MVDC AND HFAC ELECTRIC POWER SYSTEM ARCHITECTURES FOR THE TRANSFORMABLE SEA BASE CONNECTOR (T-CRAFT)

By:

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11th International Conference on Fast Sea Transportation FAST 2011, Honolulu, Hawaii, USA, 26-29 September 2011

PR 517

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11th International Conference on Fast Sea Transportation
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MVDC and HFAC Electric Power System Architectures for the Transformable Sea Base Connector (T-Craft)

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ABSTRACT

The paper presents high frequency ac (HFAC) and medium voltage dc (MVDC) power system architectures for a notional T-Craft concept design and provides a qualitative comparison of relevant performance parameters. In particular the following items are discussed as worthy of attention in view of the large potential benefits they could produce:

- Risk mitigation in operating multiple series and parallel connected power conversion modules for both rectification and inversion at multi-megawatt power levels and high peak operating frequency.
- Synchronous drive topology offering the potential benefit of eliminating the need for multi-megawatt power conversion without compromising capabilities or performance: this would significantly reduce risk by eliminating much of the power electronics and the attendant size, weight and cost.
- Circuit protection strategies and components, for either HFAC or MVDC, for a flexible architecture suitable for fault management and reconfiguration.
- Integration of compact, lightweight gearboxes, either conventional planetary or advanced magnetic gear type, with existing designs for high-speed motors at the power level required by T-Craft.

Critical technical issues for each power system architecture are identified and proposed simulation and technology development activities are described.

KEY WORDS

T-Craft, HFAC, MVDC, transformable craft

1.0 INTRODUCTION

The Sea Base Connector Transformable Craft (T-Craft) Program is an ONR Innovative Naval Prototype Program (BAA05-020) to develop designs for a novel craft envisioned to have three primary modes of operation:

- Fuel-efficient, good sea keeping mode for open ocean transits
- High-speed, shallow water mode
- Amphibious mode to enable “feet dry on the beach” capability

T-Craft designs developed by contractor teams to meet the specified performance and capabilities for the three operating modes all featured Surface Effect Ship (SES) hullforms with common propulsion system elements. Advanced waterjets were used with SES bow and stern seals and lift fans for open ocean transit and high speed shallow water operation transitioning to a fully skirted Air Cushion Vehicle (ACV) mode with air propellers for amphibious operation. Each of the operating modes imposes different requirements on the propulsion power system, driving the need for a flexible power distribution architecture that takes full advantage of the installed prime mover power, provides reliability and redundancy, and facilitates the transition between operating modes.

2.0 Notional Propulsion System

In addition to modest auxiliary and hotel loads, there are three separate propulsion subsystems that drive the power requirements for the T-Craft: waterjets, lift fans, and air propellers. To enable comparison of Medium Voltage Direct Current (MVDC) and High Frequency Alternating Current (HFAC) power system architectures a notional T-Craft propulsion system was developed. Table 1 summarizes the propulsion power requirements for each of the three primary operating modes of the notional T-Craft design and Figure 1 shows the schematic layout of the propulsion system in the two hulls.

Table 1. Operating mode propulsion power requirements for the notional T-Craft design

Operating Mode	Water Jets	Air Screws	Lift Fans	Total Power
Long Range Transit	18 MW	0 MW	4 MW	22 MW
High Speed Connector	32 MW	0 MW	6 MW	38 MW
Air Cushion Vehicle	0 MW	20 MW	8 MW	28 MW

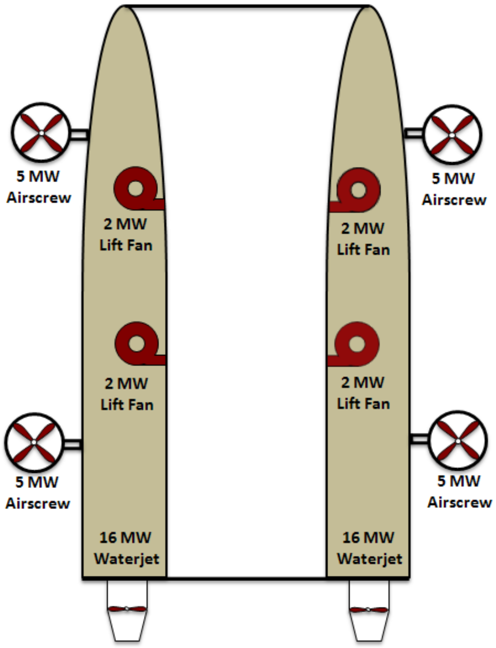

Fig. 1. Notional T-Craft propulsion system

To enable comparisons between the power distribution architectures, representative volumetric and gravimetric power densities and efficiencies were assumed for the power conversion elements. Elements common to both architectures – e.g. gearboxes and LM2500 gas turbines – were not considered in the comparison. Table 2 lists the propulsion system elements and summarizes the size and efficiency ratings used for comparison between the power distribution architectures.

