Variable Speed Electric Drive Options for Electric Ships

David Gritter, Swarn S. Kalsi, and Nancy Henderson

Abstract: Variable Speed Electric Propulsion motors are operated from a variable frequency drive (VFD), which supplies power to motors at a frequency appropriate to the desired speed. These VFD's are normally very heavy and large in size. A variety of designs are commercially available but they have characteristics unsuitable for ship applications. The objective of this study was to evaluate various options for shipboard applications and to recommend designs that meet Navy performance, weight and size constraints. It is possible to dramatically reduce the size and weight of the VFD by optimizing the VFD and the motor as a system, utilizing an optimal distribution voltage, eliminating distribution frequency transformers, and utilizing the weight and size reductions available with liquid cooling.

Three systems were studied in detail: Cycloconverters, series connected low voltage inverters, and multi-level medium voltage inverters using 6kV class IGBT's or similar switching devices.

On the basis of this evaluation, a multi-level diode-clamped pulse width modulated (PWM) drive topology is recommended for Navy ships. A three phase distribution voltage of 6 to 9 kV RMS minimizes the number of series semiconductors and control complexities of the drive.

Index Terms: Marine vehicle propulsion, Motor drives

I. INTRODUCTION

American Superconductor was funded by the Office of Naval Research to investigate the opportunities for the use of superconductor propulsion motors and generators in shipboard applications, primarily the variable speed drive for the ship propulsion and the associated electrical generators [1]. With a goal of reducing size and weight of all components, this study included an evaluation of different electrical distribution schemes employing variations in frequency, phase number, and voltage. The propulsion VFD topology was a major portion of the study, since prior experience had indicated that the VFD was possibly larger and heavier than the propulsion motor.

The study assumed that the motor design could be optimized for use with a particular inverter, and that issues related to dv/dt applied to the motor windings, common mode voltage issues, and other unfriendly VFD/electrical machine interactions [2] could be mitigated by design changes to the motor or VFD, whichever proved most economical to size and weight.

The study looked primarily at a variable speed drive consisting of a propulsion motor of 36.5 MW, operating at a base frequency of 16 Hz driven by one of several different solid state frequency converters. It assumed that the motor voltage and VFD combination could be tailored for a distribution voltage in the 6kV or 9kV range, a voltage that appears to be optimal for both motor insulation systems and reasonably simple VFD's using 6kV class IGBT's, IGCT's or thyristors.

In order to avoid disturbing other shipboard loads on the same distribution system, we assumed that the VFD could introduce no more than 10% voltage total harmonic distortion (VTHD) on the medium voltage distribution system.

Frequency of the distribution system was varied from 60 to 240 Hz. An 8kV DC distribution was included in the study, bringing the generator characteristics into consideration when evaluating the entire system. In particular, the ability of the superconductor generator to operate without significant increase in losses when absorbing significant harmonic currents proved advantageous to the DC distribution system.

Three significantly different VFD topologies were studied:

- A cycloconverter to provide minimal VFD complexity cost, size and weight.
- A series connected array of low voltage inverters for a modular approach which provides isolation between supply and motor and allows the common power electronic building blocks (PEBB's) used in low voltage power converters to be extended to medium voltage applications.
- A conventional multi-level inverter using commercially available 6kV class IGBT's or IGCT's.

Each of these topologies was evaluated in terms of waveform quality at the distribution system and at the motor terminals; motor torque ripple; and weight, size, and efficiency.

Liquid cooling was assumed for all the systems studied. Thus when estimating size and weight, we used packaging approaches that could not be used and would not be adaptable to air cooled systems. This is a significant factor in reducing size and weight from conventional industrial power converters where air cooled systems are usually preferred, and liquid cooled versions may incorporate only minor modifications to the off the shelf air cooled system.

II. CYCLOCONVERTER

The cycloconverter is an attractive choice for a propulsion motor because it employs naturally commutated thyristors to

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produce a low frequency AC waveform on the motor using direct AC-to-AC conversion This technology is already used for ship propulsion [3], with a few limitations listed below:

- Traditional cycloconverters produce subharmonic currents on the distribution system, resulting in poor power quality and possible flicker issues.
- Control problems occur in maintaining low motor current distortion because of discontinuities in conduction where the motor currents cross zero.
- Large line frequency ripple in the motor voltage: Line frequency ripple occurs at the characteristic pulse number of the thyristor bridge, so a 3-phase 60 Hz distribution using a 6-pulse bridge would impose 360 Hz harmonics on the motor voltage.
- Operation at low motor voltages results in low power factor on the distribution system.

The cycloconverter is attractive for ship propulsion in the present study because the distribution frequency may be increased to move the harmonics in the motor voltage to higher frequencies where they can be more easily mitigated. A direct coupled propulsion motor is naturally a low frequency motor suitable for cycloconverter excitation. The number of motor phases and the terminal voltage can be chosen to minimize the problems associated with cycloconverters.

