some of the Formula 1 racing cars can use a Kinetic Energy Recovery System (KERS) which has led to two of the teams using high speed energy storage flywheels that could, with development, form the basis of a naval flywheel system.

These F1 flywheels are shown on Figure 8 and Figure 9 and can withstand high vibration and shock loads.

FIG.8 - FORMULA 1 FLYWHEEL TYPE 1

This flywheel is rated at 60 kW and stores 400 kJ using a composite rotor running at 64500 RPM. The flywheel total weight is 25 kg with a rotor weight of 5 kg made using 3 types of composite materials.

FIG.9 - F1 FLYWHEEL TYPE 2

The Electro Magnetic Kinetic Integrated Technology (EMKIT) demonstrator that has now been completed and passed all the specified performance tests uses two flywheels as its PPES, as shown on Figure 10.

FIG.10 - THE EMKIT FLYWHEEL

The data for each EMKIT flywheel is:

- Based on a commercial induction motor operating at 6000 rpm;
- Continuous rating is 110 Kw;
- The stator windings have a low impedance to allow high overloads;
- Overload rating is 27:1 times the continuous rating;
- Energy stored at maximum speed is 3.2 MJ;
- Speed falls to 4700 rpm during the 0.7 second output energy pulse;
- Output voltage at 4700 rpm is 460 volts AC 3 phase rms.

The use of high power flywheels for naval ZES and PPES application is possible but will require dedicated development.

SMES & FLOW CELLS

In the past SMES systems were used to supply land based energy storage applications, however it appears that the alternative energy store technologies are replacing this technology.

Flow cells are now coming on to the market aimed at very long term energy storage, but the cell membrane is unlikely to be able to withstand the forces experienced on board a naval ship.

INTERFACING TO ENERGY STORES

There are three main methods that can be used:

- The energy store is connected directly to the DC bus of a standard Pulse Width Modulated (PWM) converter, as shown by ES1 on Figure 11. If this method is used the DC bus must be controlled to suit the charging / discharging characteristics of the energy store being used. This is a viable method but the available PWM machine bridge's AC output voltage to the motor or other loads will be reduced due to the change in the DC bus voltage. For this interface method the charging and discharging of the energy store must be controlled by the PWM converters;

- The energy store is connected by a DC to DC chopper to the DC bus of a standard PWM converter, as shown by ES2 on Figure 11. With this method the DC bus voltage can remain at the optimum voltage as the DC to DC chopper corrects the changing voltage of the energy store. This is a viable method with the benefit that the PWM converter’s AC output voltage to the motor or other loads will not be reduced. For this interface method the charging and discharging of the energy store is controlled by the DC/DC chopper;

- The energy store is connected by an AC to DC chopper to the DC bus of a standard PWM converter, as shown by ES3 on Figure 11. This method is used to interface flywheel energy stores and the DC bus voltage can remain at the optimum voltage as the DC to DC chopper corrects the changing voltage of the energy store. This is also a viable method with the benefit that the PWM converter’s AC output voltage to the motor or other loads will not be reduced. This is the method used for the EMKIT flywheel interface. For this interface method the charging and discharging of the energy store is controlled by the AC/DC chopper.

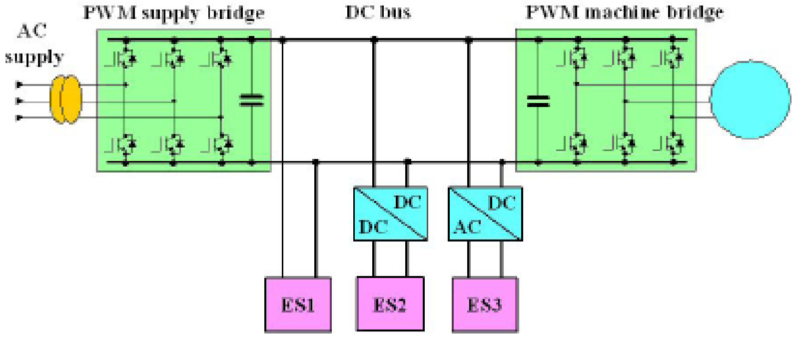

FIG.11 - INTERFACING ENERGY STORES

When designing a Lithium-ion battery or super-capacitor energy store system the selection of the ES1 or ES2 method enables the optimal cost system to be designed, taking in to account the specific voltage versus time profile for any given energy store and application.