Table 2. System element power density and efficiencies

Electric Propulsion Element	Power Density [MW/m^3]	Specific Power [kW/kg]	Efficiency [%]
Bi-directional Power Converter	0.88	1.25	97.5
Variable Frequency Drive	0.95	1.35	97.5
Inverter	1.19	1.7	98.5
High Speed Generator[2]	1.9	1.07	96.8

3.0 Propulsion System Topologies

There are a variety of approaches to provide the propulsion power requirements for the T-Craft including all mechanical systems. Fully mechanical systems tend to have larger total installed power to meet the propulsion system loads and power distribution between hulls (for redundancy or more efficient use of prime movers) is difficult. For the notional system above, the most basic mechanical propulsion system would have each load served by a dedicated prime mover. For example, each waterjet could be powered with a General Electric LM2500 gas turbine, each lift fan by a Vericor TF40 and each air screw by an Allison 501 gas turbine. This arrangement results in a total installed power of 76 MW to serve a peak load of only 38 MW. If we define a prime power utilization factor $P_{primeuse}$:

$$Pprimeuse = \frac{Peak\ \ Load}{Installed\ \ Power} \times 100 \qquad (1)$$

This translates into a prime mover utilization factor of only 50% for an all-mechanical system.

Although all-electric systems – with either ac or dc distribution -- are also feasible, these architectures tend to have lower overall efficiency and are heavier than the all-mechanical or hybrid-electric systems. The 16 MW variable frequency drives (VFD's), motors and gearboxes to match the relatively low speed of the waterjets (typically on the order of 500 rpm) would be larger and heavier than a comparable mechanical driveline.

Hybrid-electric systems provide a more optimal solution, allowing the largest single loads –16 MW to each waterjet during high speed connector mode -- to be driven mechanically from the LM2500 through a speed reduction gearbox. A high speed electric motor/generator can be driven from a power take off pad on the waterjet gearbox to supply power to the lift fans and air screws. A potential candidate for the propulsion motor/generator is the 7,000 rpm, 14 MW high speed generator currently being tested at the Land Based Test Site (LBTS) in Philadelphia (Calfo, et. Al 2007). Fig. 2 shows one version of a hybrid-electric propulsion system for the notional T-Craft. This hybrid-electric topology will be considered the baseline for evaluation of MVDC and HFAC power distribution architectures.

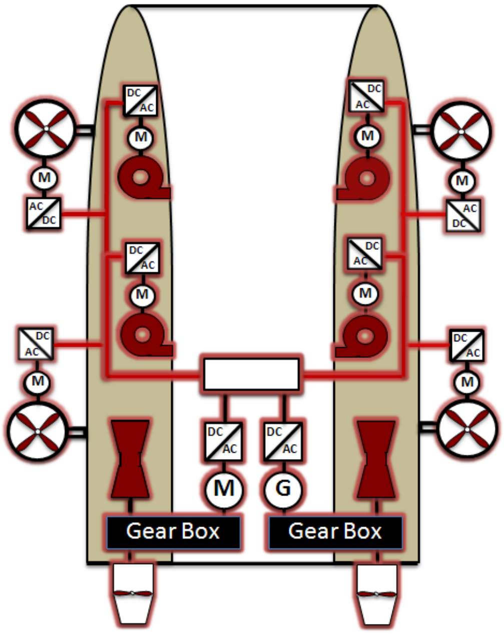

Fig. 2. Hybrid-electric MVDC propulsion system

3.1 MVDC Architecture

The block diagram shown in Figure 2 reflects MVDC architecture with power from the gearbox driven high speed generator rectified and fed to the dc distribution bus. Active bi-directional converters are used between the electric machines and the dc distribution bus to enable fault current limiting and allow for propulsion cross-connect during the long range transit mission profile. In this operating mode, a single LM2500 provides the mission power requirements, driving the mated high speed electric machine as a generator to feed power to the dc bus. The second electric machine is driven as a variable speed motor through the bi-directional converter to power the waterjet in the other hull. This configuration minimizes the specific fuel consumption of the LM2500 by allowing it to run at rated power and minimizes the operating hours on the gas turbines, extending their life and reducing maintenance requirements.

