# POWER GRID FOR A NAVAL ELECTRIC SHIP - AC VERSUS DC

Kent R. Davey, Fellow, *IEEE* and Robert E. Hebner, Fellow, *IEEE*

*Abstract*—**The debate over the best electric grid topology for an all electric ship has provoked discussion on a wide range of topics, spanning interconnection issues, transmission losses, and power preferences of electronic components, radar ranges, and propulsion motors. Surprisingly, these issues are peripheral to the real issue. The primary driver in this debate is the power source, presently the gas turbine. The physics of the gas turbine demand the use of multiple turbines operating at different speeds. This demand assumes that system efficiency is the preeminent objective after functionality. The penalty for not using this approach is severe for fuel usage. A primal commitment to such a distribution of gas turbines serves as the basis for quantitatively comparing two ac systems and one dc distribution system. The power source combined with the navy's focus on overall efficiency narrows the field of focus, and makes the rather complicated trade study tractable.**

*Index Terms*—**efficiency, eddy current, transformer, gas turbine**

## 1. INTRODUCTION

The Institute for Marine Engineering Electric Warship conference in December, 2006 witnessed several papers investigating how to switch power from propulsion to weapons [1, 2]. Many objections to ac systems are voiced, most of which have no foundation. Among the top two arguments offered in support of dc are the following:

1. dc has no frequency synchronization is required for combined sources
2. there are no conductor skin depth limitations with dc and therefore it has transmission advantages

K. R. Davey is with the University of Texas at Austin, Center for Electromechanics, 10100 Burnet Road, Austin, TX 78758, USA (phone: 512.232.1603; fax: 512.475.7700; e-mail: k.davey@mail.utexas.edu).

R.. E. Hebner, is with the University of Texas at Austin, Center for Electromechanics, 10100 Burnet Road, Austin, TX 78758, USA (phone: 512.232.1628; fax: 512.475.7700; e-mail: r.hebner@mail.utexas.edu).

In response to this the reader should note that tying multiple generators together each with different speeds into a dc bus is not trivial. Permanent magnet generators are favored. Tying these together after rectification would require very precise speed control to keep dc power from flowing among the generators. By contrast, maintaining synchronization among ac generators is rather simple if the frequency output can be closely matched.

Ac systems have in fact a 33% transmission advantage over equivalent dc return ground systems with the same conductor volume. The additional inductive load introduced by cables with conductors in close proximity is negligible, especially in lieu of the short run lengths involved. Both dc and ac systems must have a high impedance ground for safety. Dc systems long been known to have a considerable safety penalty over ac due to skin effect as evidenced by the OSHA limitation of 50 V dc. Electrical frequency synchronization is no problem for properly designed generators operating at the same frequency; it is virtually impossible in a tightly coupled system such as a ship to not run in synchronization. The skin depth, inductive voltage drop, and capacitive currents are incredibly small for 60 Hz, and can be made so for 400 Hz if cable partitioning is practiced. The additional acoustical noise introduced by H bridge and dc inverters is considerable compared to the 120 Hz from a transformer due to harmonics.

This paper addresses the fundamental aspects of this debate, culminating in a trade study chart. The intent of this exercise is a tool to assist in unemotionally evaluating this problem. The solution is source dependent and likely to change if the Navy converts to another power source such as nuclear. *The underlying theme running throughout the comparison is that system efficiency is preeminent.*

## 2. THE GAS TURBINE

A gas turbine's power output is related to the volume of air flow. Larger power turbines are thus larger in diameter. A fundamental constraint indigenous to all gas turbines is that the tip speed of the blades remain below Mach 1, the speed of sound. This leads to the fact that large power turbines have a low rotation speed while small power turbines, being smaller in radius, have a high rotation speed. The power – speed relationship is shown in Fig.1.

