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'THE EVOLUTION OF THE REVOLUTION'
THE PAST, PRESENT AND FUTURE FOR ELECTRIC PROPULSION SYSTEMS

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ABSTRACT

Predominately aimed at warships, the author reflects on 20 years of personal involvement in the commercial and naval electrical propulsion revolution from a system engineers rather than an equipment supplier's perspective. As electric propulsion enters into a more evolutionary phase over the coming years, how architectures might prudently evolve on upcoming platforms to enhance the performance, cost and ship fit benefits by maximising the use of past and current investment. From commutators to combatants, energy storage to end results, the paper also outlines the system engineers desire to match the system, rather than the equipment directly, to the requirements of the end user to achieve fully integrated power and propulsion systems.

INTRODUCTION

The flexibility and efficiency offered by electricity in all aspects of life is beyond question, we replaced gas lamps with light bulbs, we replaced steam, then diesel trains with electric locos, we are working hard to produce the viable electric car. All of these bring challenges, but are also all inevitable, it's simply the technology, timing and risk that we must manage.

The last 20 years have been revolutionary with respect to electric propulsion, not just in the military world, but in the commercial world as well. This paper is a personal commentary on that journey from the authors perspective, as an industry, what we did right, and wrong, and what we might learn from it, as well as what the future might hold.

But for an accident in timing, the author would have joined the Navy in the 1980's, but joined GEC Electrical projects instead, working on large mining motor/converter projects, as well as the Type 23 Frigate propulsion system (its just a small mine winder motor/converter/regulator after all).

Out of the blue, in the early 90's the author was then asked to contribute to writing a paper to consider the all electric propulsion concept for a surface warship, with a view to matching real equipment to the vision. He couldn't conceive that the Royal Navy would be that radical and pioneering; but thankfully, couldn't have been more wrong. After a stint in growing the company's commercial full electric propulsion market, the author returned to naval work on the LPD, AO, ESTD, T45, CVF and FSC platforms that formed the Naval IFEP revolution.

The following paper is therefore not only a commentary on what the author or his company did, it's his views on what the whole community involved achieved, and what we can learn from the experience.

Authors Biography

Nick Smith is the Chief Engineer of Naval Business for Converteam UK Ltd, where he has been involved in the conception, design and setting to work of Drive and power systems for over 20 years. Son of a steam engineer, involved in power generation and naval propulsion, the author grew up in the Far East watching the construction of the power stations that quite literally powered the tiger economies into the 21st Century. This meant that he grew up with the mantra that whilst electricity is the lifeblood of progress, steam quite literally, makes the world go round. But for an accident in timing he would have joined the Navy, but instead joined what is now Converteam in Mining Engineering, then commercial and finally Naval electric propulsion. He played a leading role on the Power and Propulsion systems for The AOs, LPDs, ESTD, Type 45 and CVF Projects prior to his current appointment. Although now a Chartered Engineer, an active FIET and member of the LRS Naval and Commercial Technical committees, his international, commissioning and ex apprentice background give him a more practical and pragmatic approach to the integration of high technology.

HISTORY AND LESSONS

What We Did Right

Revolutionised marine and naval propulsion. Many of the engineers working on these contracts also played a key role in commercial and cruise liner propulsion.

The MoD developed a vision over a period of time built on the Marine Engineering Development Strategy of the 1990s; build around three pillars, An efficient Gas Turbine Development, Full Electric Propulsion, and electrification of auxiliaries. The community bided its time, and waited for the opportunity. As well as the underpinning high tech developments required, (WR21, IPS/AIM, PMPM) there was a clear evolution policy followed: hybrid (T23), Commercial Electric on an RFA(AO), commercial electric on a warship (LPD) and Full Electric on a combatant (T45) and then a carrier (QE Class).

The wider community took this vision, was opportunistic, and was able to maximise commercial pull through and derisking from other projects such as the US IPS programme to good effect.

FIG.1 - THE 1980S - T23 LOW VOLTAGE HYBRID DC ELECTRIC

T23 led the way initially, bringing modern electric propulsion to the Navy, and was a huge success from a signature perspective, it raised propulsion efficiency greatly at lower speeds, saving a huge amount in fuel, and paving the way for other platforms to capitalise on this feature.

For all its benefits, T23 didn't truly share all its prime movers between propulsion and services and still had gearboxes; it also didn't really go electric for multi-role efficiency, the underpinning reason for the Electric Ship.

