OPTIMIZATION OF GAS TURBINE GENERATOR-SETS FOR IMPROVED POWER DENSITY

By:

M.A. Pichot
J.J. Zierer
A. Ouroua
J.H. Beno

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Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

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ABSTRACT

Many future US Navy ships will employ all-electric propulsion systems instead of mechanical drives. To help optimize performance of these systems, studies are under way at The University of Texas at Austin Center for Electromechanics (UT-CEM) to minimize the size of power generation components. These studies focus on increasing the power density of directly-coupled gas turbines and generators (gen-sets). The approach adopted in this paper uses scaling laws of gas turbines and synchronous electrical generators to examine the possibility of increasing power density by operating at higher shaft speeds. Included is consideration of inlet and exhaust turbine ducts and issues involving power electronics. Study results indicate that if inlet and exhaust duct volumes are neglected, the power density of directly coupled gas turbine-generator sets can be significantly improved by scaling to higher operating speeds. However, advantages of scaling to higher speeds are largely negated when duct volumes typically encountered on modern ships are included. This suggests locating power generation equipment near the ambient terminus of inlet and exhaust ducts, so that duct lengths are minimized and it is possible to fully exploit the power density advantages of scaling to higher shaft speeds.

INTRODUCTION

All-electric propulsion systems for naval vessels offer a number of potential benefits, including improved fuel economy, distributed power systems for enhanced attack survivability, and increased flexibility and adaptability. The advantages of all-electric propulsion were recognized by commercial shipbuilders some years ago and as a result, most recently-constructed cruise ships now employ all-electric drives. For this paper, power generation is assumed to consist of gas turbines directly coupled to electric generators. In a modern naval vessel, the electric power generated by this arrangement would be distributed throughout the ship and used as needed for propulsion drive motors, ship services, weapons systems, etc.

Power electronics play an important role in all-electric ships by allowing distributed power to properly interface with the many different loads encountered on a naval vessel. Furthermore, power electronics could enable gen-sets used for power generation to operate at higher shaft speeds than commonly used in land-based systems. Most land-based generators use wound-field, two-pole synchronous machines operating at 3,600 or 3,000 rpm for power generation at

60 Hz and 50 Hz, respectively. Since modern power electronics permit generated power to be converted to other frequencies, shaft speed need not necessarily be limited to 3,600 or 3,000 rpm.

Inlet and exhaust ducts, also known as intakes and uptakes, are used to deliver fresh air to and exhaust gases away from gas turbine engines in marine applications. In addition, these ducts play an important role in filtering, noise suppression, and preventing foreign objects from entering the turbine. In modern naval vessels, ductwork can comprise a significant volume, and in some cases, ducts dominate the volume of the ship power generation system.

If the fuel aboard ship is considered part of the power generation system, its volume typically dominates that of other power generation components. Accordingly, power generation efficiency is the most important factor in minimizing fuel volume and, consequently, the overall volume of the power generation system. This study acknowledges the importance of efficiency, but does not attempt to optimize it. Instead, this paper concentrates on minimizing the volume of the other power generation system components; i.e., gas turbines, generators, power electronics, and engine ductwork.

OPTIMIZATION USING GAS TURBINE AND GENERATOR SCALING LAWS

This study uses gas turbine scaling laws to examine the effects of engine design parameters on engine power density. It attempts to answer questions such as: what is the effect on power density if a gas turbine operates at 5,400 rpm instead of 3,600 rpm, or how large would an engine be if the desired output were doubled?

Scaling parameter groups derived from the Buckingham Pi theorem permit scaling of entire gas turbine engines, as well as the individual components that comprise the engine (Walsh and Fletcher 1998). This method is commonly used by industry in the concept design of new engines (Ramachandran and Conway). Using this approach, currently available gas turbines can be scaled to larger or smaller sizes while maintaining critical parameters constant.