A. *Cycloconverter Topology*

A traditional cycloconverter topology is shown in Fig. 1. Three banks of 12 thyristors, arranged as a full bridge, drive the terminals of a wye connected motor. This topology limits the allowable firing angle of thyristors in different bridges but connected to the same motor winding terminal. Improper firing angles will clearly result in distribution system short circuits.

If the individual motor windings are isolated, rather than wye or delta connected, this limitation disappears. We also discovered that using a 9-phase motor with the 12 thyristor bridge in a topology shown in Fig. 2, it is possible to eliminate the subharmonics and non-integral line frequency harmonics in the distribution current up to the 13th harmonic.

All thyristor based cycloconverters require an input inductor to limit the rate of change of current (di/dt) in a thyristor that is turning on. These inductors become the major contributor to the weight of the cycloconverter based VFD, so there is a significant benefit to incorporating thyristors with high di/dt ratings. A design favoring low voltage, low current thyristors is more likely to find available high di/dt thyristors. Voltage issues may be resolved by using well known techniques to series the thyristors, while a 9-phase motor design reduces the current requirement toward the bottom end of what is available in hockey-puck thyristor packages.

Capacitors can be added to the distribution system to improve the power factor to a level acceptable to the generator and distribution system.

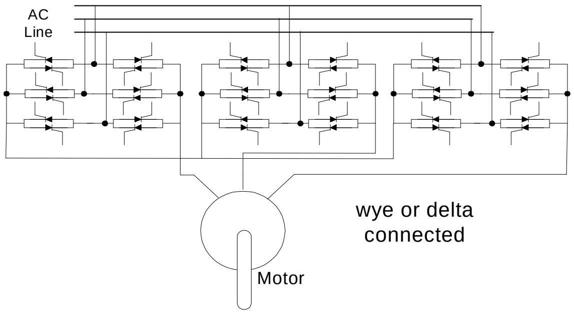

Fig. 1 Conventional cycloconverter topology

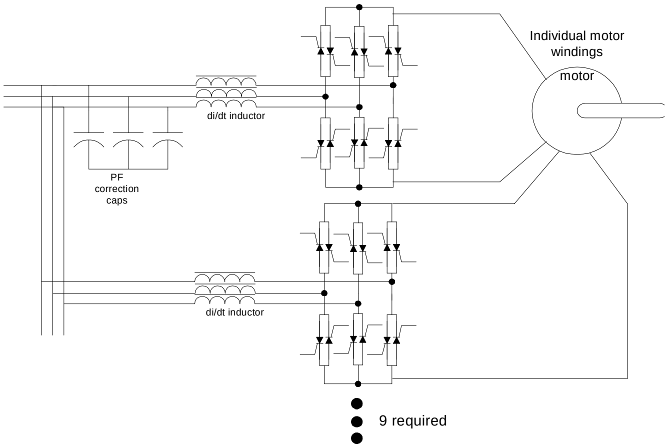

Fig. 2 Proposed cycloconverter topology

B. *Design issues*

In normal design the line side inductor is sized to limit di/dt to about 20 A/μs. Thyristors in the 6kV class are normally rated at 50 to 100 A/μs maximum, but losses increase significantly as the di/dt is increased. Thyristors with di/dt approaching 1000 A/μs are available in lower voltage ranges. Using series stacks of these could reduce the size and weight of the inductors by a factor of three from the values used to estimate VFD weight later in this paper.

The input inductors must be designed to deal with the poor power quality of the individual cycloconverter currents. Inductor current waveforms are shown in Fig. 3, showing that the quality of the current waveform does not improve until all nine building blocks are paralleled at the 3-phase AC distribution bus.

C. *Performance*

The presence of a large 6x line frequency component in the cycloconverter output voltage results in acoustic noise and torque ripple. This is a severe limitation when quiet operation is required. Evaluation of passive and active filters showed that their size and weight is such that the cycloconverter would no longer have any advantage over competitive topologies. Thus the use of a cycloconverter VFD where quiet operation is needed would require a smaller, more cost effective solution involving mechanical isolation of the motor and its drive shaft so that the 6x acoustic noise or torque ripple is confined to the motor.

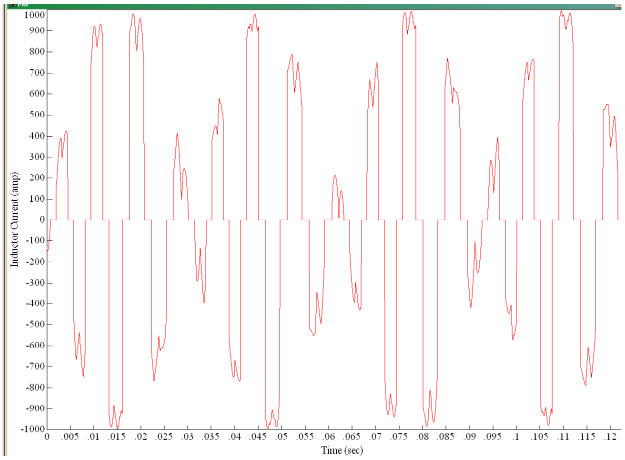

Fig. 3 Individual 6-pulse cycloconverter building block line side current

The expected performance of a cycloconverter VFD was determined by simulation using an instantaneous switching model. This model correctly models instantaneous cycloconverter behavior in creating motor voltage as a function of distribution voltage and in creating the distribution line current as a function of motor current. The VFD was controlled from a common field oriented controller that operates the motor at unity power factor. All modeling was done in VISSIM, a block diagram simulation tool. Results are shown for a 120 Hz, 3-phase distribution system feeding a 9-phase motor.