LPD and AO became the MOD's first modern all electric ships, using more commercial based technology with some hard lessons learned about equipment and system integration that would prove invaluable going forward. These ships brought high efficiency across the operating range, low maintenance gearbox less propulsion with fixed pitch propellers, consuming far less fuel than their predecessors.

With the dawning of the new millennium, Industry having just tendered the all Electric Ship Technology Demonstrator (ESTD), successful AIM and WR21 testing in the US, and Type 45 being finalised, all the elements were there to contemplate full electric propulsion for a front line combatant. Surely it was too late for T45? which was never the first target platform. A number of key other things combined, the vision met the opportunity and collective ability. For the first time, we had a great combination of the RN, the Shipbuilder, and the right industrial players that held together just long enough to pump the revolution with oxygen.

Suddenly IEP was selected for T45 and we had a challenging near term target but based on the art of the possible. We embarked on a parallel derisking strategy, that involved GTA, Back to Back and SuperFAT automation testing, we were also able to align ESTD, with its groundbreaking full power propeller load simulator, with T45 and shift the emphasis from component to system derisking.

Industry sent experts north to aid the shipbuilder in integrating this new equipment, which had not insignificant ship impacts. Although it eliminated gearboxes, CPPs and simplified shaftlines, there were new challenges, the GTA set was long, but not linked to the shaftline, and as the author predicted, when we had laid out the cabling, we then had to try to figure out how to connect it together with items of equipment.

This engagement with the shipyard/ship designer is not always contractually and politically possible, but it always pays dividends and continues to work well on later projects like CVF.

For CVF we had learnt many of the contractual and technical lessons, and we were able to form the holy grail of technical expertise in a multi-corporate central design team, engaging closely with the customer and shipbuilder at early stages of the contract.

Finally, as an industry, we put T45 to sea, and from a P&P perspective she will be unrivalled for many years to come.

Other Specific Positive Lessons

- We were able to develop common technology with the US;
- Supported British industry with world class products such as AIM and MT30 that were exported;
- We started to retire out of date standards, and produce some more relevant ones;
- We started to engage classification societies, and started to address such hot topics as software security and integrity;
- We developed better electrical modelling capability via contracts such as ESTD, not just fidelity, but validation;

- We also started to see the holy grail of model prediction of complex issues, not just resolution of problems that occurred;

- We started to model and understand more fully earthing systems and common mode current/voltage effects;

- We started to recognise graceful degradation over redundancy;

- We also put more emphasis on system interdependency for complex fully integrated systems;

- We recognised the benefits of derisking activities such as Automation and Control 'SuperFAT' testing, and the benefits of shaft 'paddle' blades to IFEP system commissioning. (paddle/brake wheels/blades are where the propeller blades are swapped for blades that produce power but no thrust, so full power propulsion commissioning can take place at the quayside);

- We embarked on CVF, from the ground up as an IFEP warship, was it the right decision to go IFEP rather than Nuclear? Wrong question, Nuclear is just the power source. There are many advantages of nuclear electric that we will come to realise in due course on future platforms.

We all have our day to day issues, and opinions, but we should not lose sight of the fact that there has been a vision driven revolution, that will deliver huge benefits, which we must continue to build upon.

FIG.2 - THE 00'S AND 10'S T45 AIM AND QEC

What We Did Wrong:

Over 20 years, there are many lessons to learn as a community. The first one is perhaps we should both celebrate and realise our success more, whilst engaging in no 'individual corporation' blame analysis of where we sometimes missed the mark.

Design Lessons

There is often too much study work of too many options in early stages, often by third parties. This can make decisions difficult to make and follow. We need to separate the variables, five A vs B decisions give 25 i.e. practically, 32 combinations, but its still only 5 decisions. The author has seen projects with dozens of options, and has often been sure that the final answer is not one of them.

We never sorted out the Acronym very well, we went from CODLAG to IEP?IFEP?FEP, we used E instead of L? Opinions differ over what is full, what is integrated? We no longer described the prime movers in the title. It's probably better to stick now at IFEP, which would help.

Early on, we tailored GTs for direct drive, and not really for generator duty. We didn't realise this early enough to match the vision for IFEP.

Also, as an industry, we sometimes concentrate too much on the motor size, and not enough on the converter, which is the more complex, faster changing technology that has larger ship fit impacts.

