# Next-Generation SiC/GaN Three-Phase Variable-Speed Drive Inverter Concepts

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## Abstract

Variable-speed drive (VSD) systems should feature high power density and low installation costs, offer wide input and/or output voltage/motor speed ranges and ensure low EMI without requiring shielded motor cables. Accordingly, next-generation high-switching-frequency SiC/GaN PWM inverters should integrate LC output filters and generate continuous output voltages to prevent conducted or radiated EMI, reflections on long motor cables, high-frequency motor losses, dv/dt-related motor insulation stresses and bearing currents, such that conventional low-cost motor technology can be utilized. This short paper complements a keynote presentation and briefly describes new three-phase buck-boost PWM inverter topologies with sinusoidal output voltages currently under research at the Power Electronic Systems Laboratory of ETH Zürich. First, a new phase-modular buck-boost inverter concept (Y-inverter) is introduced and subsequently condensed into a three-phase current DC-link DC/AC converter that employs an input-side single-bridge-leg voltage-to-current DC/DC conversion. Next, the four-quadrant switches of the converter's DC/AC stage, formed by common-source connection of conventional unipolar power MOSFETs, are replaced with novel dual-gate monolithic bidirectional GaN switches with bipolar voltage blocking capability and small chip area. The implementation of the resulting buck-boost DC/AC converter requires only a single low-volume magnetic component and allows a seamless extension to three-phase AC/AC operation. Thus, the converter concept has to be seen as potential competitor to state-of-the-art voltage DC-link converter systems for future industry applications and even as preferred choice over AC/AC matrix converters which show a higher output voltage filtering effort.

## 1 Introduction

Today, variable-speed drives (VSDs) are core elements of industrial automation and robotics, and are widely used in material processing and for driving pumps, fans and compressors. Typically, a three-phase IGBT-based PWM inverter stage with voltage DC-link (voltage source inverter, VSI) is employed for supplying the electrical machine. The switching losses of the IGBTs and anti-parallel freewheeling diodes are limiting the switching frequency to values of $f_\mathrm{s} < 16\,\mathrm{kHz}$, which is still within the audible range. Furthermore, a relatively large total chip area / power module footprint is required and the constant, i.e., current-independent, on-state voltages of the bipolar power semiconductors result in relatively low part-load efficiency.

In contrast, novel SiC or GaN power MOSFETs, which are competitive with IGBTs when considering system-level costs, feature small chip areas, internal freewheeling diodes and enable synchronous rectification with ohmic conduction characteristics and hence high part-load efficiency. Moreover, the significantly higher switching speeds of these power semiconductors enable switching frequencies of $f_\mathrm{s} > 100\,\mathrm{kHz}$. This facilitates an integration of a single-stage or a two-stage LC output filter into the inverter system housing [1]–[3], i.e., the generation of continuous (sinusoidal) output voltages. Smooth output voltages prevent harmonic losses in the motor known from IGBT-based drive systems without output filters, and prevent transient overvoltages caused by impedance mismatches in case of long motor cables, as well as common-mode ground currents that would reduce the bearings' lifetime. Furthermore, there are no conducted or radiated high-frequency electromagnetic emissions, i.e., it is