For a Lithium-ion battery energy store rated to charge at 1200 volts DC the voltage after a deep discharge will fall to approximately 930 volts DC. This voltage can be altered by a small factor by adding batteries in parallel but the effect is small.

However, for a super-capacitor energy store also rated to charge at 1200 volts DC the voltage at the full discharge point can be selected over a wide range by adding capacitors in parallel, but to recover 50 % charge the minimum voltage is 840 volts DC.

In both designs this is one of the main cost optimisation factors that have to be considered and the appropriate interface method must be selected.

The ES1 method is very viable and gives the lowest cost solution provided that the variation in the motor’s voltage is acceptable. An example of this method is shown in the Auxiliary Support Unit (ASU) energy store section.

The ES2 method has to be used if a variation in the motor’s voltage is unacceptable. An example of this method is shown in the EMKIT future energy store options section.

The other interface that may be required for an energy store is to provide a cooling system. This is most likely to be needed for PPES applications and at present forced air cooling is the normal method used.

AUXILLIARY SUPPORT UNIT ENERGY STORE

The traditional design of propulsion drive systems uses the main drive power from the propulsion bus, plus one or more sources of low power energy. This can lead to a loss of several propulsion drives if the low power energy source has a fault and trips.

One way to avoid this is to make each drive totally self sufficient and able to ride though a loss of the propulsion bus for short periods and to then independently restart producing propulsion power within a few seconds of the propulsion bus power being available. The Figure 12 shows one way of achieving this with the use of an Auxiliary Support Unit (ASU).

This enables the system to ride through a loss of the propulsion bus power, and the ZES energy store is used based on the interface method ES1 of Figure 11 for a commercial ship operating with an 11 kV propulsion bus.

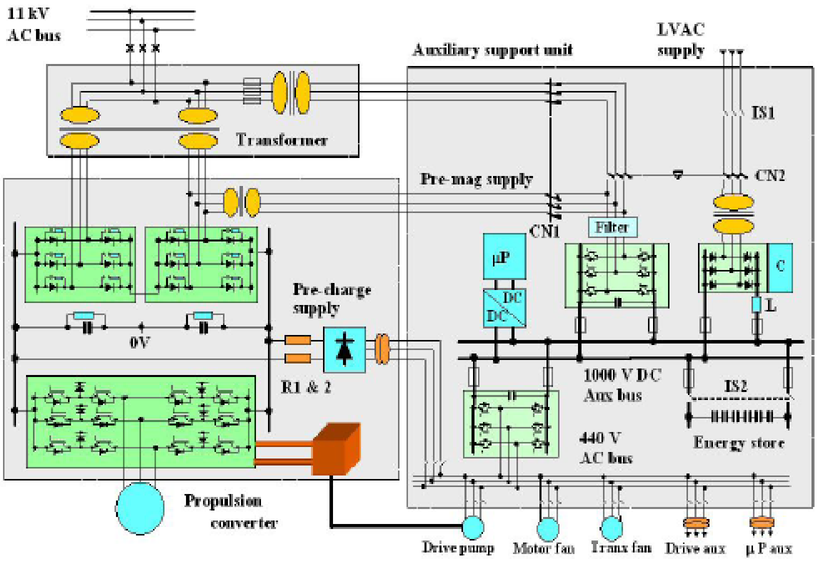

FIG.12 - PROPULSION CONVERTER WITH ASU

The ASU is typically housed in one cubicle with front access for controls and rear access for the energy store to provide the required facilities which includes:

- Feeding drive auxiliaries from the propulsion drive power source;
- Concurrent recovery actions for rapid fault recovery;
- Propulsion power available within 2 seconds of the 11 kV bus recovery;
- Maintaining all auxiliaries during loss of the 11 kV bus for up to 60 seconds;
- Pre-magnetising circuit for drive transformers to avoid system transients.

