Power Converter Design Options for the 12 kVdc Bus System

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***Abstract*— The US Navy's recent reduction of the dc bus voltage for the new surface combatant, from the original 20 kV to the new target of 12 kV, opens up the design space to a broader range of options than was possible to date. This paper is an attempt to address the opportunities and risks associated with the adoption of multi-level topologies and Silicon-Carbide switches in the design of power converters for the new ships when compared with a more evolutionary innovative path offered by using soft-switching topologies with Silicon switch technology.**

Keywords—Silicon Carbide; SiC; MMC converters; Soft Switching; Hybrid Switching

I. Introduction

For several years, the US Navy has been pursuing the goal of a dc distribution system aboard the next generation surface combatants. The Electric Ship Research and Development Consortium (ESRDC) has been an integral part of this effort and has conducted extensive exploratory designs, especially recently within the S3D tool environment [1]. The dc distribution voltage was originally targeted at 20 kV to exploit the concurrent reduction in power cable size and weight. During that early stage of the research, it became clear that, at this distribution voltage, the power conversion equipment needed on board could not be realized using conventional design and Silicon (Si) power switches without exceeding the desired goal of 10 kton for the whole ship. Rather, it was necessary to employ the emerging new wide band gap semiconductors, of which those based on Silicon Carbide (SiC) were the most promising. Thus, SiC became an enabling technology for the new surface combatant.

In the normal evolution of the project, the US Navy has recently re-targeted the distribution voltage at 12 kV dc. This change is significant because it brings again the distribution voltage within the range that can be handled by conventional converter designs based on Si technology. Therefore, an opportunity presents itself for reconsidering some of the options available in the design of shipboard electronic power converters. Thus, it is prudent to assess the value of the advantages of SiC over Si versus the probable cost increase and the lack of extended long term reliability data for the newer technology.

In addition to the alternatives available now for switch technology, the reduction of the dc bus voltage to 12 kV also presents the opportunity to re-evaluate some options regarding the topology of the inverter. For example, one should consider whether the Multi-Module Converter (MMC) topology, which has gradually gained the status of leading candidate, should remain the preferred topology within the multi-level converter design family. Indeed, going even further, the question arises as to whether a multi-level converter is strictly needed; or rather the application should be handled with the well proven two-level topology that has been the work-horse in power converters for decades. In fact, the previously mentioned ESRDC study conducted with the S3D tool [1] used as a reference design a 10 kton ship populated with several two-level hard-switched Si converters. Against this baseline design all other options were compared, and one of these options indeed contemplated the use of SiC-based MMC type converters.

The US Navy's recent reduction of the dc bus voltage for the new surface combatant, from the original 20 kV to the new target of 12 kV, opens up the design space to a broader range of options than it was possible to date. Therefore, this paper is an attempt to address the opportunities and risks associated with the adoption of the following technologies aboard the new 10 kton surface combatant:

1. Silicon-Carbide switches versus Si switches using improved techniques
2. MMC converter design versus other multi-level topologies
3. Multi-level topologies versus two-level converters.

II. SiC-Based and Si-Based Converters

SiC devices have several major advantages over their Si counterparts:

1. Higher voltage rating (approximately 3x)
2. Lower switching losses
3. Lower conduction losses
4. Higher temperature rating (operation well above 200 ^{o}C possible versus 150 ^{o}C with Si)
5. Higher thermal conductivity (approximately 3x)

It is clear that this impressive list of benefits gives converter designers much broader options for optimizing the performance of their product, options that go well beyond the power switches proper but impact other auxiliary system components as well.

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As mentioned above, the first advantage is somewhat less important today for Navy applications within the new 12 kV dc distribution system than it was only a year ago. Consequently, this study focuses primarily on the other improvements made possible in power converter design, namely higher switching frequency and reduced losses with better loss management. These, in fact, are the items that tend to be most responsible for determining the converter power density. Increasing the switching frequency allows the size reduction of all reactive components in the converter, while improving the heat dissipation ability and reducing losses allows more power to be converted in an overall smaller volume.