Fig. 4 shows the line current waveform when the motor is operating at full speed and power. Power factor is 0.784, which is well within the rating of the 36.5 MW generators and current distortion (ITHD) is 9.9 %. Fig. 5shows the equivalent line current at ½ speed (12.5% power), where significantly higher distortion (32.3%) and lower power factor (0.33) is evident

Fig. 6 shows the full speed, full load motor voltage and current. Motor current distortion is about 8%

Table I lists the torque ripple amplitude as a function of operating speed. There is a clear increase in both the amplitude and percentage of torque ripple as motor speed is reduced. The major component of ripple remains at 720 Hz, the 6th harmonic of the distribution frequency.

Simulation of the cycloconverter was also done using a 240 Hz distribution. This simulation indicated that doubling the distribution frequency doubles ripple frequency from 720 Hz to 1440Hz as expected, and halves the amplitude of the major ripple component. A 240 Hz distribution is therefore favorable to a cycloconverter based propulsion drive solution, but makes the availability of thyristors with high di/dt ratings an even more important technical issue.

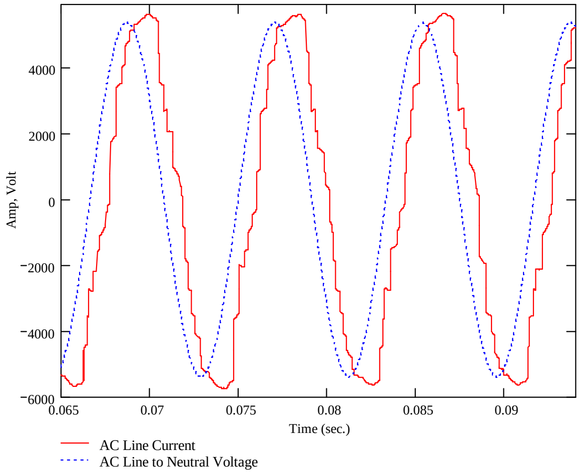

Fig. 4 Full speed, full load cycloconverter distribution current and voltage

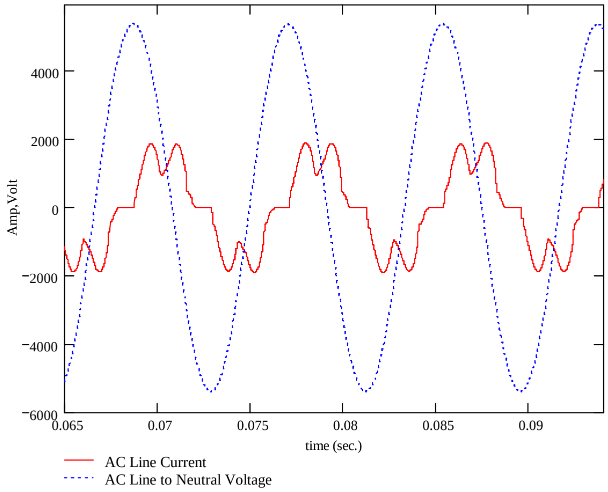

Fig. 5 Cycloconverter line current and voltage at half speed.

Table I Cycloconverter torque ripple as a function of speed.

Speed (%)	Average Torque (Nm)	RMS Torque ripple (Nm)	RMS torque ripple (% of avg.)
100	2.90E+06	2.40E+04	0.824
90	2.35E+06	5.88E+04	2.5
80	1.86E+06	9.36E+04	5.03
70	1.42E+06	1.26E+05	8.74
60	1.05E+06	1.56E+05	14.9
50	7.30E+05	1.80E+05	25

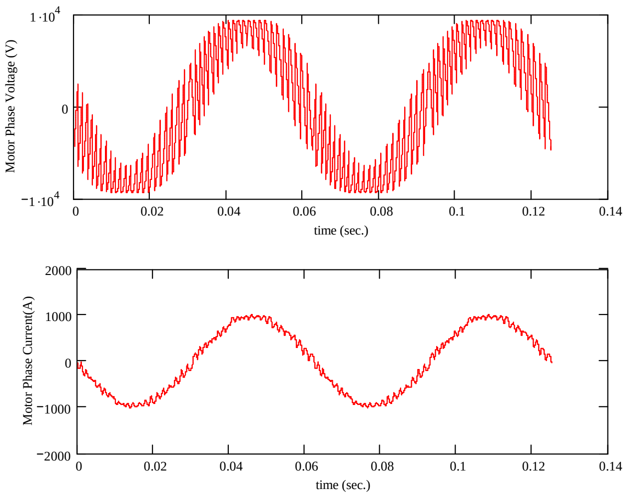

Fig. 6 Cycloconverter full speed motor voltage and current

III. DIODE RECTIFIER

The other two VFD topologies we studied require an intermediate DC bus that must be produced using a diode (passive) rectifier or active rectifier. The rectifier is located at the VFD for AC distribution systems or at the ship's main generators if a DC distribution system is used. While active rectifiers produce very clean distribution current waveforms, they are as large and costly as any other pulse width modulated VFD, and do not need to be used for their regeneration capability, since the shipboard distribution system cannot absorb significant power from the propulsion drives. Thus regenerative operation of a propulsion drive requires that the power be sent either to a resistive load or to another propulsion drive. Both of these can be managed using DC bus connections, making a diode rectifier suitable for the conversion of distribution voltage to the intermediate DC bus.