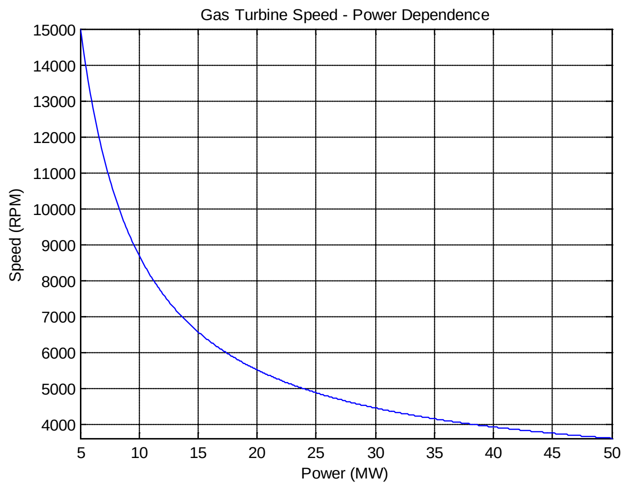


Fig. 1 Gas Turbine speed versus power relationship demanded by the physical demand that tip speed remain below Mach 1.

The second driving fundamental is that the specific fuel consumption increases nonlinearly with partial power turbine operation. Fig. 2 shows the specific fuel consumption dependence with power for 6 commercial turbines. Note that the smaller turbines have improved specific fuel consumption at low power, but that the larger turbine efficiency is superior to the best performance of the smaller faster turbines. The fuel penalty for not having gas turbines spread over the speed range shown in Fig. 1 is immense.

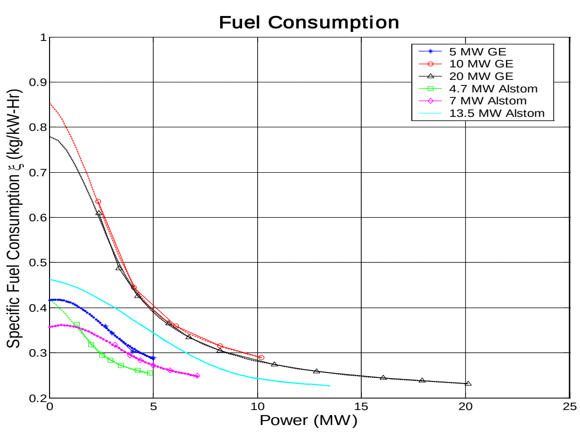


Fig. 2 Specific fuel consumption for six commercial gas turbines.

When it becomes necessary to bring on additional units due to a power demand increase, a lower specific fuel consumption results if the larger less efficient units are operated at higher power settings where their efficiency is improved. These findings become the foundational driver for the optimal power grid choice.

## 3. PUTTING THE AC VERSUS DC DEBATE IN PERSPECTIVE

Turbine scheduling with a spread of differently sized turbines constitutes a 250-600 $m^3$ mission dependent saving in fuel over a smart scheduled system with equal sized turbines (80 MW destroyer 2 week mission). This practice should be considered mandatory if efficiency is a priority. The ac versus dc debate is primarily about saving 10% of this volume, i.e., about 60 additional cubic meters of fuel. Secondarily, it is about extending component life and reducing maintenance costs.

## 4. POWER ELECTRONICS

The deleterious effect of full bridge rectifiers on the output of an ac generator deserves attention by the Naval community. The harmonics witnessed at the stator of the generator not only introduce hysteresis and eddy current losses, but voltage spikes which impact the life of the generator. In house simulation and experimentation show that a full three phase rectification bridge introduces 28.56 % total harmonic distortion back into the generator.

Cavallini [3] attempts to quantify the effects of a distorted waveform through two other indices which are weakly linked. The first is Kp, the ratio of the peak voltage of the distorted waveform to the sinusoidal rated voltage. The second involves a ratio of the product of the inverter switching frequency and the inverse rise time to the sinusoidal system frequency. Increasing the frequency from a nominal 50-60 Hz to 10 kHz reduces insulation life by three orders of magnitude. Pillay quantifies the magnitude of the problem as it concerns induction motors fed by any unbalanced supply [4]. Any unbalance that increases the temperature by 14.3°C reduces the life by 55.3%.

A number of techniques have been suggested for lowering the total harmonic distortion. The simplest is to increase the number of phases in the generator. This option increases both the generator cost and the diode part count slightly. Matrix converters [5][1] and resonance converters [6] provide alternatives.

## 5. CABLE LOSS ARGUMENT

Assume an rms operating line voltage V and a resistance R per conductor for the three phase ac system shown in Fig. 3(a).

conservative, assume the transmission loss for the complete system is 1%. This is likely to be high. If the ship is fed using 650,000 mil cable, the dc, 60 Hz ac, and 420 Hz ac eddy current and proximity losses per meter are shown in Fig. 4. A boundary element code is used to compute these numbers [7]. These ratios will be used to compute relative transmission losses between three systems.