However, as of this writing, despite all the penetration of SiC devices in commercial, industrial, or military applications remains very low, probably less than 1% [2]. One obvious reason for this is the fact that a new technology has to overcome some initial obstacles to gain acceptance, amortize the initial development costs, and generate the volume production that can produce the economy of scale and reduce device costs to acceptable levels. Another reason is that, despite their similar ultimate functionality as power switches, SiC devices cannot be treated as simple drop-in replacements in products designed and built with Si devices. SiC devices have characteristics that are different enough from their Si counterparts that transitioning from Si to SiC devices requires an in-depth understanding of their properties and their impact at the system level in order not only to exploit their potential benefits, but also to avoid possibly incorrect implementations.

In fact, the impact at the system level of the use of what we may consider the best approximation of an ideal switch can become a determining factor. Thus, while the ability of SiC devices to operate at a much higher frequency than Si devices leads to an improvement of power density by allowing the reduction of the size of passive reactive components, it also forces more stringent attention to distributed parasitic reactive elements (stray inductances and capacitances). Any delay in the power circuit, for example, between the gate driver and the SiC device, becomes more of a problem, and even the effect of any signal latency in the control circuit can be amplified in its severity. Thus, the need of particular attention to the interconnections and to the control electronics that must now operate at much higher speed than in Si based designs. In summary, higher costs and potential reliability issues are cascaded from those of the switches themselves up to involving those of the rest of the circuit.

Likewise, in regard to their better thermal performance, if SiC devices are truly used close to their thermal ratings, more heat dissipation must be managed from essentially the same area. Furthermore, this may force the operation at higher temperatures of other circuit components.

Finally, if on one hand operation at ultrasonic switching frequencies results in a reduction of audible noise, it also makes any EMI emission more difficult to manage.

In summary, only after the potential advantages are inserted into a coherent system design strategy can the benefits of SiC be evaluated on par with Si.

A contribution to such holistic design approach is the study done within the ESRDC of SiC converters specifically for shipboard duty [3-4]. The intent was to avoid macroscopic safety design factors but base all on realistic and realizable hardware implementation suitable for deployment on a Navy vessel. The converter topology of choice in this study was the modular multi-level converter (MMC) for which a scalable model was developed using either Si or SiC devices. Table I shows the results for comparable designs implemented with Si and SiC devices. The two SiC alternatives refer to two different methods for making the projections, one using the conventional approach (design 1) and the other using an optimized selection of passive components (design 2).

TABLE I. MMC CONVERTER DESIGNS USING SI AND SIC MODULES (CONVERTERS RATED FOR 6 KVDC BUS AND SHIPBOARD DUTY) [3]

	Si IGBT	SiC MOSFET 1	SiC MOSFET 2
Rated Power, MW	1.25	1.75	2.90
Power Density, (MW/m^3)	0.137	0.169	0.220
Power Density SiC/Si, % up	-	23.4	60.6

From the results reported in this study, it is clear that SiC is the technology of choice, also because it is to be expected that the continuing R&D expended in its support will eventually allow the designs of even better converters for a shipboard applications with a 12 kV dc bus than can be projected at the present time. What is also quite interesting is the difficulty of translating its preponderant advantages in device specifications into proportional gains at the system level. As Table I shows, despite the considerably superior specifications of SiC versus Si devices, the power density improvement is projected to be in the 25-60% range.

One temptation when comparing an emerging technology with a mature one is to compare optimized point designs employing the new components with an otherwise static background of established designs using the old ones. This ignores the fact that alternative improved methods of using the old technology are continuously being developed. If they are not commonly used, it is typically due to economic market pressures, but very often they could be implemented with additional costs that are still much smaller than those required by the new methods. Thus, the old technology becomes now a moving target, and, even if it cannot be pushed to match the performance of the new, it usually retains an advantage in terms of cost, availability, and established reliability.

This is certainly the case of Si based converters for 12 kV dc service. The study in [3] used as reference a commercial MMC converter using Si devices, which most likely had no provision for reducing switching losses, since this is the norm in the commercial market. Switching losses are by far the dominant losses in high switching frequency applications like those envisioned for shipboard applications, typically dwarfing conduction losses.