Fig. 7 shows a typical diode rectifier current when the rectifier is operated from the generator alone (that is, the waveshape is determined by the internal impedance of the generator.) This level of distortion proved to be low enough that the efficiency of superconducting generator was not adversely affected. However, when an AC distribution system is used, the resulting voltage distortion is unacceptable. Thus when the rectifier is placed at the VFD, it is necessary to add an input inductor and 5th and 7th harmonic trap filters in order to maintain a voltage distortion of less than 10%. The resultant distribution voltage and rectifier current waveforms are shown in Fig. 8

IV. SERIES CONNECTED LOW VOLTAGE INVERTERS

There are significant advantages to applying low voltage IGBTs to the propulsion drive. 1200V IGBTs are readily available from a wide variety of vendors. They are rugged, well-proven devices used in low voltage motor control. They switch efficiently in the 4 to 8 kHz range, and exhibit on state voltages of about 2V. Several topologies that utilize low voltage inverters were investigated, including a concept employing low voltage H-bridge inverters connected in series [4] as shown in Fig. 9. Each series connected inverter operates from an isolated DC bus. Obtaining the isolated bus without incurring the cost of a large distribution frequency transformer as is often done for commercial medium voltage drives requires some type of high frequency power conversion stage to reduce transformer size.

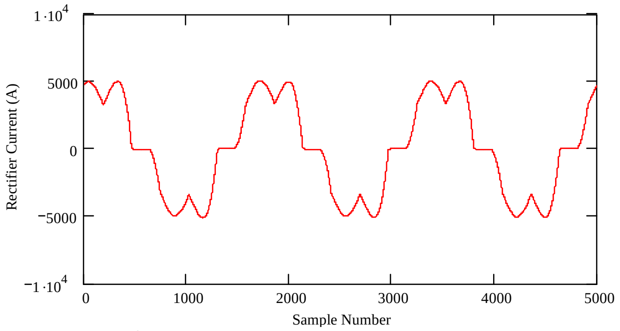

Fig. 7 Diode rectifier current waveshape

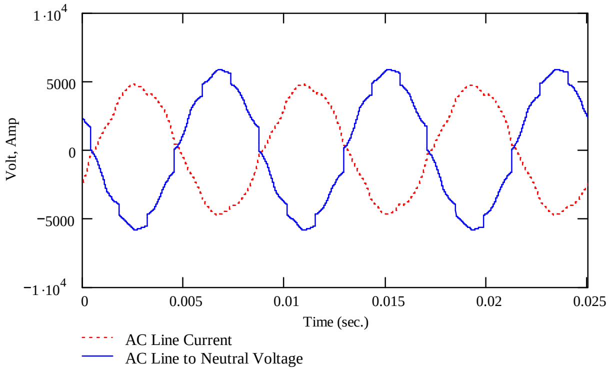

Fig. 8 Distribution line voltage and current with harmonic filtering.

The advantages of this approach are:

- Wide availability of standard semiconductors
- Common building blocks for all shipboard inverters, both medium voltage and low voltage using Power Electronic Building Blocks (PEBBs)[5]
- Isolation minimizes motor common mode voltage problems (wye connected series inverter neutral may be grounded.)
- High switching frequency for very low motor noise
- Small voltage steps to minimize motor winding problems due to dv/dt
- N+1 redundancy obtained at relatively small increase in size, weight, and volume

The disadvantages of this approach include the following:

- Four stages of power conversion are required: distribution frequency rectifier, high frequency inverter, high frequency rectification, and motor stator frequency inverter. This increases the size and decreases the efficiency of this solution.
- The DC bus of the H-bridge inverters feeding the motor see single-phase ripple current, and may need to be significantly larger than in a conventional 3-phase inverters which have a common DC bus feeding all 3-phases. This issue becomes a significant driver of

inverter size if it is feeding a motor at lagging power factor, because the DC-to-DC converter with transformer isolation is capable of only unidirectional power flow. For Operation of synchronous motors, this is not as severe an issue, since the motor can be operated at unity power factor.

- Regenerative operation of the motor is not possible without a significant increase in the complexity of the isolated DC-to-DC converters.
- The DC-to-DC converter does not operate well under lightly loaded conditions, since a quasi-resonant inverter topology is employed which requires a fixed minimum current to insure that inverter commutation is successful.