Scaling of existing gas turbines has some inherent limitations. For example, changes in engine size often deviate from the pure linear scaling assumed in this method, and it is therefore suggested that scaling dimensions by a factor greater than 1.5 be avoided (Walsh and Fletcher 1998). In addition, scaling is sufficient only for first order accuracy; to account for higher order effects requires additional assessment.

Following is a brief introduction to the use of scaling parameters. When scaling a gas turbine engine from one size to another, the following parameter groups are assumed to remain constant (Walsh and Fletcher 1998):

$$\frac{W * \theta}{(DI)^2 * \delta} = \text{constant} \quad (1)$$

$$\frac{(DI) * N}{\sqrt{\theta}} = \text{constant} \quad (2)$$

$$\frac{PW}{(DI)^2 * \delta * \sqrt{\theta}} = \text{constant} \quad (3)$$

where W is engine mass flow, θ is the ratio of inlet to reference temperature, DI is engine diameter, δ is the ratio of inlet to reference pressure, N is rotational speed, and PW is shaft power. These equations imply that if the dimensions of an existing gas turbine are scaled upward by a factor of two, mass flow will increase by a factor of four, rotational speed will decrease by a factor of two, and shaft power will increase by a factor of four. The following critical engine parameters would remain unchanged during scaling: cycle temperatures and pressures, blade tip speed and disc rim speed, and specific fuel consumption (efficiency). Since these parameters are held constant during scaling, an existing engine design can be scaled using this method with the expectation that no new technology would be required to produce the scaled design.

To evaluate the overall power density of gas turbines directly coupled to generators, it is desirable to scale existing (baseline) generator designs in the same manner as discussed above. This is done through the use of the following equation, which relates key parameters for synchronous electric machines (Nasar 1987):

$$\text{Power} = kD^2lBAf_m \quad (4)$$

where k is a proportionality constant, D is generator air gap diameter, l is active length, B is air gap magnetic flux density, A is conductor line current density, and f_m is mechanical frequency. Note that this equation relates generator air gap dimensions only, and provides no direct information about the outer dimensions of the machine.

For an existing generator design, all the variables in equation (4) are known except the proportionality constant k , which can be readily calculated. Thus, given a desired new operating speed and power output, the air gap dimensions of a scaled generator can be determined from an existing design (assuming that B and A are held constant, and D is constrained to maintain the same rotor tip speed as for the baseline generator). To calculate machine outer dimensions requires further consideration. The method employed in this study is to use magnetic circuit analysis to ensure that as the generator is scaled, important stator parameters such as magnetic flux densities and current densities are maintained at the same levels as the existing generator design.

The following example illustrates how a gas turbine and a generator can be scaled separately, then have the results combined to determine an overall power density for a gas turbine gen-set. In this example, a Rolls Royce MT-30 turbine (nominal operation conditions of 36 MW at 3,600 rpm) is scaled to a higher speed (16 MW at 5,400 rpm). Then an existing radial flux permanent magnet (RFPM) generator design developed by UT-CEM, with nominal operation conditions of 20 MW at 3,600 rpm (Beno, et al. 2003), is scaled to match the power and speed characteristics of the scaled gas turbine. A list of the baseline UT-CEM generator design parameters are shown in Table 1. Note that the total enclosed volume listed in the figure includes generator bearing assemblies and mounting pedestals; for scaling, however, only the stator housing enclosed

volume is considered. Results of scaling the MT-30 gas turbine and the baseline generator to 4,830 and 5,400 rpm are shown in Table 2.

Table 1. UT-CEM RFPM baseline generator design parameters

Machine type		Surface-mounted radial flux permanent magnet synchronous generator	
Machine Ratings		Machine Dimensions	
Power	25 MVA	Stator OD	1.04 m
Voltage	4,160 V _{LL}	Stator ID	0.782 m
Power factor	0.8 to 0.9	Air gap	0.01 m
Speed	3,600 rpm	Rotor OD	0.762 m
Design Parameters		Shield OD	0.749 m
		Magnet OD	0.743 m
		Backiron OD	0.703 m
		Backiron ID	0.653 m
		Active length	1.4 m
		Weight	13 tonnes
		Total enclosed volume	7.5 m ³
		Stator housing enclosed volume	2.19 m ³
		Machine Cooling	
		Stator coils cooling	Direct water
		Stator coil cooling	Forced air
		Rotor cooling	Forced air
		Estimated efficiency	~97%