In the last 30 years, several concepts for reducing switching losses have been developed using, for example, so called soft-switching techniques for Si based converters. With these methods, switches are turned on or off at either zero voltage across the switches or with zero current through the switches. Therefore, in such conditions, the switching losses would be theoretically zero. Of course, these techniques for Si converters come at the price of more complex topologies and controls, but with a total cost still well below that of new SiC based designs. Their improved performance has been well demonstrated [e.g. 5-6]. Furthermore, soft-switching can be implemented in both 2-level and multi-level converters [7].

The implementation of soft-switching in Si converters will essentially eliminate one of the main advantages of SiC devices, namely lower switching losses. It will also allow operation at switching frequencies comparable to those achievable with SiC devices, thus making possible a projected reduction of reactive components similar to those anticipated for the SiC designs.

Another technique proposed for reducing switching losses is that of using hybrid switching, which means that each IGBT switch in the converter is paralleled by a MOSFET switch [8]. This hybrid combination combines the advantages of both types of switches, namely the higher switching speed of the MOSFET and the lower conduction loss of the IGBT. Although this method doubles the number of switches it is typically simpler than the soft-switching method. In any case, hybrid switches can be used also in a soft-switching converter architecture combining, therefore, both methods [9].

Keeping these considerations in mind, it is fair to conclude that the projected 25-60% improvement in power density of SiC converters will be much smaller with respect to Si-based converters, whether using soft-switching, hybrid switching, or both.

III. CONVERTER TOPOLOGIES

Another observation that can be made looking at the data reported in Table 1 is the very low power density of the reference Si design. It is true that this reference design includes provisions for shipboard use, which make it less power dense than its commercial counterpart. In [3], since the commercial MMC Si converter is reported to have a power density of 0.201 MW/m^3 while that for shipboard use is 0.137 MW/m^3, the penalty in power density due to qualification for maritime duty is approximately 32%.

In any case, a 1.25 MW commercial duty Si converter with a 6 kV dc bus should have a power density larger than 0.201 MW/m^3. A cursory look at commercially available converters with these specifications would indicate that a power density of at least 0.4 MW/m^3 is common in multi-level industrial converters and is often higher [10]. This is twice the power density of the commercial MMC converter used as reference in [3]. The difference can only be attributed to the different topologies used, since most commercial converters are based on the Neutral Point Clamped (NPC) topology instead of the MMC topology.

A legitimate question, then, is what makes the MMC topology compelling, and why not adopt a more power dense topology like the NPC? A strong case can indeed be made for the MMC topology based on the following points [11]:

a. strictly modular construction

b. nearly sinusoidal voltages and currents

c. no need for ac filters

d. no dc bus capacitor

e. fast control of both ac and dc side including fault blocking capability.

Among its disadvantages can be cited the more complex control, the potential for circulating currents, and the more challenging power density.

Another element of concern is the reliability of the MMC converter due in part to the larger number of components used. The benefits of cell redundancy on reliability have been discussed but it has also been noted a diminishing return after a certain level of redundancy due to the ever more complex control required [12]. Additionally, the benefit afforded by the MMC topology of switching individual cells at lower frequency to reduce switching losses is balanced by the increase in voltage ripple across the capacitors, which affects negatively their and thus the converter’s reliability [13]. Along the same line, it is worth remembering that the MMC is one of the newer topologies and, therefore, one with the fewer number of operating hours in the field.

It is worth mentioning that a study conducted for a private sponsor by the Center for Electromechanics of the University of Texas in 2010, which included a very detailed performance and reliability analysis among various Si-based converter options for a 5 kV dc bus, 2 MW applications, resulted in the scores tabulated in Table II. While this study did not include MMC converters proper, it did include their precursor topology, the cascaded H-bridge. What is striking about the results is that, using the scoring criteria of the sponsor, all topologies scored within +/- 8% of the average, although the 3-level NPC topology scored the highest. Furthermore, it cannot be ignored that the standard 2-level voltage source inverter scored very close to the average. It is very probable that the scoring that resulted at the time of this study would not be very different from one that could be done today, if the criteria used are not abnormal. This is also borne out by a simple visual evaluation of the tabulated data.