A. Topology

The basic topology is shown in Fig. 9. A group of series connected isolated DC to DC converters is connected across the rectified DC bus of approximately 9kV. The output of each DC-to-DC converter is an isolated 800V DC bus that feeds an H-bridge inverter using 1200V IGBT's. Inverter H-bridges are wired in series to produce a multi-level output voltage. The series sets are wired in a wye configuration to feed the motor, reducing the number of series connections needed to generate the proper motor line to line voltage. The top H-bridge in each wye leg feeds a motor terminal.

For a 6 kV motor, a 9-phase inverter arrangement is advantageous. This arrangement requires 126 300kW inverter modules. Each series stack requires 7 H-bridges. 18 separate series stacks feed the motor. 18 separate motor windings makes for the simplest and lowest cost VFD, but it is also possible to parallel two series stacks through small sharing inductors to allow 9 individual motor windings.

At low motor power it is possible to operate from only one of the three sets of 3-phase windings in a 9-phase motor. The PEBB concept employed in this topology allows 3-phase sets of series inverters to be re-connected to power a second motor, be de-activated, or have one of two paralleled sets re-connected to a second motor. This flexibility allows continued operation of the entire ship propulsion system in the event of multiple PEBB failures.

B. Transformer

The 300 kW high frequency transformer is constructed using standard nano-crystalline toroidal cores [6]. Each core has an OD of 165 mm and an ID of 105 mm and a thickness of 28.5 mm. A stack of 6 cores is required for the transformer. Primary and secondary windings are 5 turns each when the operating frequency is 50kHz. Litz wire is used to make the windings. Core losses are expected to be about 500W and the flux change within the core is designed to be about 0.3T. The final transformer weighs 28kg and is 0.21m high and 0.195m diameter.

C. DC-to-DC Converter.

The DC-to-DC converter shown in Fig. 10 is a 600kW module built up using two high frequency transformers, each driven by a quasi-resonant H-bridge inverter. A common controller generates and phase shifts the gating signals associated with each transformer so that the input and output DC bus voltage ripple is reduced. Each transformer output voltage is fed to a rectifier employing fast recovery diodes to produce a DC output. Small output inductors are included to allow the inverter to perform limited voltage regulation functions by phase shifting the gating signals between the half bridges of the resonant inverter.

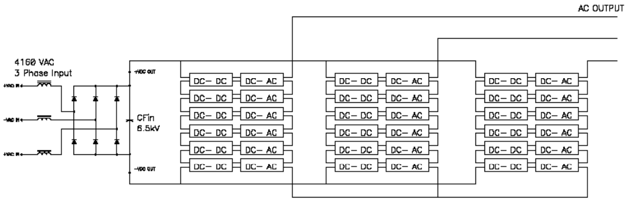

Fig. 9 Series connected low voltage inverters with isolated DC-to-DC converter

Quasi-resonant operation is accomplished by placing a resonant capacitor across each IGBT. When the IGBT is turned off, current commutates into the capacitor, insuring a zero or low voltage IGBT turn-off. Once the capacitor is charged, current commutates to the opposite diode. Once current is flowing in the diode, its paralleled IGBT can be gated for a zero current turn-on. The diode current commutates to the IGBT at the current zero crossing, so there is no significant diode reverse recovery loss. IGBTs optimized for this type of operation have been chosen in conventional electrically isolated modules that can be mounted directly to a chill plate. The final 600 kW DC-to DC converter is estimated to weigh 81kg and measure 0.25m x 0.4m x 0.45m.

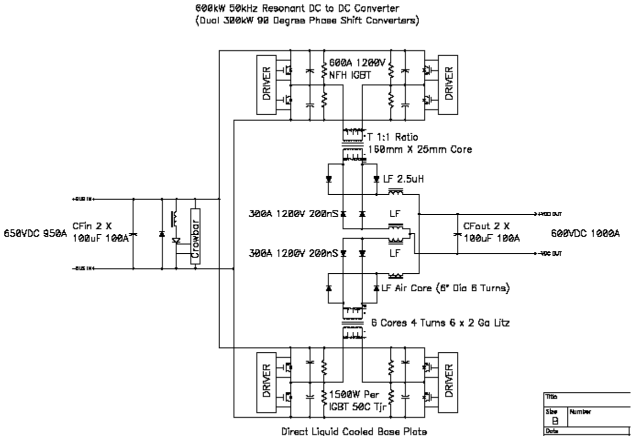

Fig. 10 Isolated DC-to-DC converter schematic

D. DC-to-AC inverter

The low voltage inverter H-bridges that are arranged in series to generate the motor voltage waveform is built using 300 kW modules made from a multitude of paralleled low voltage IGBTs in TO-247 packages. This design is optimized around a liquid cooling system that allows easy mounting of IGBTs to a power printed circuit board. The unit weighs 6.7 kg and measures 0.1m x 0.26m x 0.37 m.

The PEBB building block approach employed for the system allows N+1 redundancy by adding an extra set of converters to each series string. Crowbar thyristors may be added across the input DC bus of the DC-to-DC converter and the output of each H-bridge inverter to short out a failed converter.