In the mechanical analogy to motor/converters, we marvel at the core engine size of a GT, and seem to worry later about the large array of supporting skids/equipment that is required.

The smallest DGs always seem to be too small on IFEP platforms (LPD, T45, AO), Hopefully we have finally fixed this on CVF and FSC, 4 platforms later.

There are too many legacy constraints on Prime Mover Selection (physical, contractual, political), Have we ever chosen a prime mover best for system?

We failed to agree on shaftline jacking pumps! The futility of asking an OEM to remove pumps without increasing bearing size due to somebody else's experience, who is not prepared to take responsibility, cannot be over emphasised.

LV Supply Definition remains a problem. We spend a long time debating the meaning of Essential, Vital and Non Essential suppliers. We also fail to choose where the vital and essential supplies will be predominately located, early enough in the design resulting in architectural and functional impacts as well as a plethora of UPS's. A global definition of these terms, how long they need to be supported, and a key requirement to physically state where the majority of vital and essential supplies are, would be a significant help. You really don't need ultimate detail to do this, 20% effort removes 80% risk.

Sizing the amount of LV Load is also an issue. Some of our current approaches are too bottom up, we count the watts and miss the kilowatts. I would suggest that a historical trend approach would be more appropriate here. This is an area that I think that IFEP has not helped, since no longer do you have to fix LV prime mover capacity early any more, but you do have to fix HV/LV conversion . Main Ship Services Transformer kWs are inexpensive, and LV systems have redundancy that can double as additional distribution.

There is too much 'Specsmanship' rather than robust engineering when wrestling with QPS. We have shown the ultimate way forward 10 years ago on ESTD and recently on DC Architecture demonstration which fixes QPS so successfully we haven't used it. The same engineers that argue against Electronic derived Vital Supplies, often end up fitting a plethora of more fragile UPS's further down the chain.

Value engineering has too often minimised cost savings and maximised impact. We lost ring Mains, individual Channel CBs on T45, giving us reconfiguration challenges, we lost individual Prop Tx breakers on LPD, giving rise to inrush issues, and we cut out circuit breakers on CVF late on. The authors hypothesis is that removing them has a psychological effect on the single line diagram, which belies the impact.

Late decisions on key requirements like shock and signature, dilutes cost benefit tradeoffs, in and out, in and out, generally tends to leave cost in and takes capability out.

In hindsight T23 Motors are just too small, hybrids need more powerful motors. However more powerful, bigger motors, whilst still retaining gearboxes and additional prime movers, strengthens the case for IFEP.

With respect to electrical modelling, certain parts of the community have too much belief in a single electrical system model. We will never be saved by processing power here, as the power increases, to allow model complexity; the model becomes too difficult to understand. How do you study an elephant? Not in one go, or even one piece at a time, but as a whole, with one piece under a magnifying glass at any one time.

Contracting Lessons

As a community we didn't define and appoint the role of System Integrator very well especially on early projects, the system integrator needs to be the best person/team for the job, and importantly that team often needs to change with the phases of the job.

We failed to align things like fire fighting vs equipment enclosures and UPS requirements. Sometimes these things are not technical oversights, or surprises, but they require not only more global technical ownership and physical integration skills but also incentives to heed concerns voiced, and to pick up the baton.

As a community we perhaps have proactively addressed the big risks, such as SIT, but we have been more reactive and contractual with smaller items, like IP ratings/coolers etc.

We have as yet, failed to bring electric propulsion and modernisation of electrics into the underwater fleet, so the Navy has to continue to support gearboxes, gets less commonality, and loses the economies of scale/sharing of development budgets.

Some key decisions are made behind closed doors without the wider stakeholders. Wider engagement but quick decisions are the key here, otherwise there is the double whammy of potentially uninformed and certainly less bought into choices made here.

As a community we perhaps tried to apply permanent magnet machines too early, we certainly underestimated the size of the converters needed to drive the earlier versions, and now, 15 years later it has made us too cautious? We also don't always realise that Permanent Magnet is an method of removing excitation, its not a machine in its own right, you can have an Advanced Propulsion Motor (APM) with Active Stator and Permanent Magnet technology.

We exploited opportunities to export the spin off technologies, motors, converters, GTs, Switchgear, but not the whole platform. This will require the innovation from the whole community at all levels to succeed, not just the shipyard. Nor should it drive to a certain lowest common denominator technology as some would have us believe.

