# DESIGN AND ANALYSIS OF A 20 MW PROPULSION POWER TRAIN

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# Design and analysis of a 20 MW propulsion power train

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The electric ship research program at the University of Texas at Austin focuses on the development of power system technology for future electric ships. The main goal of the on-going research activity is to identify critical, high pay-off technology development needed to enable major improvement, in size and functionality, of navy ships power systems. Initial efforts were directed towards the establishment of a baseline power train which highlights various constraints and provides a basis for later optimization efforts. A 20 MW power train system was chosen for such a baseline, and all components, from fuel to propulsion motor, were considered and their impact on the whole power system assessed. The baseline design consists of a 25 MVA/3600 rpm radial flux permanent magnet generator, a 22 MVA PWM converter, and a 20 MW/150 rpm radial flux permanent magnet motor, along with the amount of fuel sized for an assumed mission profile, and the widely used LM2500 gas turbine. The analysis shows that fuel is by far the dominant component contributing to weight and volume and, consequently, overall efficiency of power train components is the most relevant parameter to reduce weight and volume. The 3600 rpm generator is the smallest component. The 150 rpm motor is the heaviest component, other than fuel, weighing close to 100 tonnes.

## INTRODUCTION

The integration of electrical power on board future navy ships represents a major challenge that requires a significant improvement of present-day shipboard power systems as well as development of new technologies. The incorporation of electric propulsion within a single power system is perhaps the most stringent requirement for a successfully integrated power system. Other challenges include the integration of ship service loads, high power loads, and most likely, energy storage. While the advantages of an integrated power system are well recognized, issues that need to be addressed, in order to achieve such advantages, include power density, efficiency, stability, re-configurability, thermal management, as well as mechanical performance. The aim of the research effort at the University of Texas is to provide tools that can help guide the design of integrated power systems of future electric ships.

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**Authors' biographies**

Dr. Joe Beno has BS and MS degrees in engineering physics and a PhD in electrical engineering. He is an Associate Director at the U.T Center for Electromechanics where he leads programs in electric vehicles, electric ship technology, and advanced vehicular suspension systems.

Dr. Mark Flynn obtained his PhD, MS, and BS degrees in electrical engineering from the University of Texas at Austin. His work concentration is in power electronics and motor drives.

Mr. Richard Hayes received his BSME from the University of Texas in 1980 and worked on generator design and manufacturing prior to joining CEM in 1986. While at CEM he has worked primarily on electric gun and energy storage technology.

Dr. Robert Hebner has a PhD in physics and is currently serving as the Director of the Center for Electromechanics at the University of Texas at Austin. He is a past president of the IEEE Dielectrics and Electrical Insulation Society, a fellow of the IEEE, and has published extensively in the field of electrical insulation.

Mr. Rex Jackson has been a technical staff associate at the University of Texas at Austin since 1986.

Dr. Hamid Ouroua obtained his PhD, MS, and BS degrees in physics from the University of Texas, University of California at Los Angeles, and University of Algiers respectively. His work concentration is in EM design and analysis of electric machines.

Dr. Mark Pichot received BS and MS degrees in mechanical engineering, and a PhD in electrical engineering, all from the University of Texas at Austin. His work concentration is in design of high-speed rotating machinery.

Ms. Emily Schroeder has a Bachelor of Science degree in mechanical engineering from the University of Texas. Her work includes thermal management, component integration, and motor/generator fabrication.

Mr. Joseph Zierer has BS and MS degrees in mechanical engineering from Texas A&M University. His work concentration is in mechanical analysis of rotating machines.

Mr. Damon Weeks obtained his MSE and BSEE degrees in engineering from the University of Texas at Austin. His work concentration is in modeling and verification of EM systems.

Our initial task was geared towards understanding parts of the power system that constitute the propulsion power train while deferring issues associated with ship services and other auxiliary loads to future studies. The goal of this task is to help identify critical, high pay-off technology needs that enable a major improvement in the propulsion power train size and functionality.

The primary components of the propulsion power train are a prime mover with fuel, a generator, a converter, and a propulsion motor. A block diagram of a generic power train is shown in Fig 1.