The operation of the ASU is:

1. The thyristor bridge is used for initial commissioning and to pre-charge the energy store.
2. With the LVAC supply selected will be able to pre-commission all the auxiliaries.

3. When the propulsion drive is requested to be ready to start the first step is to run up the propulsion converter's main DC link by slowly raising the 440 volt AC bus via the output converter.
4. This will charge the propulsion DC link via the transformer and diodes shown.
5. When the propulsion DC link is fully charged and the 440 volt AC bus is operational the system can start the drive's cooling pump, the motor's fan, the transformer's fan and all the drive auxiliaries.
6. These will continue to be fed from the LVAC until the drive is ready to operate.
7. When the drive is requested to start the CN2 will change to the supply from the drive position, but the power will now come from the energy store.
8. The contactor CN1 will then be energised so that the input converter will operate in reverse to pre-magnetize the main transformer.
9. The input converter will rapidly synchronise the transformer's voltages to be in phase with the 11 kV AC bus, so that the drive VCCB can be closed without any delay and without any inrush surge.
10. With the VCCB closed the CN1 contactor can be turned off and the input converter will then supply power to the DC bus. This will supply the auxiliaries and keep the energy store charged.
11. The propulsion pre-charge supply can then be turned off and the propulsion drive is then ready to operate.
12. If the AC bus trips the energy store will keep the 440 volt AC bus operational for up to 60 seconds so that a very fast restart is possible.
13. If an AC bus fault occurs the actions are the same as the items 7 to 12, and the drive will be able to rapidly pre-magnetise the transformer, close the drives VCCB without a surge and to start the propulsion operating in less than 2 seconds.

To provide the required storage the DC link is designed to start at an initial voltage of 1000 volts DC and can fall down to a voltage of 700 volt DC during the ASU support time.

The inverters are rated for the 1000 volts DC voltage level as they are 690 volts rated. The inverter feeding the 440 volt AC bus will be able to supply the bus for any DC link voltage in the range 1000 to 700 volts DC.

The design permits the use of either supper-capacitors or Lithium-ion batteries to store the energy. The selection would be based on the actual storage time for a given application.

EMKIT FUTURE ENERGY STORE OPTIONS

The EMKIT demonstrator has been constructed by Converteam at the Bruntingthorpe airfield and has successfully completed all its proving tests. The EMKIT system was designed to demonstrate the ability of Advanced Linear Induction Motors (ALIMs) to launch UAVs like the Hermes 450 airframe in a short distance. The Hermes 450 airframe has a mass of 450 kg and a cruise speed of 36 meters per second. The EMKIT circuit is shown on Figure 13 and uses two high speed rotary energy stores to supply the launch energy.

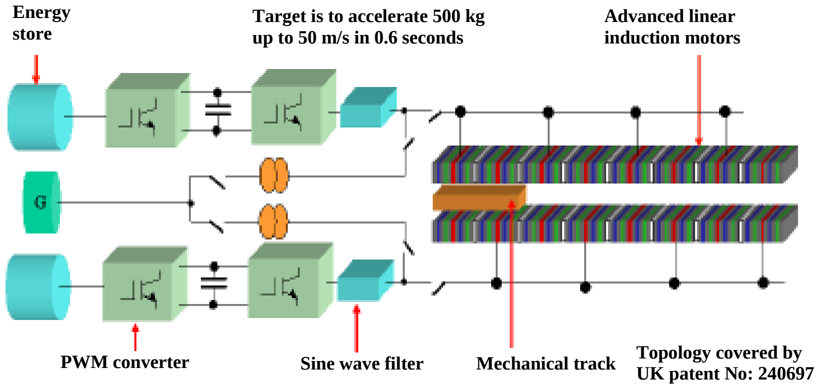

FIG.13 - THE EMKIT CIRCUIT

The system is on a green field site shown on Figure 14. This shows the ALIMs in the foreground, the building with windows houses the power converters and the diesel generator is housed in the container with louvers. The energy stores are located outdoors, and are visible between the converter building and the diesel's container.