E. Performance

Performance of this DC-AC inverter system was studied by simulation. Since a diode rectifier front end common to other schemes was used, the distribution bus interface and power quality issues have not been re-addressed here. VISSIM was used to establish the expected motor current waveforms and torque ripple. A combination of SPICE simulations and data from similar power converters was used to establish DC-to-DC converter and H-bridge inverter losses.

Current waveforms were determined assuming a series stack of seven H-bridge inverters. A control algorithm was developed which allows each H-bridge to switch in a sequence where each H-bridge takes its turn in sequence in generating a fraction of the motor voltage. Each H-bridge inverter can generate three output voltage levels: +V, 0V, and –V where V is the DC bus voltage of the H-bridge inverter. This makes the total series string equivalent a 14-level inverter.

The PWM carrier frequency was set at 8kHz, but the effective switching frequency of any one H-bridge is 1/7th of this, or slightly greater than 1 kHz.The resultant motor voltage and current is shown in Fig. 11. Motor current measures only 0.6% THD and the voltage steps of about 800V minimize dv/dt effects on the motor.

Torque ripple at full speed and load is less than 0.05% of average torque, and at half speed (12.5% load) it remained less than 0.2%. Torque ripple is lowest of any system studied, and the ripple torque amplitude is almost completely independent of speed or load.

Table II categorizes the losses for each component of a 600kW building block. With the multiple stages of power conversion, the efficiency of this system is the lowest of the three systems studied.

V. Multilevel Inverters.

Multi-level inverter topologies operating from a common, non-isolated DC bus are well understood. In particular, the diode clamped and flying capacitor topologies of Fig. 12 are commonly used [7] [8]. Although there is not likely to be a significant difference in size and weight between these schemes, the diode clamped arrangement was chosen for study since the voltage on all DC bus capacitors is always the same, which allows a single component to be used for all capacitors. This topology therefore allows the construction of a modular multilevel building block that can be stacked in series to yield varying numbers of inverter levels for adaptation to different distribution voltages

Inverters designs for a 6.6kV distribution bus and a 9.9kV distribution bus were investigated. Available medium voltage semiconductors, including IGBT's and IGCT's are rated at 6kV breakdown and are designed to operate from a 3.6kV DC bus. Thus it is necessary to employ a 4-level design for the 6.6kV distribution where DC bus voltage is about 9.3kV, and a 5-level design for 9.9kV distribution where the total DC bus voltage is about 14kV. The voltage steps on the motor correspond exactly to the bus voltage per level so the motor winding insulation needs to be designed to tolerate a 3.6kV voltage step with dv/dt of 2 to 6kV/µs

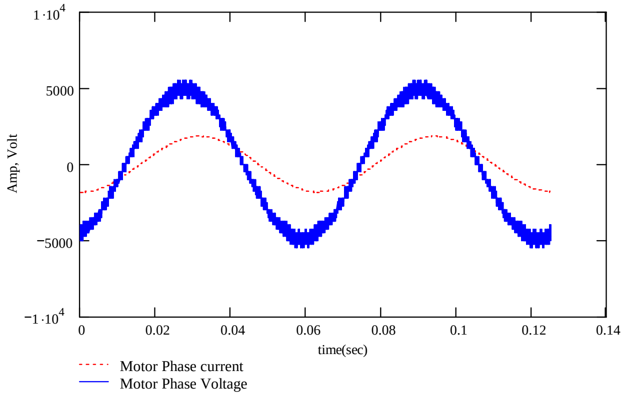

Fig. 11 Series connected low voltage inverter current and voltage waveforms

Table II Series connected low voltage inverter building block losses

Component at 600 kW	losses (watt)	efficiency
DC to DC converter	15360	97.50%
High Frequency Transformer	600	99.90%
Inverter	4000	99.34%
total	19960	96.78%

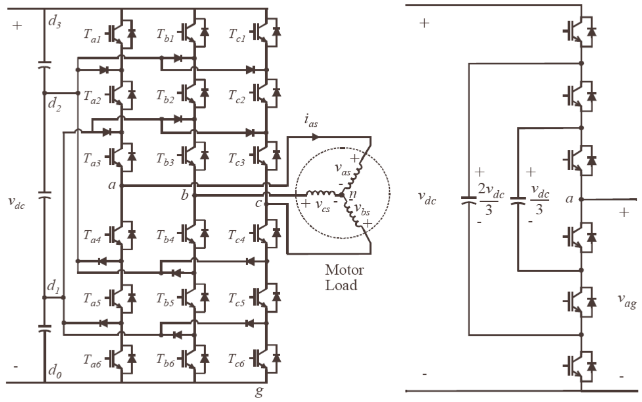

Fig. 12 Diode clamped and flying capacitor multi-level inverters.

A pulse width modulation algorithm that uses a space vector technique with a 1 kHz carrier controls the power semiconductors. This results in an average switching frequency of about 0.4kHz, since every device does not switch during each carrier cycle. The DC voltage on each of the series capacitors is individually measured, and the balance of voltage between the series DC bus capacitors is maintained by modifying the PWM gate signals to employ redundant inverter states. Redundant states apply the same effective voltage to the motor with different combinations of IGBT's turned on. Different redundant states change the way motor current is flowing into or out of the DC bus capacitors; so intelligent selection of the inverter states allows the controller to balance the DC bus voltages [9].