The remaining lift fan and air screw drive motors are driven through variable frequency dc-ac inverters. A central power distribution module allows for transfer of power from either hull, increasing reliability and distributing operating hours on the two main prime movers.

For this configuration, the prime power utilization factor is:

$$Pprimeuse = \frac{38\ MW}{44\ MW} = 86.4\%$$

The higher prime power utilization factor illustrates one of the significant benefits of electric or hybrid electric power architectures –more effective use of the installed prime movers enabled by the flexibility of the electric power distribution.

Using the figures in Table 2, an overall efficiency of 92.9% can be calculated from the gas turbine gearbox output to the lift fan and air screw loads. Table 3 shows the estimated weight and volume of the power conversion components for the MVDC distribution system.

Table 3. MVDC power conversion component weight and volume estimates

MVDC System	Qty.	Power [MW]	Volume $[m^3]$	Weight [kg]
Bi-directional Converter	2	14	31.82	22400
Air Screw dc-ac Inverter	4	5	16.81	11765
Lift Fan dc-ac Inverter	4	2	6.72	4706
Totals			55.35	38871

3.2 HFAC Architecture

Figure 3 shows a block diagram of a hybrid electric propulsion system with HFAC distribution architecture. In this system, the two gearbox driven high speed electric machines feed the high frequency ac distribution bus. A single large bi-directional VFD is used between the motor/generators for propulsion cross connect to ensure positive control of the driven motor with the potential for severe transient loads seen by the waterjets. An isolation switch is used to isolate the two halves of the power system, effectively avoiding the need for active synchronization of the frequencies of the two generators. In addition to the propulsion cross connect VFD, conventional variable frequency drives with an internal dc link are used for variable speed operation of the lift fans and air screws.

For this configuration, the prime power utilization factor is also:

$$Pprimeuse = \frac{38\ MW}{44\ MW} = 86.4\%$$

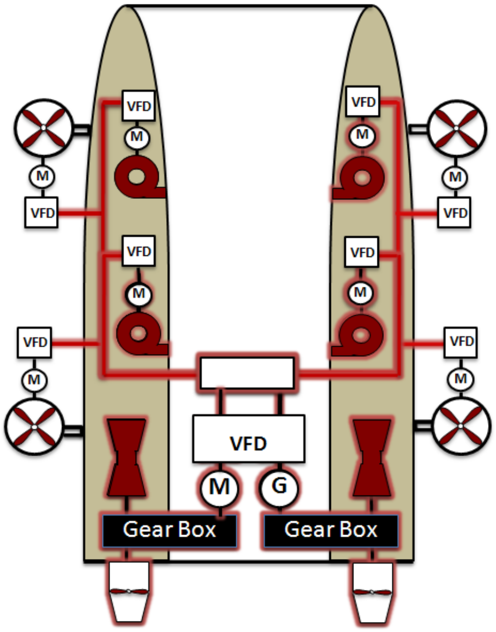

Fig. 3. Hybrid-electric HFAC propulsion system

Using the figures in Table 2, an overall efficiency of 92.0% can be calculated from the gas turbine gearbox output to the lift fan and air screw loads. Table 4 shows the estimated weight and volume of the power conversion components for the HFAC distribution system.

Table 4. HFAC power conversion component weight and volume estimates

HFAC System	Qty.	Power	Volume	Weight
		[MW]	$[m^3]$	[kg]
Bi-directional Converter	1	14	15.91	11200
Air Screw VFD	4	5	21.05	14815
Lift Fan VFD	4	2	8.42	5926
Totals			45.38	31941

3.3 Synchronous Drive Architecture

A variant of the HFAC architecture also considered for the T-Craft uses fixed speed synchronous drive of the air screw motors, eliminating the need for four 5 MW VFD's in the system. Figure 4 shows the HFAC architecture with synchronous drive of the air screws.