CVF with its alliancing approach gave a real opportunity to avoid the contractual and fix the technical issues of the past programmes, which as an engineer was both liberating and productive. We do have to recognise however, that saving further money with an alliance approach will prove challenging when the room to innovate is limited by a mature design. It's a Catch 22.

Build Lessons

The physical Integration of IFEP lagged behind the momentum for it, we saw Late Change to LPD from mechanical to electric and from Type 45 to IFEP from hybrid, and it was not really until CVF till we saw a IFEP warship designed from the ground up.

Entrenched standards and modern high power converter equipment collided to give us too much conflict on cabling requirements, installation etc, especially in the areas of EMC and earthing.

Classification Society Involvement has been slow. We seem to have struggled for a decade to combine Naval and classification society approaches. There is much work to do here, especially with Naval rules, as rapidly advancing technology and prescriptive rules are a challenge. We have to help classification societies to be more proactive, and the naval community to be more receptive.

There has been too much ad hoc use of UPSs, and not enough centralised system ride through/auto restart. Most of this type of equipment, is really designed for steady land based power systems feeding 'office' equipment, not variable generation feeding rotating loads.

There is sometimes not enough incentive to make 'no brainer' changes during design and build if not contractually liable, leading to counterproductive 'modify later', at large cost, nature of some early contracts.

Commissioning and Support

We perhaps don't fully recognise that crews observation of system operation during sea trials can become locked in as culture afterwards. These flexible systems, must be flexed by the crew, they are self protecting as we will never be able to try all the permutations during sea trials.

Sea water cooler debates raged, materials vs system flow rate vs particulates/debris vs dosing etc has caused much more wattless energy than mandating more robust units in the first place, to deal with the 'variables' that Naval systems seem to see over commercial ones, from wherever they come.

We seem to consistently use load banks that are too small for effective IFEP commissioning, and sometimes prioritised them wrongly, with too much emphasis on individual generator set, rather than overall system compliance.

We haven't introduced consolidated onboard diagnostics/data recording for analysis, there tends to be adhoc systems in place. There is no technical reason for this; it's financial and timing as these systems are easy targets for late budget cuts.

We never seem to get spares support in place early enough on contracts, this must commence during build and not following the ISD. Like diagnostics, it's not given the up front attention it deserves.

Commissioning time is always squeezed progressively too much throughout the project for whatever reason. Commission in haste, repent at leisure.

Where we were brave?:

- Selection of Hybrid Propulsion for T23;
- Selection of IFEP for LPD in a ships hull designed for a mechanical propulsion fit;
- Direct sea water cooled HV Converters;
- Selection of IFEP for T45;
- Selection of WR21 for T45;
- ESTD System level Derisking and Modelling;
- Realignment of ESTD to T45;
- No Shore test for CVF;
- Power and Propulsion Suballiance for CVF;
- T45 subcontracting for availability.

Where we were too cautious?:

- LV System design, are we HV brave and LV Cautious?
- Link Converters and Zonal Power Supply Units have always worked so well, but we have never adopted them due to risk? Cost?
    - In Hindsight T45 LC+Tx was no more risk or cost than Tx+Active Filter, which delivers fewer benefits.
- Lack of application of energy storage other than at UPS level;
- Failed to exploit the possibility of much relaxed QPS on HV whilst maintaining DEFSTAN on LV.

FUTURE OF IFEP

Technology Trends

We are starting to see permanent magnet machines in the marketplace in increasing numbers, having been slow to pick up, but this will increase, especially in the generator arena.

Superconducting machines which show so much promise that they will probably be the ultimate winner in many applications, always remain tantalisingly 5 years out of reach of being economically viable.

Active Stator Machines, such as the Advanced Propulsion Motor, will come to the fore. In time, it will appear quaint in naval applications to have had separate motors and converters.

Power electronics will continue to increase in reliability and greater performance will reduce number count, and simplify converters.

Direct liquid cooling of electronics, stators and rotors will improve power density, and will include other fluids other than water.

DC Systems remain a likely long term winner, feasible but expensive at LV, so I suspect hybrid LV systems will come first, with inexpensive AC distribution perhaps with a DC backbone for vital supplies. DC at HV is a hearts and minds, rather than a technical issue, can we rely on rectifiers rather than circuit breakers for protection?

Hopefully we will see the graded introduction of Energy store, none for non essential, 4-5 seconds for essential to allow changeovers, 4-5 minutes for vital to ride through damage/blackouts etc.