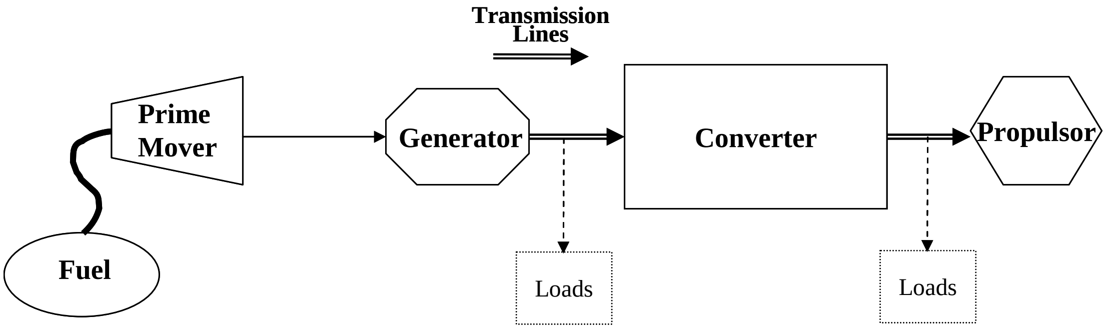


Fig 1: Block diagram of a generic power train.

The main considerations for this research activity were:

- Establish a reasonable baseline system volume and mass for future comparisons
- Guide the selection of high payoff technologies for further investigation and development
- Develop an understanding of  issues and design drivers
- Develop an understanding of the impact of subsystem design choices on overall power system

## SELECTION OF POWER TRAIN COMPONENTS

The approach to establishing a baseline power train system was to focus on “good choices” of current technology rather than existing hardware or anticipated future technologies that are not yet developed.  The only exception was the selection of  the prime mover where the LM2500 gas turbine was chosen for its wide use in present navy ships. This approach permits the baseline to be current state-of-the-art technology even though it has not yet been tested in service, as a system, at the 20 MW power level. The range of options available for component choice is summarized in Fig 2.

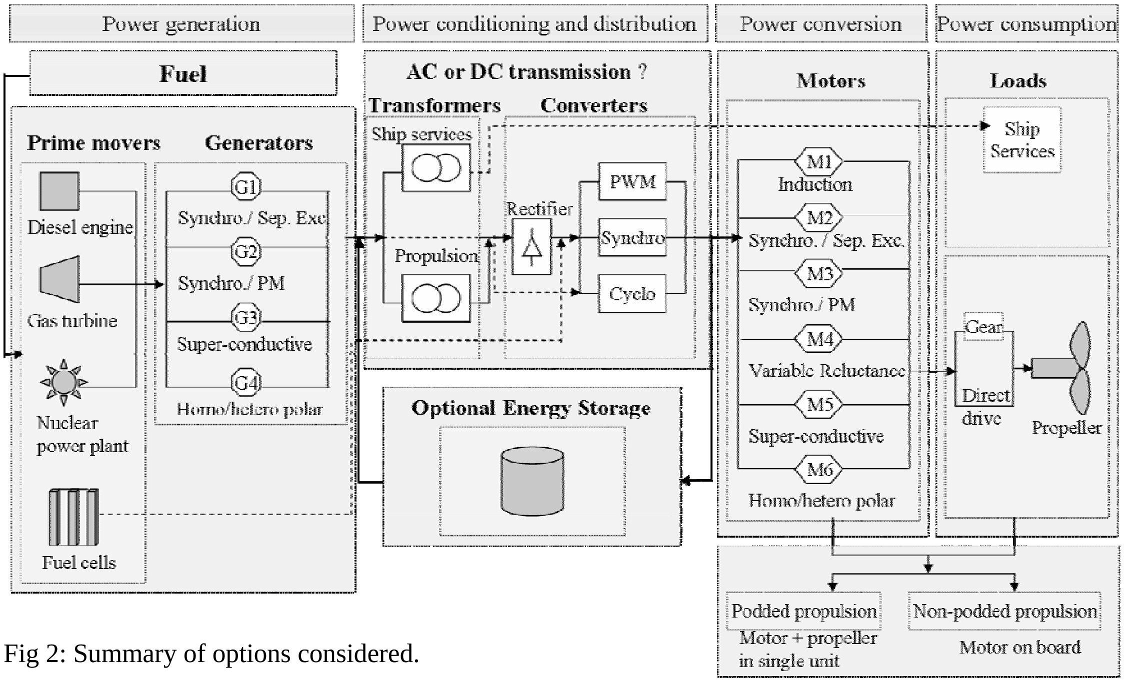


Fig 2: Summary of options considered.