Table 2. Scaled MT-30/RFPM generator results

Result	Units	3,600 rpm	4,830 rpm	5,400 rpm
Power	MW	36	20	16
Electrical frequency	Hz	480	644	720
Engine volume	m ³	115	4.77	3.41
Generator volume	m ³	3.41	1.67	1.29
Total volume	m ³	14.9	6.44	4.70
Engine power density	MW / m ³	3.13	4.20	4.70
Generator power density	MW / m ³	10.6	11.98	12.45
Overall power density	MW / m ³	2.41	3.11	3.40

This scaling exercise indicates that scaling the gen-set from 3,600 to 5,400 rpm results in a 41% improvement in overall power density. Note that as the gas turbine is scaled to higher speed, its power output decreases in accordance with equations (2) and (3), so more gen-sets might be required for a given application to meet the overall power generation requirement. At this point in the discussion, the volume of air ducts, power electronics, and gen-set auxiliaries are not included in the analysis; the overall power densities listed in table 2 reflect only the volumes of the bare gas turbine engine and the generator stator housing. Therefore these results provide an optimistic upper bound to power density improvement.

As a further illustration, consider a fictitious ship installation in which a total power of 144 MW is required. Four 3,600 rpm gen-sets would be required to meet this requirement and occupy a total volume of 59.6 m³. If, on the other hand, nine gen-sets scaled to 5,400 rpm were used to obtain the same power output, the total volume would be 42.3 m³. Thus, to first order accuracy, the required volume is reduced by 29% by scaling the gen-sets to the higher speed. As noted above, power density improves by 41%.

In figures 1 and 2, power density, power density improvement, volume, and speed are plotted as a function of output power for the entire allowable scaling range for the MT-30/RFPM generator gen-set. In this figure, the allowable range is assumed to be constrained by turbine scaling limitations; i.e., turbine dimensions are scaled by no more than a factor of 1.5.

Figure 1. Power/volume results for scaled RR MT-30/RFPM generator

Figure 2. Volume results for scaled RR MT-30/RFPM generator

GEN-SET SCALING: INFLUENCE OF DISTRIBUTION SYSTEM ON POWER ELECTRONICS

Choice of ac or dc distribution systems can have a significant impact on the overall power density of propulsion systems, especially if high-speed machines are used for power generation. For example, if a power distribution system operates at 60 Hz but employs directly coupled gas turbine gen-sets operating at speeds greater than 3,600 rpm, some form of frequency inverters are required to provide the desired 60 Hz distribution power (since a two pole generator produces 60 Hz output at 3,600 rpm). Moreover, the power density of present-day power electronics is relatively low compared to the gas turbine and generator power densities listed in Table 2. For

example, the U.S. Navy Integrated Power System (IPS) power electronics installation, which is considered to exhibit state-of-the-art power density, has a converter power density of approximately 1.09 MW/m^3 (Benatmane, et al. 1998). (The IPS uses pulse width modulation (PWM) power converters.) Therefore, the requirement for a frequency converter can add substantial volume to the power generation system and have a negative impact on overall power density.

Consider a scaled MT-30 gas turbine and RFPM generator operating at 5,400 rpm and 16 MW (at the permissible scaling limit). For this 720 Hz output frequency gen-set, the power density is predicted to be 3.40 MW/m^3 (Table 2). If the distribution system operates at 60 Hz, then the required volume for an IPS-type frequency converter to convert from 720 to 60 Hz is approximately $(16 \text{ MW})/(1.09 \text{ MW/m}^3) = 14.7 \text{ m}^3$. Adding this to the gen-set volume results in an overall power density of 0.83 MW/m^3 , a factor of about four lower than for the gen-set alone. In addition, for ship propulsion the 60 Hz distribution system in this example has the disadvantage that the generator output must be converted to dc twice: first in the PWM frequency converter to provide 60 Hz for distribution and then again in the variable speed PWM motor drives. This would adversely affect power density and efficiency.