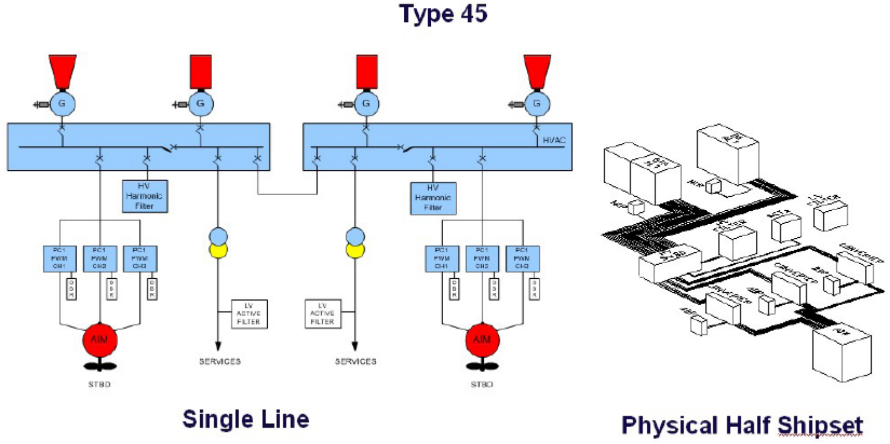

FIG.3 - THE REVOLUTION - T45 AIM AC IFEP

We have had our revolution (fig 3), now we need to evolve, especially in the current climate where there will be more dependence on industrial rather than MoD derisking budgets.

We will probably see a more gradual introduction of technologies, with steps to refine IFEP at the propulsion or generation end perhaps up to that shown in figure 4 with its obvious size and cost advantages. We will need more relevant and co-ordinated road maps to achieve this, consolidating the small steps, rather than the larger strides we have seen in the past.

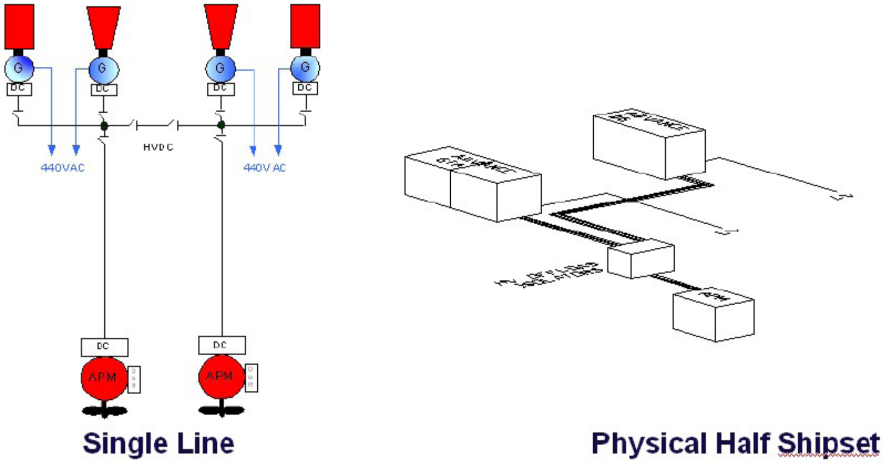

FIG.4 - THE MOST COMPACT FUTURE EVOLUTION? DC ACTIVE STATOR MOTORS AND DUAL WOUND GENERATORS

Potential Evolutionary Steps

The list below, summaries in figure 5 shows what some of the evolutionary steps might be, and if you break it into its component parts, many of them are nearer term and less risk than they might first appear. The other key thing to realise is we may choose to adopt only a few steps along the way on a particular platform, and still realise significant benefit.

1. AC Fed Link Converters (which are no more complex, bulky, expensive or risky than Active filters on T45, but have many QPS advantages) tested 8 yrs ago at ESTD successfully;
2. Energy Store, interfaced very successfully at ESTD and DC architecture Demonstrator. The key here is the time, only 5-10 seconds to allow reconfiguration, with 5 mins blackout Ride through is at ZPSU level;
3. Active Stator Machine Such as APM with various substems:
    a) With AC off machine supply converter, already available;
    b) Or AC on machine supply converter, using same components as Machine Bridge;
    c) Liquid Cooled Rotor (Current Machine);
    d) Or Permanent Magnet Rotor;
    e) Or Superconducting Rotor.