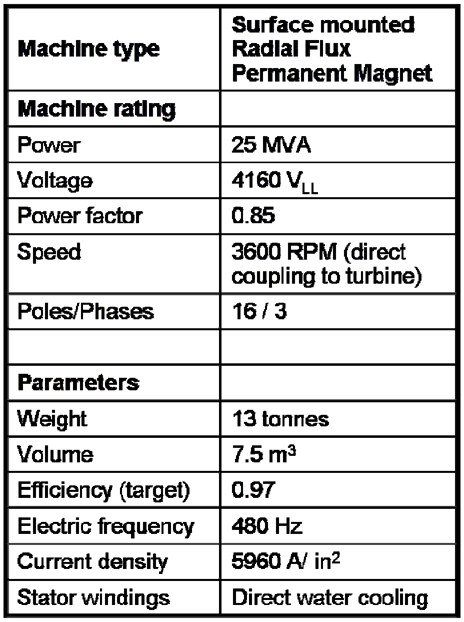
As can be seen in Fig 2, combinations of various components result in a very large number of possible power trains. The power train selected consists of a gas turbine, a radial-flux permanent-magnet synchronous generator directly coupled to the gas turbine (no gear box), a rectifier and PWM inverter, and a 150 rpm radial-flux permanent-magnet motor for onboard use, in contrast to podded permanent-magnet motors used on some modern cruise ships.

## FUEL AND PRIME MOVER

Fuel accounts for about 20% of the displacement of a naval vessel. A key implication is that any effort to reduce the size and weight of any power train component at the detriment of efficiency is likely to be unacceptable from a system perspective. Efficiency is, therefore, a key factor in choosing the prime mover. Diesel engines and gas turbines are the main prime power sources used in present-day ships. The advantages of diesel engines are that their technology is well-established, and an efficiency that is less sensitive to load variations as compared to gas turbines. Gas turbines, however, generate more power per unit volume and unit weight than diesel engines. Since high power density is a major goal, a gas turbine was chosen. Once this choice was made, two additional questions were examined. The first was a preliminary look at the implications of choosing various sizes of gas turbines and the second was a similar look at the feasibility of mating a gas turbine with a fuel cell to increase fuel efficiency and to use heat that would otherwise be wasted. In summary, it was found that a turbine optimization with both small and large turbines provides substantial reduction in prime power volume [1]. For the hybrid systems, consisting of fuel cells and gas turbines, it was found that the most efficient system, at the 20 MW level, would require an extremely large fuel cell and, as a result, research that aims to reduce the size of a 20 MW fuel cell may have high payoff for future naval applications.