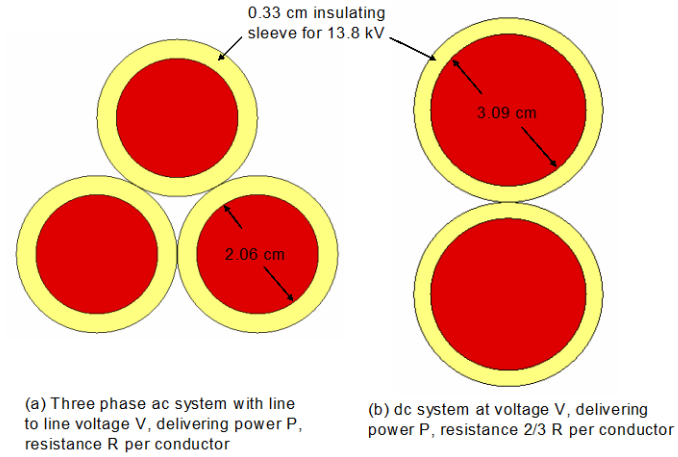


Fig. 3 Configuration for comparing dissipative loss for ac and dc systems delivering the same load power.

If power P is delivered by this transmission line into a unity power factor load, the current per line will be

$$I = \frac{P}{\sqrt{3}\,V} \tag{1}$$

The dissipative line loss for all three lines ignoring skin effect and proximity effect will be

$$Loss = 3\left(\frac{P}{\sqrt{3}V}\right)^2 R = \frac{P^2}{V^2} R \tag{2}$$

Take one of the three conductors, cut it in half, and combine it with the remaining two conductors to form the equivalent copper system of Fig. 3(b). The resistance of one of these conductors will be 2/3 of that in the ac system. Assume the same operating voltage V but now in dc. If the dc system delivers the same power P, its dissipative line loss for the two line feed will be

$$Loss = 2\left(\frac{P}{V}\right)^2 \frac{2}{3} R = \frac{4}{3}\left(\frac{P}{V}\right)^2 R \tag{3}$$

Ignoring skin effect and proximity effect, the ac system has a 33% advantage over dc. The dc system must have 33% more copper for the transmission losses to equal the ac system. The reason is that the three phase ac system has two lines for the return when the current is peaking in any one phase. The reader may object that the power factor of the cable is unacceptable, but as will be shown shortly, this objection is specious because of the length of the conductor and the inductive nature of the load.

## 6. TRANSMISSION LOSSES

A land based power system has a 5% power distribution loss from the generator to the customer. Defining the transmission loss for a ship involves some speculation since the length and choice of cable are ill defined. To be

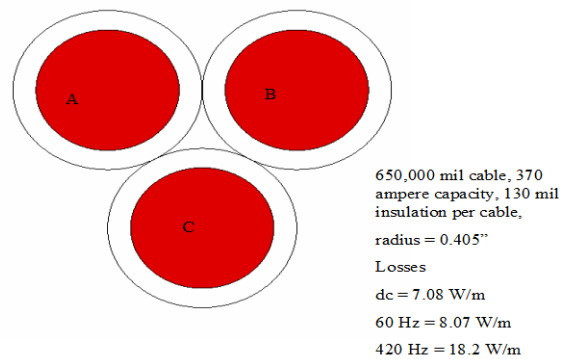


Fig. 4 Cable losses for dc, 60 Hz, and 420 Hz systems.

## 7. SYSTEM COMPARISON DESCRIPTION

We wish to compare the dc system in Fig. 5, the 60 Hz ac system Fig. 6, and the 420 Hz ac system in Fig. 7 at full load. Of the 80 MW load, 8 MW is hotel power including some weapons and the radar range, typically 750 kW to 1 MW. Of the 8 MW load, 1 MW will be allocated as a high voltage dc load (e.g. the radar range). The electronic loads are primarily dc, but generally all at low voltage. Computers generally require 5 and ±12V. The 72 MW propulsion system requires low frequency (10-40 Hz) ac. The greatest losses occur within the gas turbines, but all three systems employ the same gas turbine mix, with speeds varying from 3600 RPM to 12,600 RPM. As such the loss for the gas turbines will be assumed identical for all three systems.