On the other hand, if a dc distribution system is used, ac to dc rectification is required regardless of the gen-set output frequency. For uncontrolled diode rectifiers, additional rectifier volume would probably not be required to rectify the 720 Hz generator frequency of this example versus a 60 Hz gen-set, since standard diodes have sufficient capabilities to switch at frequencies up to 1 kHz. Therefore there would be no power electronics volume penalty involved in running at higher speeds, and a power density advantage is gained by scaling the gen-set to higher speed. (For a controlled rectifier system, additional rectifier volume may be required for the 720 Hz generator frequency, depending on the type switching elements used.)

GEN-SET SCALING: EFFECT ON INLET AND EXHAUST DUCT VOLUMES

As the power of a given gen-set is scaled to different levels, the size of required inlet and exhaust ducts will also change. The air mass flow rate through the ducts scales linearly with gas turbine power, per equations (1) and (3). That is, the air mass flow for a 20 MW gas turbine is approximately one-half that of the same machine scaled to 40 MW. In this study, the mass flow through a turbine is assumed approximately equal on inlet and exit sides. This is justifiable because the fuel addition in the combustion chamber increases the exhaust side mass flow only by about 2%, which is negligible considering the first-order accuracy of these calculations.

SCALING RESULTS: POWER DENSITY STUDY FOR SCALED COMMERCIAL MARINE GAS TURBINES

Scaling studies were conducted for the commercially available engine models listed below; this list (not intended to be comprehensive) includes gas turbines with rated power of at least 5 MW. References for engine dimensions and performance parameters are indicated.

These gas turbines were scaled to the permissible upper and lower scaling limits, with results shown in Figure 3. Note that for each curve, minimum speed corresponds to maximum power, and maximum speed corresponds to minimum power (Figures 1 and 2). The engines are also grouped according to engine topology, with the most power density in each category shown in Table 4. For engines with outputs greater than 10 MW, the Rolls Royce MT-30 and MT-50 engines offer the best power density of the turbines examined in this study.

Table 3. Generator models considered

Company	Models	Reference
General Electric	LM 2500 LM 2500+ LM 6000PC LM 500 LM 1600	Gas Turbine World Handbook 2003
Rolls Royce	MT-30 MT-50 WR-21	Rolls Royce
Kawasaki Heavy Industries	Spey SM1C Spey SM1A Olympus TM3B	Gas Turbine World Handbook 2003
Ishikawajima-Harima Heavy Industries	Spey SM1C Spey SM1A Olympus TM3B	Gas Turbine World Handbook 2003
MAN Turbomas- chinen AG	THM1304-11 FT8 FT8+	Gas Turbine World Handbook 2003
Mitsubishi Heavy Industries	MFT-8	Gas Turbine World Handbook 2003
Zorya-Mashproekt	UGT-25000 UGT-16000 UGT-15000+ UGT-10000	Gas Turbine World Handbook 2003
Pratt & Whitney	MFT8	Moeller 2004
Solar Turbines	Titan 130	Rocha and Etheridge 1998

Figure 3. Gas Turbine scaling results

Table 4. Gas turbine scaling results
(numbers in parentheses denote data sample size for a given turbine configuration)