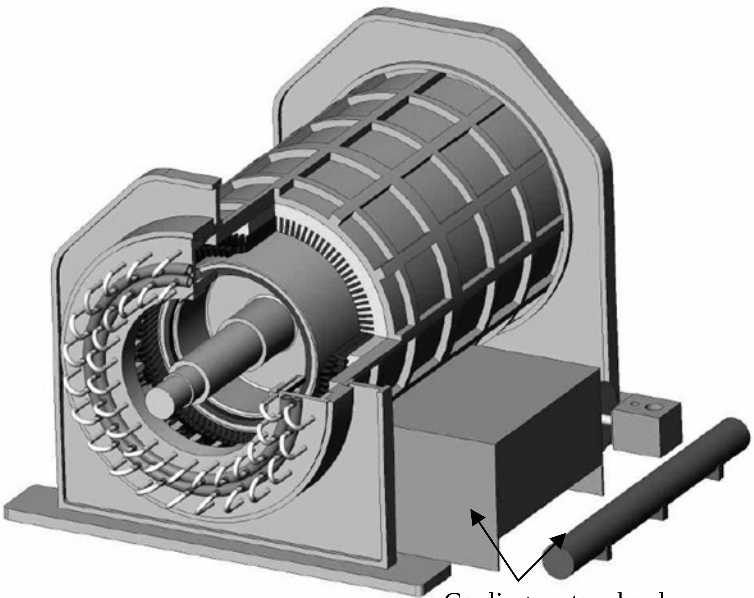
## GENERATOR

The generator selected for the baseline power train is a 3600 rpm permanent-magnet synchronous machine. The 3600 rpm speed was chosen to match that of the LM2500 gas turbine for direct coupling. The generator parameters are summarized in Table 1, and an overall view is shown in Fig 3. The 25 MVA generator weighs 13 tonnes and has a 7.5 $m^3$ volume. The neodymium-iron-boron (NdFeB) magnets are mounted on the surface of the rotor back iron and held in place by composite bandings producing a radial flux topology. A copper sheet between the magnets and the banding acts as a shield against stator windings harmonics. Circulating water is used to cool the stator windings. Mechanical analyses show that the structural design and the 1-cm physical air-gap are adequate under a “35 g” shock load where stresses in various parts of the machine, and rotor and stator deflections, are acceptable. Spin induced rotor stresses are also found to be acceptable up to 3600 rpm. The first and second critical speeds are 2330 rpm and 6330 rpm respectively, indicating safe operation between these two modes.



| **Machine type** | **Surface mounted Radial Flux Permanent Magnet** |
|---|---|
| **Machine rating** | |
| Power | 25 MVA |
| Voltage | 4160 $V_{LL}$ |
| Power factor | 0.85 |
| Speed | 3600 RPM (direct coupling to turbine) |
| Poles/Phases | 16 / 3 |
| | |
| **Parameters** | |
| Weight | 13 tonnes |
| Volume | 7.5 $m^3$ |
| Efficiency (target) | 0.97 |
| Electric frequency | 480 Hz |
| Current density | 5960 A/ $in^2$ |
| Stator windings | Direct water cooling |

Table 1: Generator main parameters



Cooling system hardware.

Fig 3: 25 MVA, 3600 rpm permanent magnet generator.

## PROPULSION MOTOR

The inverter-driven propulsion motor is also a radial-flux permanent-magnet synchronous machine, designed for onboard installation and operates within a speed range of 0 to 150 rpm. The low speed and, consequently, high torque drive the machine size up significantly compared to the higher speed generator. The number of poles and number of phases were chosen to be similar to those of the 19 MW induction motor used by the US Navy in their integrated power system full-scale advanced development program [2, 3]. The motor stator windings are also actively water cooled. The NdFeB magnets produce a 0.9 Tesla peak flux density in the air-gap, and are selected such that the risks of permanent demagnetization, under fault conditions, are minimized. Mechanical and rotor dynamic analyses, including the 35 g shock loading, confirm the structural integrity and stability of the machine. The permanent-magnet propulsion motor weighs 97 tonnes and has a volume of 49 $m^3$. Motor parameters are summarized in Table 2, and a motor section view is shown in Fig 4.

| **Machine type** | Surface mounted Radial Flux Permanent Magnet |
|---|---|
| **Machine rating** | |
| Power | 20 MW |
| Voltage | 3700 Vrms |
| Speed | 0-150 rpm |
| | |
| **Parameters** | |
| Weight | 97 tonnes |
| Volume | 49 $m^3$ |
| Efficiency (target) | 0.965 @ rated power |
| Electric frequency | 15 Hz |
| Current density | 6470 A/ $in^2$ |
| Stator windings | Direct water cooling |

Table 2: Propulsion motor main parameters.

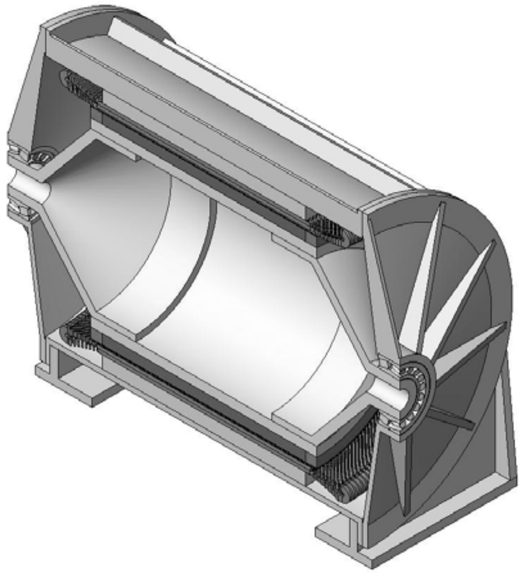


Fig 4: Section view of the 20 MW propulsion motor.