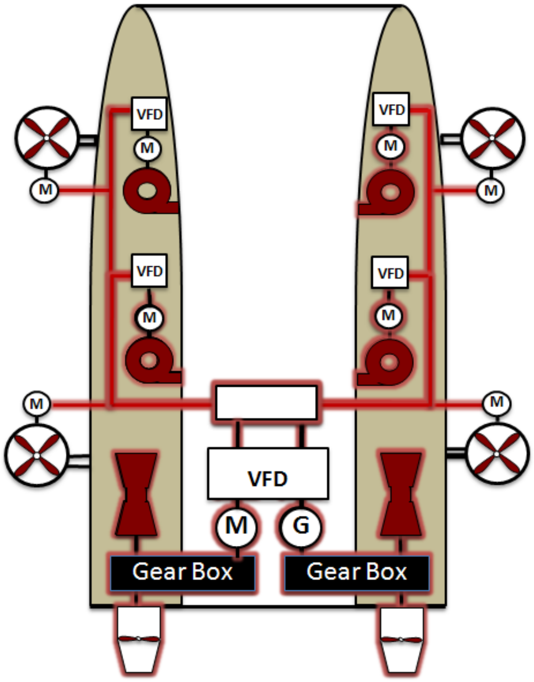

Fig. 4. Hybrid-electric HFAC propulsion system with synchronous drive of air screws.

Because the lift fans are fixed volume centrifugal blowers it will likely be necessary to retain the four 2 MW VFD's for controlled variable speed operation of the lift fans, especially if active ride control systems are employed. The use of controllable pitch propellers is a requirement for this mode of operation since all four air screws would operate at the same speed. Operation of the air screw motors in this mode is analogous to across-the-line start of conventional motors from the 60 Hz utility grid. The air screws are only used during amphibious operation in air cushion vehicle (ACV) mode which is only a small fraction (~5%) of the overall T-Craft mission profile. Synchronous operation would eliminate heavy, expensive power conversion equipment that is not effectively used in the T-Craft application. Table 5 shows the estimated weight and volume of the power conversion components for the HFAC system with synchronous drive of the air screws.

Table 5. HFAC with synchronous drive power conversion component weight and volume estimates

Synchronous System	Qty.	Power	Volume	Weight
		[MW]	[m^3]	[kg]
Bi-directional Converter	1	28	31.82	22400
Lift Fan VFD	4	2	8.42	5926
Totals			24.33	17126

Start up of the air screw motors would take place sequentially during the transition between high speed connector and amphibious mode, potentially enabling the initial start up and synchronization of the four motors to take place with lower voltage and frequency on the ac distribution bus. The air screws also represent "soft" loads, with no rapid transients or step load changes as could be seen with the waerjets under broaching conditions. As an initial evaluation of this concept, UT-CEM performed simulations of the start of a notional 8 MW synchronous permanent magnet machine. Figure 5-7 shows the per-unit line-to-line voltage, line current and line power during start up of the permanent magnet motor; the transients are quite manageable.

The qualitative comparison of the three power distribution systems favors the HFAC system with synchronous drive of the four air screws. HFAC with synchronous drive system is about 55% smaller and lighter than the baseline MVDC and 45% smaller and lighter than the baseline HFAC systems. This is especially significant because of the short duration of the amphibious operating mode – the weight savings will result in fuel savings spread over the majority of the mission profile.

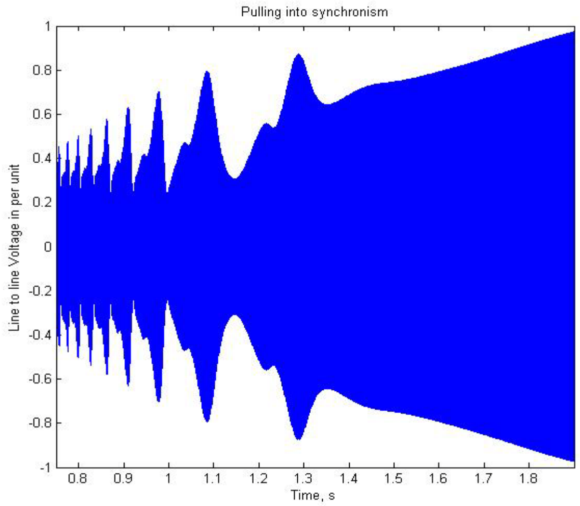

Fig. 5. Line to line voltage during synchronization and start up of a notional 8 MW permanent magnet motor