### 7.1. The dc system

The dc system uses 3 turbines at 3600, 5,000, and 12,000 RPM, rated 50 MW, 20 MW, and 10 MW respectively. The most efficient generator will be a permanent magnet generator. Typically it has about 1% better efficiency over a wound rotor with exciter due to the elimination of the rotor $I^2R$ losses. If permanent magnet generators are employed, governor based speed control must be employed to ensure the three units have similar voltages. The output from these three generators will be rectified and tied to a common bus. 72 MW goes to propulsion and 8 MW to hotel power. Dc to dc converter efficiency is slightly less than converter efficiency, but for the purposes of this comparison, a loss of 5% will be used for converters and dc to dc conversion. Only one load will be assumed sufficiently close to the dc voltage distribution to circumvent this conversion, the 1 MW radar range.

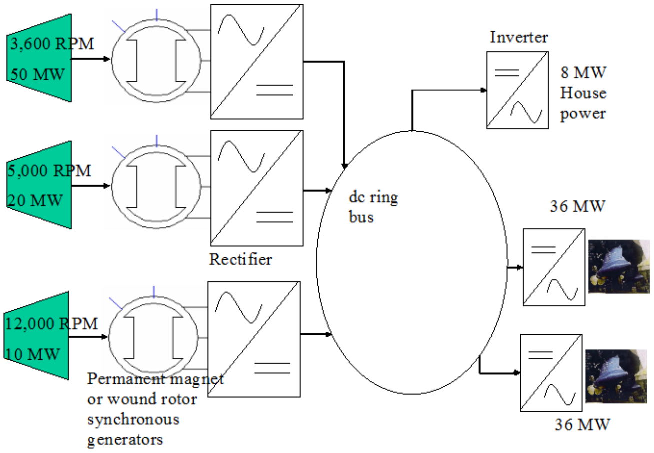


Fig. 5 dc grid.

We have measured the loss in synchronous generators here at the Center for Electromechanics's lab. At 12,000 RPM, the efficiency has dropped to 94.5%. It is 97.5% and 96.6% at 3600 and 5,000 RPM respectively. The loss increases due to eddy currents in the windings and eddy currents and hysteresis in the steel.

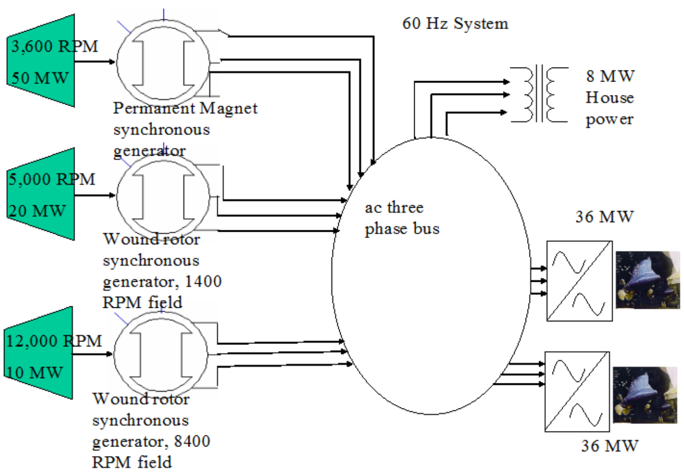


Fig. 6 60 Hz ac grid.

### 7.2. The 60 Hz ac system

The 60 Hz ac system in Fig. 6 uses the same three gas turbines as the dc system. The 3600 turbine will be connected to a 2 pole permanent magnet generator. The 5,000 RPM and 12,000 RPM turbines require a different technology to get 60 Hz out. Two options surface. One is to excite the rotor with a traveling wave for the field so the difference frequency remains at 60 Hz. The second is to use a resonant ac-ac inverter to convert the 20 and 10 MW output to 60 Hz. This modification reduces the efficiency an additional 1.5% below that of the dc case. An ac to ac resonant inverter is used for the 72 MW propulsion power conversion; it has a 2% greater efficiency than the dc converter due to the fact that all switching occurs at zero current crossings [8]. The 8 MW of house power must be passed through a transformer for use by the ship. 60 Hz transformers have an efficiency in excess of 99%, but a 1 % loss will be used for the conversion. An additional 1.5 % loss is required for the rectification necessary for the 1 MW dc hotel load.