The next 3 steps are closely linked and would be required as a set:

4. HVDC Off Load Disconnect Switches (Available);
5. HVDC Link Converter Fed Variant, (Available Converter, ESTD had DC fed LCs);
6. Off generator AC Fed DC Converter, (Converter Available, foldback employed on DC Architecture Demo, still protected by AC VCM in Converter);
7. Active Stator Generator.

As there was on T45, there will be some contract packaging work of some of the available electronics required as was successfully undertaken on for example, the Active Filter.

Figure 5, physically the smallest and lowest UPC option, and easiest to fit, is less risky than the full DC option, as link converters are replaced by dual wound generators, with an HV and LV winding, so all QPS issues disappear (its as good as an MG set), LCs and Active and Passive Filters are not required either, but there are a few functional nuances to consider.

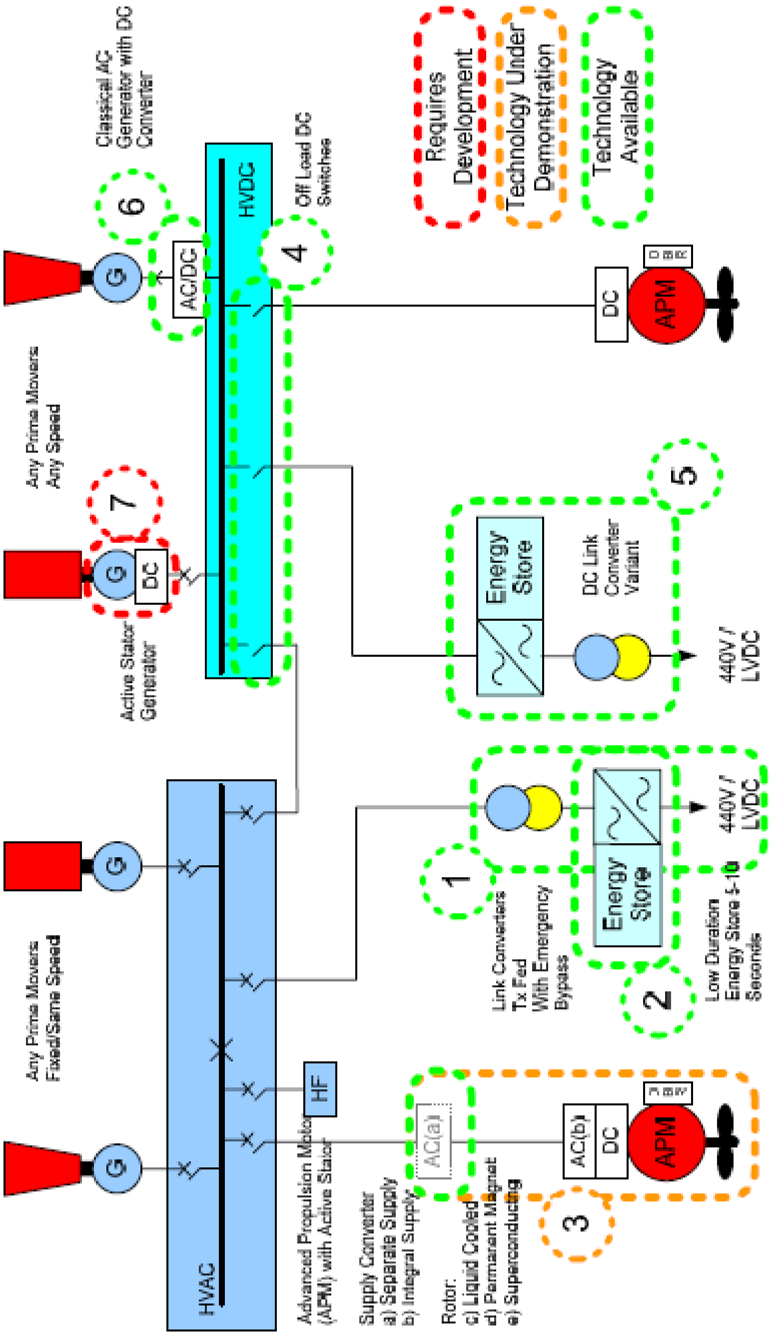

FIG.5 - EVOLUTIONARY STEPS FROM T45 TO FULL DC IFEP

Can a return to gearboxes, controllable pitched propellers, separate propulsion and generation and less flexible systems be realistically contemplated? some things should be left in the 80's. The commercial world is electrifying at electrifying speed, gearboxes continue to be driven away from all industries, just look at wind turbines, perhaps the answer really is blowing in the wind?