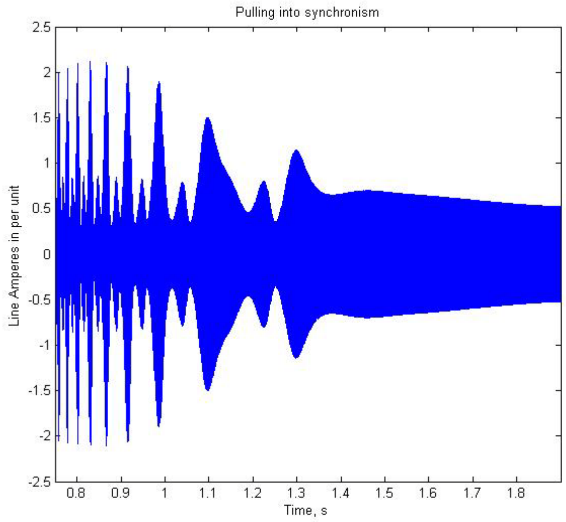

Fig. 6. Line current during synchronization and start up of a notional 8 MW permanent magnet motor

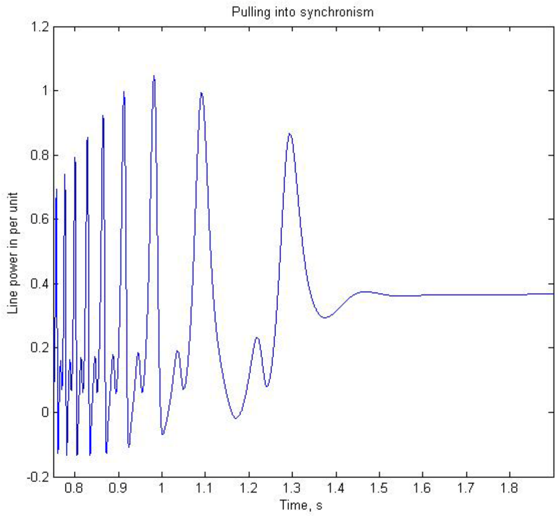

Fig. 7. Power transients during synchronization and start up of a notional 8 MW synchronous PM motor

4.0 Power Conversion Interactions

The MVDC and HFAC architectures presented here use both series and parallel connected power conversion modules at megawatt power levels. A concern with islanded high power distribution systems with multiple dynamic loads is the potential for instabilities caused by the interaction of the interconnected power conversion modules. Both systems also use high speed generators with the associated high frequency ac fed to at least some of the power conversion modules. This is of particular concern with the HFAC synchronous drive system because there is no active control of the air screws on this portion of the HFAC distribution bus. High fidelity simulation of this system is required to assess the likelihood and impact of instabilities in this system, including the dynamic loads from the controllable pitch air screws and VFD driven lift fan loads.

Although bus instabilities have been observed in MVDC systems, they can be controlled through the use of active rectifiers – which are likely needed to limit fault currents anyway – or through control of the field excitation on the high speed generators. UT-CEM has modeled the use of field control to manage bus instabilities in dc systems with passive rectifiers. Figure 5 shows an example of active field control of two wound field synchronous generators. The first plot shows the oscillations of generator and dc bus power without active control; the second plot shows the system under active control of the generator field excitation.