Redundant state selection may affect the common mode voltage applied to the motor, requiring special considerations in motor design.

A. *Semiconductor Choice*

IGBTs and IGCTs are the devices available for building a diode clamped multi-level inverter, and it is not immediately clear which is the most suitable device. IGBT's are available at 5.2kV or 6.5k0V ratings in conventional isolated modules up to 600A (Eupec) and as hockey puck devices to 900A (Westcode). IGBT ratings are typically given as continuous DC current ratings, which generally translate to AC, output RMS current ratings of about ½ the DC rating. IGCTs are available at half cycle RMS current ratings of about 1800A, which translates to an AC output RMS current of about 2000A in a practical design.

Since IGCTs result in a bigger building block, there will be different topologies chosen. For example, a 6-phase 6kV motor requires a phase current of 1756A; therefore a single leg of an IGCT drive is required per phase. A 9-phase motor would therefore under-utilize the available IGCTs. IGBTs, on the other hand, result in the need for paralleled devices per phase and favor 9-phase motor designs.

IGCTs typically have switching losses of over 20 J per switching cycle while IGBT's typically have losses less than 10 J.

IGBTs require a relatively small gate drive circuit and no snubbers unless other circuit considerations require them, while IGCT circuits typically incorporate a very large built in gate driver and require snubbers and other component to limit di/dt and dv/dt.

Hockey puck devices appear to be more appropriate for series strings of devices, because packaging and electrical connections flow naturally. Hockey puck devices may be easier to cool, but if SiN chill plates are used to allow a soft water cooling loop, we find the thermal impedance of hockey puck devices is comparable to that obtained with the electrically isolated IGBT modules.

Rough designs were done using hockey puck IGBTs, electrically isolated IGBT modules, and IGCTs to obtain an estimate of size and weight. Table III summarizes the results.

There is a significant increase in weight and size for the IGCT design, so it was ruled out. We chose to pursue the design using IGBT's in standard isolated modules, since this gave a slightly higher weight and size than hockey puck devices, and would therefore result in a bit more conservative estimate of multi-level VSD size and weight. These devices are also available from multiple vendors and are more likely to evolve due to competitive pressures.

Table III Evaluation of VFD size and weight using available 6kV class semiconductors

Device	Relative weight	Relative size
Isolated IGBT Module	1	1
Hockey puck IGBT Module	0.785	0.8
Hockey puck IGCT Module	2.9	1.24

B. *Performance*

The diode clamped multi-level inverter performance was characterized by simulation of a 9-phase system. Since a 4-level inverter model could not be developed within the scope of the project, a 3-level inverter was simulated. The performance of a 4-level inverter in terms of torque ripple and current and voltage waveform quality would be even better. Fig. 13 shows the motor voltage and current at full load. The voltage steps in excess of 3kV are clearly visible, but the motor current distortion is very low.

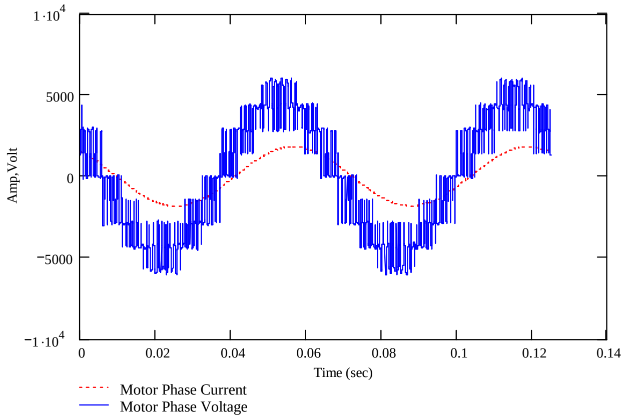

Fig. 13 Full load motor voltage and current with multilevel inverter.

Table IV identifies the torque ripple as a function of speed and load. Simulation showed that at full load there was a significant component of ripple at 6x the distribution frequency because of voltage ripple on the inverter DC bus. At lighter loads, the carrier frequency ripple became the predominant source of torque ripple.

Efficiency calculation was obtained from the simulation by modeling the IGBT's voltage drop as a fixed voltage drop in series with a resistance. Switching loss is estimated from the instantaneous current at turn-on and turn-off using the joule/amp switching loss characteristics provided on the IGBT data sheet. The simulation averages the conductive and switching loss over a full cycle of motor voltage.

Table IV Diode clamped multilevel inverter torque ripple vs. speed

Speed (%)	Average Torque (Nm)	RMS Torque ripple (Nm)	RMS torque ripple (% of avg.)
100	2.90E+06	1.22E+04	4.21E-01
90	2.35E+06	1.86E+04	7.91E-01
80	1.86E+06	2.14E+04	1.15E+00
70	1.42E+06	1.30E+04	9.15E-01
60	1.05E+06	5.62E+03	5.35E-01
50	7.25E+05	1.47E+04	2.03E+00

Because a 3-level simulation was used, the losses for the extra semiconductors in a 4-level inverter were estimated from the 3-level equivalent devices with suitable corrections different switching rates or current flow patterns.