System, Not Equipment Requirements

Purist top down requirement approaches are as wrong as equipment driven bottom up approaches. But where the art of the possible, meets the functional, and aligns with the world trends, good things happen. Get obsessed with what the products deliver, not what they are, this is the system engineering approach.

Full Electric Propulsion is by its nature an integrated system, what will the system requirements be? Permanent Magnet, Superconducting are just subcomponents of technologies that will evolve, we need to ask wider more practical questions on future platforms.

- How will LV be Derived?
- What QPS do we really want and to which consumers?
- Which supplies should we back up, for how long, and using which energy storage?
- What redundancy will we require in the propulsion drive train?
- What pattern of prime movers fit best?
- Is High or Low Voltage more appropriate?
- Is AC or DC more appropriate to the propulsion technology/LV architecture?
- Hybrid or IFEP?

None of these are equipment questions, they are system questions, and the best way to answer them is not to draw out equipments and see what the resulting functionality might be but to decide which questions are can be addressed in isolation, which have dependencies, and write specific practical requirements/drivers for each. Then a much smaller list of practical options will result.

Personal Highlights

- Ability to align industrial and MoD requirements;
- Working hand in hand with talented engineers whether competitors, the Royal Navy or shipbuilders;
- Late nights commissioning at sea;

- Pushing technology forward and leading the world;
- Bringing Induction Motor Drives at HV into being, now a standard industrial offer;
- Collaboration with our US colleagues;
- Full Power at ESTD and T45 Back to Back for the first time;
- First on shore Full Power Crash Reversal at ESTD;
- First Sea trials on T45;
- DC Architecture Demonstration.

Final Conclusions

The revolution will continue to evolve. Sail to steam, coal to oil, steam to GTs, Hybrid Electric, Full Electric, Active Stators, AC to DC, Superconducting machines.

We must be careful that we don't become too risk averse. We tend to manage the risks we identify quite well. Some of these evolutionary steps are available now, and others are small steps that can be taken individually. We should also benchmark our evolution by looking for the inevitable trends outside the naval arena.

There are few true surprises, a 'lesson learnt' is normally an opportunity missed due to a voice ignored.

Value engineering is not just about saving money, it's about maintaining or increasing value, by reducing costs faster than benefits. High end industrial companies are good at this, let them do it, innovation headroom is important and reduces rather than increases risk.

In the UK Naval sector, industrial infighting is Watt less energy. When suppliers, shipbuilders and the MoD/RN, sit down and not only see what they contribute, but realise where their prejudices impede, then good things happen.

Electrification and the replacement of mechanicals by electronics is inevitable, as we climb this ladder, progress is not linear, we may pause on certain rungs, but backward steps are always backward steps.

GLOSSARY

AIM	– Advanced Induction Motor
AO	– Auxiliary Oilers for the RFA 'Wave' Class
APM	– Advanced Propulsion Motor
CODLAG	– Combined Diesel Electric and Gas Type 23 Hybrid Propulsion System

CPP	– Controllable Pitch Propeller
CVF	– Future Aircraft Carrier, now designated 'Queen Elizabeth Class'
DEFSTAN	– Defence Standard
DG	– Diesel Generator
ESTD	– Electric Ship Technology Demonstrator Test Site
FAT	– Factory Acceptance Test
GT	– Gas Turbine
GTA	– Gas Turbine Alternator
HV	– High Voltage (Defined by RN as > 1000Vac)
IFEP	– Integrated Full Electric Propulsion
IPS	– Integrated Power System Programme in the US
LC	– Link Converter
LPD	– Landing Platform Docks for the RN 'Albion' Class
LV	– Low Voltage
MG	– Motor Generator Set
OEM	– Original Equipment Manufacturer
P&P	– Power and Propulsion
PMPM	– Permanent Magnet Propulsion Motor Contract
QEC	– Queen Elizabeth Class aircraft carrier, formerly CVF
QPS	– Quality of Power Supply
T45	– Type 45 Destroyer 'Daring' Class.
T23	– Type 23 Frigate 'Duke' Class
Tx	– Transformer
UPC	– Unit Production Cost
UPS	– Uninterruptible Power Supply
WR21	– Advanced Gas Turbine selected for T45