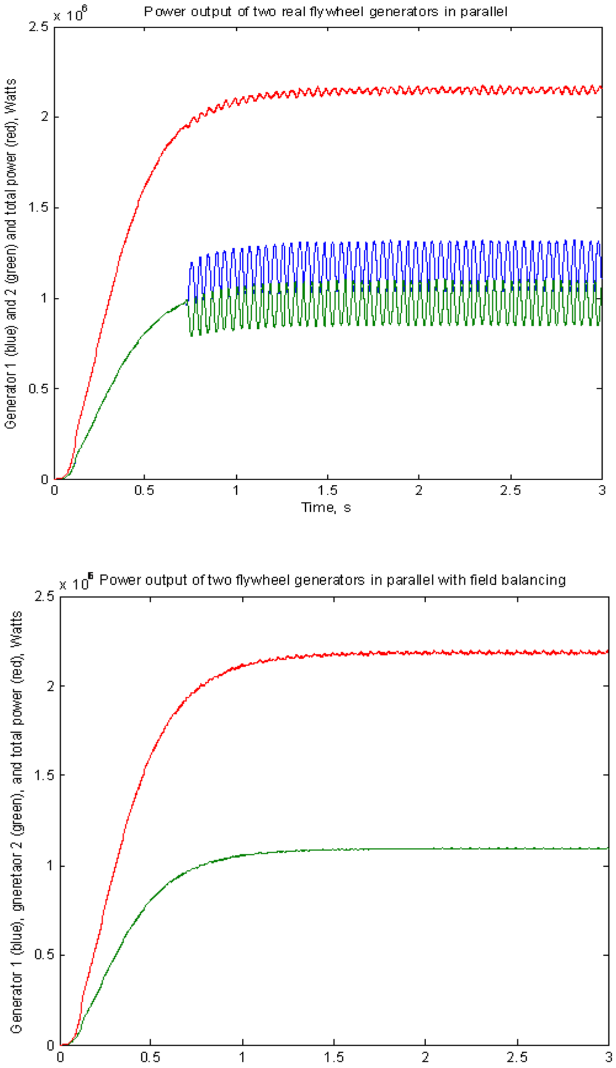

Fig. 8. Example of active field excitation control to manage instabilities on a dc distribution bus

Great care will have to be taken to ensure that the system of series and parallel connected power conversion equipment can be operated reliably and safely throughout the T-Craft mission profile.

5.0 Circuit Protection

Circuit protection is a critical issue in high power islanded power systems and research into circuit protection for MVDC distribution systems is underway at several organizations within the Electric Ship Research and Development Consortium (ESRDC). The challenge is interruption of high currents in high power dc systems with no inherent current and voltage zero crossings to help extinguish arcs drawn as the circuit opens. Multiple approaches are being evaluated, including the use of active rectification to allow for fault current limiting and transient shutdown of the dc bus for switching and reconfiguration.

Significant research and component testing has also been conducted into the use of conventional circuit protection equipment designed for operation at 60 Hz on higher frequency ac distribution systems. The 60 Hz components must typically be de-rated for the higher frequency service, but the equipment should operate reliably in the higher frequency systems with some reduction in capacity if the frequency is not too high.

Interestingly, it is easier to find information on the de-rating of 60 Hz high power breakers for use in dc systems than for use in systems with frequency higher than 60 Hz. This is probably due to the fact that dc power equipment has always been used whereas high power equipment operating at frequencies larger than 60 Hz is a relatively new development. The case of aircraft components operating on 400 Hz systems is an exception, but it is also one that is limited to relatively small power ratings far from the MW class under consideration here.

In both cases of MVDC and HFAC, the de-rating is a function of multiple variables. For example, if the use of a thermal-magnetic breaker is considered, one must arrive at a separate de-rating factor for each of the following:

a. Thermal performance
b. Magnetic performance
c. Current interrupting capacity

Furthermore, attention must be paid to the performance of all the auxiliary circuitry that ensures proper operation of the breaker (e.g. any sensing circuit) in the new operational mode (Schneider, Eaton 2011).

The issue of circuit protection is a serious one that deserves careful consideration. It is revealing of the present status of technology readiness level that a request for quote in January of 2011 for a circuit breaker rated 8 MW and suitable for use on 200 Hz resulted in a negative response from all major potential suppliers.

6.0 Cable Size and Weight

The issue of cable size and weight within the context of a decision in favor of HFAC or MVDC distribution has received a lot of attention (e.g. Pekarek et.al, 2011 and Robinson et.al 2010). At its most basic level, the issue can be looked at as follows: given the need to transfer a given power P over a distribution system, at a system voltage V, what is the relative size and weight of a dc versus an ac system? Thus:

$$\begin{aligned} dc\ power = V_{dc} I_{dc} = P = ac\ power \\ = \sqrt{3}\, V_{ac} I_{ac} \cos\varphi \end{aligned} \qquad (2)$$

where

V_{dc} = rail-to-rail voltage in dc system
I_{dc} = current in each conductor (two needed) in the dc system
V_{ac} =line-to-line voltage in ac system
sI_{ac} = current in each conductor (three needed) in ac system
$cos\varphi$ = ac system power factor

Assuming the need to maintain an equal current density J in the conductors of the two systems (this is commonly referred to as the "ampacity" of the cables), if S_{dc} and S_{ac} are respectively the effective cross sectional areas of the dc and ac cables, we can write the previous equation as follows:

$$V_{dc} J S_{dc} = \sqrt{3}\, V_{ac} J S_{ac} \cos\varphi \qquad (3)$$

If we introduce now the following:

α = coefficient to account for loss of conduction area in ac system due to skin depth effect ($\alpha < 1$)
A_{dc} = total cross sectional area of dc cables = $2S_{dc}$
A_{ac} = total cross sectional area of ac cables = $3S_{ac} / \alpha$

We obtain the following relationship between the total cross sectional areas in the two systems:

$$\frac{A_{dc}}{A_{ac}} = \frac{V_{ac}}{V_{dc}} \left(\frac{2\alpha \cos\varphi}{\sqrt{3}} \right) \qquad (4)$$

Since the length of the cables is the same, this ratio will determine also the ratio of size and weight between the two systems. The following considerations can now be made:

- The voltage ratio may be taken to be essentially equal to one, since there is no intrinsic reason why a dc system could be realized with a higher voltage than an ac system or vice-versa.
- Everything, then, depends on the term in parenthesis, which, depending on the value of the product $\alpha\ cos\varphi$, can swing from being greater than one to being less

than one, thus favoring respectively the ac or the dc system. This is particularly important today when not only passive but also active power factor correction methods have become commonplace.

- The skin effect coefficient α will depend on the chosen line frequency. This, however, expands the considerations to the global system and to the other benefits of using higher frequency (e.g. size reductions of other components) even if at the cost of larger distribution conductors due to skin depth issues.

Remaining within the strict confines of the size of distribution conductors, it would seem that the formula derived above gives the dc system an advantage. For any reasonable frequency increase over the standard 60 Hz, the factor α becomes quickly small enough that $A_{dc} < A_{ac}$.

This seems to be the conclusion reached by several groups that have been evaluating these issues in the last few years. For example, a dc distribution system seems to be preferred by people working on subsea power systems for oil and gas extraction (Asplund 2008). In fact, while some of the comparisons reported by industry are quite startling and decisively favor dc distribution (Heyman, 2010) a dc based system can generally be expected to save probably from 25% up to possibly 50% of the cable weight of its ac counterpart. Figure 9 shows a comparison of ac and dc cables done by ABB; note that two dc cables and three ac cables would be required for the transmission system.

Fig. 9. Comparison of ac and dc cable cross sections from ABB.

The above considerations, however, should always keep in mind the different perspectives between a static subsea installation long hundreds of miles and that aboard a ship, subject to dynamic mechanical stresses and only a few hundred feet long. Furthermore, cable size is only one term of a multi-element optimization procedure that must take into account many other system issues of a more global nature (e.g. protection schemes, etc.).

7.0 Summary and Conclusions

A qualitative comparison of MVDC and HFAC hybrid-electric power distribution architectures has been presented, including a synchronous drive variant of the HFAC system. When compared with all mechanical drive systems with a dedicated prime mover for each propulsion system load, the hybrid electric power distribution architectures are significantly more effective in using the installed prime power. This illustrates one of the key advantages of Integrated Power Systems – the ability to redirect power to efficiently serve a variety of loads distributed throughout the ship.

The power conversion equipment for the HFAC architecture is smaller and lighter than that required for the MVDC system, primarily due to the need for a second 14 MW converter on the output of the high speed generator in the MVDC architecture. The use of synchronous drive for the air screws further reduces the size and weight of the power conversion equipment for the HFAC architecture.

Consideration of circuit protection also tends to favor the HFAC architectures. The use of de-rated 60 Hz equipment enables well proven, conventional approaches to circuit protection with a relatively small penalty (~20%) in size and weight of the circuit protection components. Circuit protection in MVDC systems is still the subject of significant research with the attendant uncertainty in the configuration of the final system.

Cable size and weight appears to decisively favor the MVDC architecture; however, the use of active power factor correction can mitigate the difference between the two systems.

In conclusion, an initial qualitative comparison of power distribution architectures for the notional T-Craft propulsion system presented here favors an HFAC system with synchronous drive of the four 5 MW air screw motors. The power conversion equipment for this configuration is approximately 50% smaller and lighter than the comparable MVDC or baseline HFAC architecture. High fidelity simulation of this topology for an actual T-Craft propulsion system will be required for a more rigorous evaluation of the power system stability and performance. A more rigorous evaluation of the cable size and weight of the two architectures is also recommended to quantify the “penalty” associated with operation at higher frequencies.

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ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the support of the Office of Naval Research and the ONR T-Craft Program Manager, Kelly Cooper, for their support of this research.