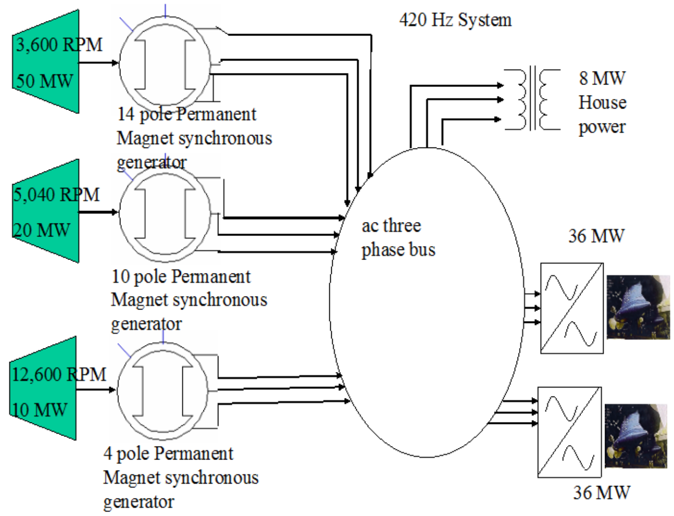


Fig. 7 420 Hz ac system.

### 7.3. The 420 Hz ac system

A higher frequency ac system has the advantage that the higher speed turbines can be directly coupled to a permanent magnet machine and still maintain synchronous operation. A lower pole count is required as the turbine speed increases. The speeds are slightly altered from the previous two cases to achieve 420 Hz. Smaller laminations are required on these generators to keep the loss small. The 3600 RPM generator will incur an additional 0.75% loss due to the higher frequency. The 5,040 and 12,600 RPM generators will have a loss of 3.4% and 5.5%, identical to the dc case. The 420 Hz transformer incurs an additional 1% loss over the 60 Hz case. Rectification adds an additional 2.5 % loss for the 1 MW load for the higher frequency switching losses. A resonant ac to ac inverter is used for the propulsion power, having a 3% loss identical to the 60 Hz case.

## 8. TRANSFORMER VERSUS POWER ELECTRONICS

The 60 Hz system posited uses a transformer. Although an ac to ac resonance inverter is another possibility, it is worth considering this option for hotel power because of the very high efficiency (>99%) and essentially zero maintenance. 60 Hz transformers are heavier and larger than their power electronic counterparts. The difference is often greatly exaggerated. Table I shows a survey of several commercial grade inverter systems. The scr inverter highlighted in bold was scaled from the commercial system in the previous line. The 8 MW GE transformer was taken directly from the GE engineering representative for a commercial unit. The transformer weighs 68% more and has 65% more volume. A 4-5 level converter would be required to get close to the 99.3% efficiency of the transformer, and this would approximately triple converter the size.

Table I

Survey of various commercial grade inverters.

| Type | Power MVA | Weight kg | Volume m^3 | kVA/ kg | kVA/ m^3 |
|---|---|---|---|---|---|
| IGCT based 3-level NPC | 3.1 | 3680 | 8.48 | 0.842 | 365.566 |
| IGCT based 3-level NPC | 3.6 | 3680 | 8.48 | 0.978 | 424.528 |
| IGCT based 3-level NPC | 4 | 3680 | 8.48 | 1.087 | 471.698 |
| IGCT based 3-level NPC | 4.5 | 3680 | 8.48 | 1.223 | 530.660 |
| IGCT based 3-level NPC | 4.9 | 3680 | 8.48 | 1.332 | 577.830 |
| IGCT based 3-level NPC | 5.3 | 3680 | 8.48 | 1.440 | 625.000 |
| IGCT based 3-level NPC | 5.8 | 3680 | 8.48 | 1.576 | 683.962 |
| SCR-Cycloconverter | 11.2 | 9032 | 24.6 | 1.240 | 455.285 |
| SCR-Synchroconverter | 7 | 9447 | 25.27 | 0.741 | 277.008 |
| **SCR - cycloconverter estimated** | **8** | **10797** | **28.88** | **0.741** | **277.008** |
| **GE 60 HZ, 8 MW Transformer, 99.3% efficient** | **8** | **18182** | **47.585** | **0.440** | **168.120** |
| IGBT Isolated H-bridge per phase, 15 phases | 21.8 | 17000 | 20 | 1.282 | 1090.000 |
| 5-level IGBT diode clamped | 50 | 55000 | 76 | 0.909 | 657.895 |
| UT CEM's ARCP for ALPS | 4 | | 13 | | 307.692 |