### POWER ELECTRONICS

The converter selected to drive the 15-phase propulsion motor consists of three DC links established by three separate thyristor-based rectifiers. Each DC link powers five IGBT-based, hard switched, three-level H-bridge inverters. Each of the 15 H-bridge inverters independently drives one of the 15 motor phases, allowing operation with 5, 10, or 15 phases. This topology has relatively low distortion, redundancy, and regeneration characteristics and can incorporate switch technology improvements without inverter redesign. This architecture is similar to the IPS architecture [2] but uses newer IGBTs with enhanced ratings (3300 V, 1200 A) vs. (1600 V, 1200 A). This results in an improved converter which weighs 16.2 tonnes and has a volume of 18.9 $m^3$.

## CONCLUSIONS

Weights and volumes of the various components of the 20 MW baseline propulsion power train are shown in Fig 5. The amount of fuel was sized for a 15-day mission of a frigate [4] with two 20 MW propulsors.

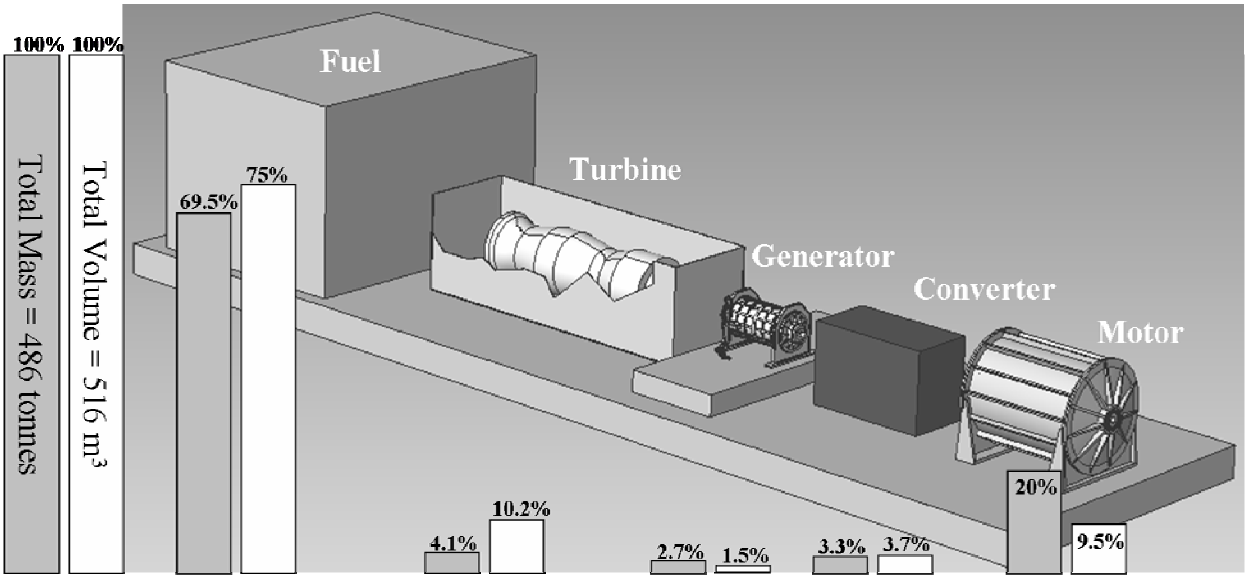


Fig 5: Baseline power train weight and volume comparison.

The design and analyses of the 20 MW baseline power train reveal that the fuel makes, by far, the largest contribution to mass and volume. Consequently, efficiency improvement offers the highest mass and volume payoff. It is not, however, immediately clear if ship designers would use the additional efficiency to increase range or to include additional capability

The low speed propulsion motor is the next best opportunity for mass and volume reduction. While podded propulsors place a greater premium on space, reducing the size of the drive motors is useful for both onboard and podded applications. Size reductions are limited by technology and materials needed to achieve the required air gap field strength, so advances in those areas are showing promise for more compact motors in the future.,

While improving generator technology has the least impact on the power train overall size, there may be advantages to a reduced weight turbine-generator combination. With sufficient size reduction, designers would have more flexibility in locating these components within the hull possibly leading to more efficient designs.

Multi-variable optimization can lead to non-intuitive component specification. This approach was used, for example, to determine the number and sizes of gas turbines that represent an optimum set, in terms of mass, volume, and efficiency, for various power levels. The same mathematical approach is expected to be used in higher levels of system optimization as the component choices become better defined.

## ACKNOWLEDGEMENT

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