Fig. 14 shows the expected VFD efficiency vs. speed characteristic, assuming that output power is proportional to the cube of speed.

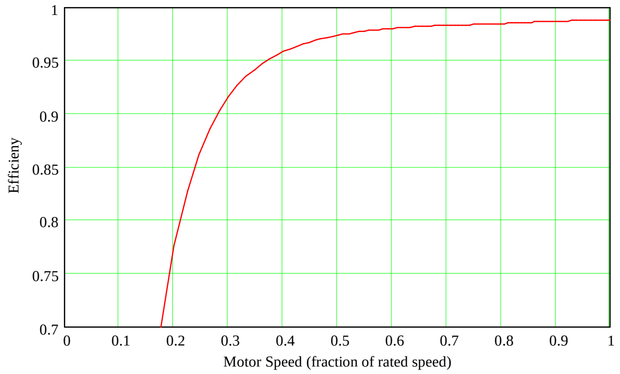

Fig. 14 Multilevel VFD efficiency vs. speed when power is proportional to the cube of speed.

VI. Comparisons and Conclusions

Table V summarizes the estimated volume, weight, and efficiency of a typical VFD for a 36.5 MW propulsion motor, including all magnetic components, harmonic filters and diode rectifiers necessary in an AC distribution system. Weight and volume were estimated by adding up the individual component weight and volume and multiplying the results by factors that have been used in similar studies [10]. Magnetic component weight remains a very significant factor in the total weight of every VFD considered. Efficiency is based on efficiency estimates from the individual VFD simulations.

Cycloconverters are the obvious choice where size, weight, and efficiency are the most critical issues. However they have a disadvantage in power factor, and they produce severe torque ripple in the motor, which makes them unacceptable without special system design effort where quiet operation is important. A cycloconverter based propulsion drive favors ship power distribution design at higher frequencies, with 120 and 240 Hz distribution systems providing significant advantage to reductions in torque ripple.

The series low voltage inverter Topology produces the best motor current waveform and eliminates common mode voltage issues at the motor, but suffers a weight and efficiency penalty due to multiple stages of power conversion and the isolating transformer.

The diode clamped multi-level inverter using 6kV class IGBTs appears, therefore, to be the best general purpose solution for ship propulsion drives where performance, size, and low acoustic noise are all important requirements.

The use of a propulsion VFD that uses an intermediate DC link favors a DC distribution system in the ship, since a diode rectifier located near the power generator may eliminate the size and weight of extra magnetic components and harmonic filters which are otherwise needed to maintain the power quality of an AC distribution system. In the case of the multi-level drive this may represent as much as 25% of the total propulsion system weight.

Table V Diode Clamped Multilevel VSD Size and Weight

Drive Technology	Cyclo-converter	Multilevel	Series connected low voltage
Total weight kg	3850	9820	13700
Magnetics weight kg	3060	2405	6311
Size m^3	7.6	11.13	21.4
Efficiency %	99.3	98.7	97.6

VII. References

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[1] S. S. Kalsi, N. Henderson, D. Gritter, O. Nayak, C. Gallagher, "Benefits of HTS Technology to Ship Systems" presented at IEEE ESTS Workshop, Philadelphia, PA, 2005

[2] D. Gritter, Swarn S. Kalsi, "Ship Electrical System Architecture" Presented at the ACES annual conference, Monterey CA, March 24, 2003

[3] M. Murphy "Variable Speed Drives for Marine Electric Propulsion" Imarest publication, 05/12/1995 Available online from http://www.imarest.org

[4] P.W. Hammond, "Medium Voltage PWM Drive and Method," *U.S. Patent Number 5,625,545*, April 1997.

[5] T. Ericsen et. Al, "Standardized Power Switch System Modules (Power Electronics Building Blocks)", Intertec Power Systems World '97, Sept. 9-13, 1997

[6]Tape-Wound Cores in Power Transformers for Switched Mode Power Supplies [Online] Available at http://www.vacuumschmelze.de/dynamic/en/home/products/coresampinductivecomponents/applications/transformer/powertransformer/coresforpowertransformer.php

[7] K.A. Corzine, "Multi-Level Converters," *The Handbook on Power Electronics*, Edited by T.L.Skvarenina, pages 6-1 to 6-23, CRC Press, 2002.

[8] X. Kou, K.A. Corzine, and Y.L. Familiant, "Full Binary Combination Schema for Floating Voltage Source Multi-Level Inverters," *IEEE Transactions on Power Electronics*, 2001

[9] M. Fracchia, T. Ghiara, M. Marchesoni, and M. Mazzucchelli, "Optimized Modulation Techniques for the Generalized N-Level Converter", *Proceedings of the IEEE Power Electronics Specialist Conference*, Volume 2, pages 1205-1213, 1992

[10] "Superconducting Generator Study Final Report" Prepared by Science Applications International Corporation et. al. , December 2002.