FIG.14 - THE EMKIT DEMONSTRATOR

To have sufficient launch energy the two energy stores are accelerated up to the maximum speed at a low rate via the PWM converters, using energy from the low power diesel generator set.

When a launch sequence is initiated the PWM converters take the energy from the energy stores, transform the AC energy to DC and then supply the optimum variable AC voltage, AC current and AC frequency to power the ALIMs. This is the interface method ES3 shown on Figure 11.

A typical set of the ALIM stator currents for a full speed launch are shown on Figure 15. This shows how each ALIM stator only draws the appropriate magnetising current, which automatically increases to supply the accelerating thrust to the aluminium reaction plate as it enters each ALIM stator in turn. Each set of ALIM stator currents has well controlled current changes due to the control algorithms used.

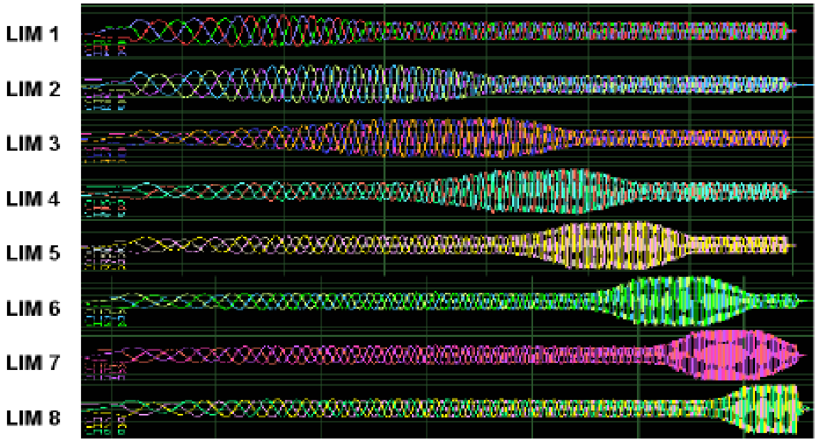

FIG.15 - THE ALIM STATOR CURRENTS

The EMKIT system has achieved the following:

- Launching 513 kg to 50 m/s (112 mph) in 14.8 m launch length at 8.6 g of acceleration in 0.7 seconds...;
- A cycle time between launches of less than 2 minutes;
- A time to launch from cold with all supplies isolated of less than 5 minutes;
- More than 5 launches per hour;
- A controllable low jerk start;
- Has exceeded the specified thrust of 54 kN;
- A thrust density within a factor of 2:1 of the thrust need for full size combat airframes;
- Open loop control with a launch speed error of less than 1% for all conditions;

- A very low temperature rise of less than 4.5 °C per launch, with natural air cooling;

- Launching 1033 kg to 38 m/s in 15 m, which is sufficient to launch a Predator A UAV.

When the EMKIT system was designed, in 2005, it used flywheel energy stores as they represented the optimal technology available. Now super-capacitors have developed to the point where they could be used to supply the launch energy as shown on Figure 16.