## 9. COMPARISON – RESULTS

Table II summarizes the above discussion for loss for the three systems shown in Fig. 5 - Fig. 7. The last row of the table uses the boundary element data summarized in Fig. 4. Note the additional dc transmission loss due to the result from (3).Table III quantifies the information for loss. The 60 Hz system shows the greatest efficiency, followed by the 420 Hz system, followed by the dc system.

Table II

Summary of losses for the separate systems.

| | dc | 60 Hz ac | 420 Hz ac |
|---|---|---|---|
| **Gas Turbine Generators** | - | - | - |
| **50 MW 3600 RPM** | 2.5% @ 50 MW | 2.5% @ 50 MW | 3.25% @ 50 MW |
| **20 MW 5000 RPM** | 3.4% @ 20 MW | 4.9% @ 20 MW | 3.4% @ 20 MW |
| **10 MW 12,000 RPM** | 5.5% @ 10 MW | 7% @ 10 MW | 5.5% @ 10 MW |
| **Converter** | 5% @ 79 MW | 2.5% @ 1 MW + 1% @ 7 MW + 3% @ 72 MW | 4.5% @ 1 MW + 2% @ 7 MW + 3% @ 72 MW |
| **Transmission** | 1.33% @ 80 MW | 1%*1.139 @ 80 MW | 1%*(2.207) @ 80 MW |

Table III

Losses computed for an 80 MW Destroyer using a dc, a 60 Hz and a 420 Hz system.

| | **dc fraction loss** | **dc loss (W)** | **60 Hz fraction** | **60 Hz loss** | **420 Hz fraction** | **420 Hz loss** |
|---|---|---|---|---|---|---|
| Gas Turbine Generators | - | | - | | - | |
| 50 | 0.025 | 1.25 | 0.025 | 1.25 | 0.0325 | 1.625 |
| 20 | 0.034 | 0.68 | 0.049 | 0.98 | 0.034 | 0.68 |
| 10 | 0.055 | 0.55 | 0.07 | 0.70 | 0.055 | 0.55 |
| Converter | 5% @ 79 MW | 3.95 | 2.5%@ 1 MW + 1% @ 7 MW + 3% @ 72 MW | 2.255 | 4.5%@ 1 MW + 2%@ 7 MW + 3% @ 72 MW | 2.345 |
| Transmission | 1.33% @ 80 MW | 1.064 | 1%*1.139 @ 80 MW | 0.9112 | 1%*(2.207) @ 80 MW | 1.7656 |
| Total loss | | 7.49 | | 6.10 | | 6.97 |

## 10. DISCUSSION

There are obviously many complex issues which surface in evaluating the right ship distribution system. Reliability and ease of maintenance are certainly two additional considerations. Both would argue for the 60 Hz system as well. The multiple pumps and smaller motors throughout the ship become standard off the shelf components. The number of solid state devices requiring possible repair goes down. Fault interruption is straightforward. Only one 8 MW transformer is required; it has a high efficiency and demands no maintenance.

An argument presented in defense of the dc system is that so much of the load is already dc, or could be. This is a veiled truth. Florescent lighting will want ac, and it is the most efficient for lumens/watt. Computers will require 5 V and +/- 12 V. Unless the additional lights are switched to these voltages, yet another dc voltage is required. Every dc system requires dc to dc converters either at the site of use or another distribution system is required. The dc system will demand multiple dc to dc conversions, all of which incur more loss than an ac converter. All interrupt devices will be larger and more costly for a dc system.

The fact that a 420 Hz system is becoming increasingly less efficient is fundamental to the reason that the airline industry uses 400 Hz and not 1 kHz. Motors, generators, and transformers all become smaller, but the loss becomes unacceptable.