Maximum power densities (MW/m ³) derived from scaling existing gas turbines (no speed constraint imposed)						
Gas turbine configuration	5 MW	10 MW	20 MW	30 MW	40 MW	60 MW
Single shaft (1)		0.831	0.587	0.480		
		Solar Titan 130				
Split shaft (6)	7.32	5.18	1.69	1.38	1.20	0.978
	Ishika-Harima 601-KF9		GE LM2500+			
Dual spool (1)			1.74	1.42	1.23	1.01
			GE LM6000PC			
Dual spool w/power turbine (7)		1.32	4.20	3.43	2.97	2.43
		GE LM1600	Rolls Royce MT-30			
Dual spool w/power turbine, intercooled, recuperated (1)			1.21	0.987	0.855	
			Rolls Royce WR21			
Triple spool (1)				2.74	2.37	1.93
				Rolls Royce MT-60		
Maximum for all configurations	7.32	5.18	4.20	3.43	2.97	2.43
	Split shaft		Dual spool with power turbine			
Highest power density at 3,600 rpm: 3.42 MW/m ³ @ 30.3 MW (Rolls Royce MT-30 (speed constrained to 3,600 rpm)						

GEN-SET SCALING RESULTS

The five most power-dense engines discussed above (for power ratings in the 20 to 60 MW range) were assumed directly coupled to scaled UT-CEM RFPM generators, and curves were generated over the allowable scaling range. Figure 4 shows the percent power density improvement as a function of output power. This plot shows that the maximum percent power density improvement is relatively independent of the gas turbine used. In Figure 5, speed and volume are plotted against power for the five gen-sets.

Figure 4. Gen-set scaling results

Figure 5. Gen-set scaling results

EFFECT OF AIR DUCTS ON POWER DENSITY

To evaluate the effect of air ducts on overall power density, air duct dimensional information for an LM2500 gas turbine installation in U.S. Navy Arleigh Burke class destroyers was employed (Northrop Grumman). Although the gas turbines used in these destroyers are mechanically coupled to the propeller, in this exercise it is assumed that each turbine is directly coupled to a UT-CEM RFPM generator, which is appropriately scaled to match the scaled gas turbines. Inlet air velocity in the destroyer gas turbine ducts was calculated as 7.4 m/s, and exhaust gas velocity 64 m/s. By holding these fluid velocities at predetermined levels as the gas turbine is scaled through its allowable range, required duct areas and volumes are calculated.

In Figures 6 and 7, the results of this analysis are shown for “baseline duct lengths” (the same lengths as used on the destroyers) and for “short duct lengths,” which are half the length of the baseline ducts. Curves are provided for two inlet velocities, 7.4 m/s (the baseline case), and 14.8 m/s (an increased velocity case that requires improved inlet filter technology). In all curves, the exhaust velocity is held constant at 64 m/s. For reference, the plots also include gen-set curves without ducts.

Figure 6. Scaled LM2500 gen-set including ducts

Figure 7. Scaled LM2500 gen-set including ducts

These results indicate that for an Arleigh Burke installation, required duct volume dominates gen-set volume, and that including duct volume in the analysis has a dramatic impact on overall gen-set power density. Furthermore, including inlet and exhaust duct volumes appears to largely negate power density advantages of scaling to higher speeds. This is illustrated in Figure 6, in which all three curves that include duct volume show little variation of power density with changing power (and speed), indicating that apparent advantages of scaling to higher speeds seen previously in this paper are not applicable when substantial duct volumes are included.

This suggests that to take full advantage of scaling to higher speeds, duct lengths should be minimized. That is, gen-sets should be mounted near the terminus of the inlet and exhaust ducts, if possible. This mounting approach has already been adopted in the design of some recently commissioned all-electric cruise ships, in which gas turbines are installed in ship funnels ("Coral Princess ..." 2002).

CONCLUSIONS

If inlet and exhaust duct volumes are neglected, the power density of directly coupled gas turbine-generator sets can be significantly improved by scaling to higher operating speeds. Furthermore, if high-speed gen-sets are utilized, dc power distribution systems offer power density advantages over ac distribution.

For naval vessels with relatively long intake and exhaust ducts, duct volume often dominates power generation system volume. Moreover, large duct volumes can negate power density advantages of scaling gen-sets to higher speeds. Therefore the greatest improvement in power density of power generation components can be achieved by reducing duct length. This suggests locating power generation equipment as near as possible to the terminus of inlet and exhaust ducts, where duct lengths are minimized and it is possible to fully exploit the power density advantages of scaling to higher shaft speeds.

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