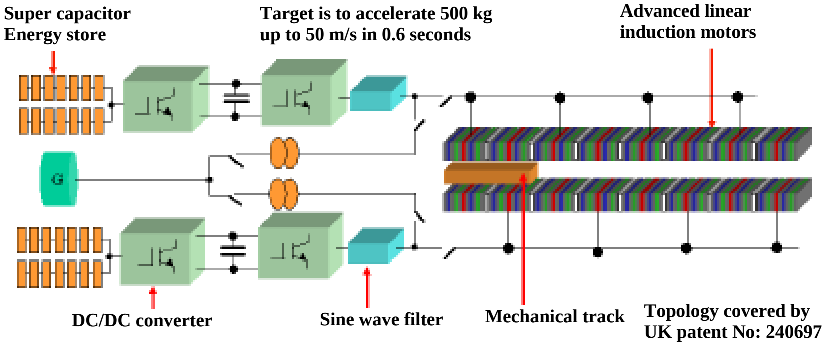

FIG.16 - THE EMKIT SYSTEM WITH SUPER-CAPACITOR ENERGY STORES

With the existing PWM inverters it is essential to maintain the DC link voltage at the maximum value, so the interface method uses DC to DC choppers. This is the interface method ES2 as shown on Figure 11. Within one year a new range of PWM inverters will have the ability to accept the voltage variations in the DC link that are needed to implement the interface method ES1, as shown on Figure 11 and this would enable the DC to DC choppers to be omitted.

ALIM SYSTEMS FOR LAUNCHING LARGE AIRFRAMES

The ALIM technology can be developed to launch a wide range of airframes. A typical USA naval airframe is the E2C Hawkeye that provides an airborne radar facility. Without a catapult the E2C requires a take off run of 564m but with a catapult delivering a thrust of 300 kN the E2C can be launched in 90m as shown on Figure 17. The EMKIT thrust is 54 kN therefore with scaling a 3 track ALIM with the same length of reaction plate, but with a 100 % depth increase could launch the E2C airframe.

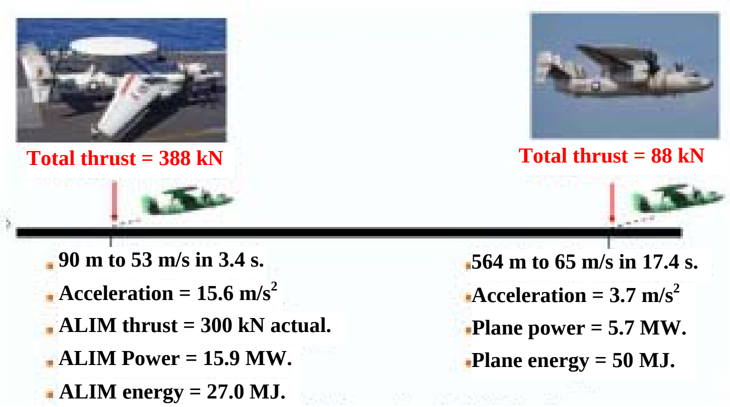

FIG.17 - LAUNCHING THE E2C HAWKEYE

CONCLUSIONS

The available energy storage systems that can be used for naval ships are increasing and they will continue to increase.

At present super-capacitors are readily available from COTS suppliers to build ZES and PPES energy stores.

The use of Lithium-ion batteries is also viable for ZES energy stores but due to the complex monitoring requirements a development will be required, unless Lithium-ion-phosphate batteries are used with a voltage below 1000 volts DC.

Super-capacitors and Lithium-ion batteries have high short circuit currents but these are compatible with inverter systems, however the potential of certain types of Lithium-ion batteries to overheat and emit flames when damaged does restrict the types that can be used for naval applications.

The energy study has not identified any COTS flywheel units that are viable for use in naval applications, but suitably designed flywheels could be developed to provide a viable means of supplying the energy for naval ZES and PPES applications.

The use of energy storage systems in future naval platforms will provide many opportunities to improve the availability, fault ride through, quality of power supplies (QPS), especially when future loads with increasingly complex and pulsating power demands are used.

The development of bidirectional and multifunctional energy storage systems can provide economical solutions to the growing complexity and power demands of future combatants.

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