TABLE II. COMPARISON OF VARIOUS MV CONVERTER TOPOLOGIES

(2L-VSI = 2-LEVEL VOLTAGE SOURCE INVERTER

3L-NPC = 3-LEVEL NEUTRAL POINT CLAMPED

3L-CHB = 3-LEVEL CASCADED H-BRIDGE

3L-FC = 3-LEVEL FLYING CAPACITOR

PWM CSI = PWM CURRENT SOURCE)

ITEM	2L-VSI	3L-NPC	3L-CHB	3L-FC	PWM CSI
Redundant states	~	YES	YES	YES	~
Control complexity	LOW	~	~	HIGH	LOW
Capacitor voltage balance required	NO	YES	YES	YES	NO
Modularity	YES	NO	YES	YES	YES
Fault tolerance	GOOD	~	GOOD	GOOD	GOOD
Regenerative design complexity	~	~	HIGH	~	LOW
Isolated dc bus supplies	NO	NO	YES	NO	NO
Auxiliary capacitors needed	NO	NO	NO	YES	NO
Auxiliary diodes needed	NO	YES	NO	NO	NO
Freewheeling diodes needed	YES	YES	YES	YES	NO
Load filter capacitance needed	~	~	NO	~	YES
Load filter inductance needed	~	~	NO	~	NO
Suitable for low switching frequencies	~	YES	YES	NO	YES
Harmonics, dv/dt output	HIGH	MEDIUM	LOW	MEDIUM	LOW
Dc link inductor needed	NO	NO	NO	NO	YES
Dc link capacitor needed	YES	YES	YES	YES	NO
Inherent open circuit protection	YES	YES	YES	YES	NO
Inherent short circuit protection	NO	NO	NO	NO	YES
Potential LC resonances	~	~	~	YES	YES
Dynamic response	GOOD	GOOD	GOOD	GOOD	POOR
Efficient control at fractional loads	GOOD	GOOD	GOOD	GOOD	POOR
Scalability	NO	~	YES	YES	YES

All these various considerations seem to point out that the decision in favor of a topology is not an easy one. For example, the ability of SiC to withstand higher voltages would be best exploited using it in a 2-level converter, which also would result in high reliability of operation, based on the fact that this topology has been the industry work-horse for several decades. This choice may also result in a very good power density, although it would not include intrinsically a fault blocking capability and would have poorer performance from the standpoint of harmonics.

IV. Conclusions

A basic comparative examination is presented in this paper between converters designed with SiC switches, and converters designed with Si switches configured and driven in a manner to minimize switching losses (soft-switching mode and/or hybrid switching). Unquestionably, SiC is expected to be the preferred choice for future switch technology for converters in the MW power range. At the present time, however, despite continuing progress [14], SiC devices are still handicapped by high manufacturing costs and low availability.

It is to be noted, that both these alternatives, SiC and Si switches with techniques minimizing losses, would represent an advancement of the state of the art, as no converter of either type is currently being manufactured in the MW power class. Both these options promise the best power density specifically for converters considered for operation directly off the 12 kV dc bus of the planned new Navy surface ships.

Likewise, some basic considerations have been made about the MMC topology and its comparative advantages with respect to other topologies. Ultimately, the question that must be addressed is whether the many benefits of MMC are worth reducing converter power density by a ratio that can approach 2:1.

Overall, it does not seem that a compelling reason exists at the present time for adopting SiC switches due to a significant performance advantage with respect to soft-switched/hybrid-switched Si technology in a 12 kV dc bus system. Likewise, a persuasive case cannot be made for implementing a multi-level MMC topology on the same bus system. In any case, it must also be observed that, even if the answer to both these questions is affirmative, not all converters aboard a ship would need to be SiC-based and/or MMC-type. It is likely that these new technologies will be reserved for the higher power converters only, and that all other converters below a certain threshold will remain of the more conventional types. Even so, given the much less extensive experience base accumulated to date with the new technologies, their potential higher costs, and the tight timetable for deploying the units on board the new vessels, it would seem prudent to adopt designs that, while still innovative, reduce considerably the risks of the final product.

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