## 11. CONCLUSION

The Navy can offset cost by maximizing efficiency, an emphasis that is receiving greater attention. To the extent that this directive is preeminent, the ac 60 HZ system should be favored. The 60 Hz system shares the following additional advantages:

11.1. fault interruption ease

11.2. lower maintenance for hotel loads

11.3. component availability and low cost for small pumps and motors

Inherent stability of the grid since a generator failure is first met with a systemic frequency reduction commensurate with reduction in load.

## 12. ACKNOWLEDGMENTS

The authors would like to thank Mark Flynn for many helpful power converter discussions and for the commercial converter survey table.

## 13. REFERENCES

[1] Y. Khersonsky, P. Steimer, and J. Sullivam, “Architectural transformation and innovations in electrical warship power systems,” IMAREST, Engine as a Weapon Conference, London, UK, December 5-6, 2006, pp. 71-80.

[2] J. B. Zgliczynski and E. E. Bowles, “DC link architecture for electric ship integrated power systems enables high power combat systems,” IMAREST, Engine as a Weapon Conference, London, UK, December 5-6, 2006, pp. 13-18.

[3] A. Cavallini, D. Fabiani, G. Mazzanti, and G.C. Montanari, “Voltage endurance of electrical components supplied by distorted voltage waveforms,” International symposium on electrical insulation, Anaheim, CA, April 2-5, 2000, pp. 73-76.

[4] P. Pillay and M. Manyage, “Loss of life in induction machines operating with unbalanced supplies,” IEEE Trans. Energy Conversion, vol. 21, no. 4, Dec. 2006, pp. 813-822.

[5] S. Kim, S.-K. Sul, and Thomas Lipo, “Ac/Ac power conversion based on matrix converter topology with unidirectional switches,” IEEE Trans. Indus. Applications, vol. 36, no. 1, pp. 139-145.

[6] V. Agarwal and S. Nema, “Resonant AC to AC Converter,” IEEE ISIE Conference, Dubrovnik, Croatia, June 20-23, 2005, pp. 495-498.

[7] K. R. Davey and D. Zheng, “ Prediction and use of impedance matrices for eddy current problems,” IEEE Transactions on Magnetics, Vol. 33, No. 4, pp. 2478-2485, July 1997.

[8] William Siegel, Manager, Electric Power Technologies Division, SAIC, 10100 Battleview Parkway, Manassas, VA 20109-2334, personal communication, January 23, 2007.

## 14. BIOGRAPHIES

**Kent Davey** became a Member of IEEE in 1980, a Senior Member in 1986, and a Fellow in 2004. He was born in New Orleans, Louisiana in 1952. He received his BS in EE from Tulane in 1974, his MS in Power Engineering from Carnegie Mellon in 1976, and his MS in physics from the University of Pittsburgh in 1976. He received his PhD in EE from the Massachusetts Institute of Technology in 1980. He completed a Fulbright in Finland on atmospheric physics in 1981.

From 1974 to 1976 he worked at Westinghouse as a large turbine generator designer. From 1979 to 1980 he served as an assistant professor at Texas A&M University. From 1980 to 1994 he served as a tenured associate professor at the Georgia Institute of Technology. From 1994 to 2002, he served as technical director of American Maglev Technology in Edgewater, Florida. He presently serves as a senior research scientist at the Center for Electromechanics at the University of Texas in Austin, Texas. Dr. Davey has research activity in electromechanical machine design, pulsed electromechanical devices, HTS Trapped Field magnets, electroporation, and magnetic stimulation of biological tissue.

Dr. Davey is a Fellow with IEEE and presently serves as editor of IEEE Transactions on Magnetics. He is actively involved in the review of conference and journal papers for various IEEE activities.

**Robert E. Hebner**, Ph.D., is Director of the Center for Electromechanics at the University of Texas at Austin. The Center develops technology, primarily novel motors, generators, and suspension components, and teams with companies to get the technology into the market.

Previously, Dr. Hebner was the acting Director of the U.S. National Institute of Standards and Technology (NIST). In addition, he has directed NIST's Electronic and Electrical Engineering Laboratory, a laboratory with a staff of more than 250. He also worked at the Defense Advanced Research Projects Agency where he developed programs to improve semiconductor manufacturing.

Throughout his career, Dr. Hebner has been active in having authored or coauthored more than one hundred technical papers and reports. He has extensive experience in international technology programs. This work included the modernization of the measurement systems needed to support global trade and the assessment of the effectiveness of government technology programs in stimulating domestic economies.