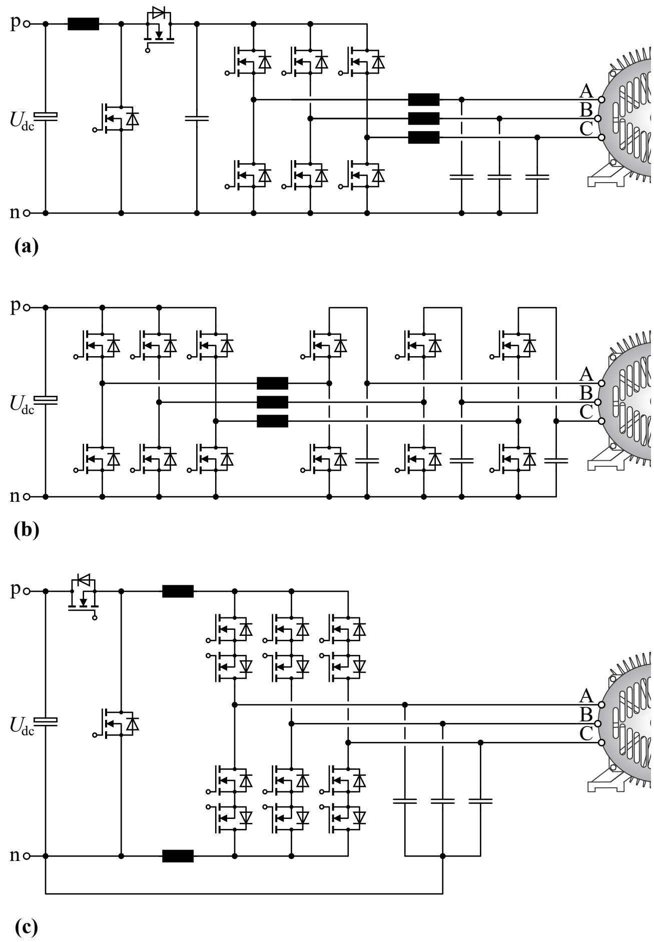


**Fig. 1:** **(a)** Realization of a three-phase buck-boost DC/AC converter by combining a DC/DC boost converter and a conventional voltage source inverter (VSI) topology with LC output filter referenced to the negative DC rail. This filter arrangement provides simultaneous differential-mode and common-mode attenuation and facilitates independent operation of each bridge-leg with triangular filter inductor current (S-TCM, [4]), ensuring zero-voltage switching (ZVS) over the full fundamental output voltage period and thus high power conversion efficiency at high switching frequencies. **(b)** Novel phase-modular inverter topology (Y-Inverter, [5]), which distributes the boost-type bridge-leg of (a) among the phases and utilizes the filter inductor of each phase for achieving buck-boost functionality. **(c)** Combining the input-side buck-type bridge-legs and inductors of (b) into single components results in a three-phase buck-boost current source inverter (CSI) structure with input-side voltage-current conversion. The four-quadrant switches of the DC/AC output stage are advantageously replaced with single devices, i.e., monolithic bidirectional switches (see Fig. 2b), resulting in a low-complexity and low-volume converter system.

not necessary to employ shielded motor cables. All in all, this clearly simplifies the installation of drive systems. Moreover, compared to direct connection of inverter and motor, i.e., without an output filter, lower requirements with respect to motor winding insulation and high-frequency losses facilitate a notable cost reduction. In addition, the audible noise typical for IGBT PWM inverters operating with relatively low switching frequencies can be avoided, and an improvement of the part-load efficiency of the overall system, i.e., of inverter and motor, by several percentage points can be achieved. Initial commercial products [2] and publications of academic institutions [6] demonstrate these benefits.

The further development of drive systems targets the minimization of the output filter's construction volume by employing high switching frequencies and operating modes with low switching losses or multilevel realizations of the inverter bridge-legs. Furthermore, the inverter functionality should be extended to comprise buck-boost capability. As an ultimate goal, the inverter stage should be integrated into the motor housing [1], [7].

For the sake of brevity, only the buck-boost extension of the basic VSI topology to enable wider input or output voltage ranges, i.e., a wide speed range of the motor, is outlined in the following. Inverters of this type are currently a core research topic of the Power Electronic Systems Laboratory of ETH Zürich. In view of the prospective availability of monolithic GaN and SiC power semiconductors with bipolar voltage blocking capability and full control of the bidirectional current flow, this research covers also inverter topologies with current DC-link (current source inverters, CSI). For a more detailed description of the functionality and the design of the circuits discussed in the following, please refer to the literature [1], [4], [5], [8]–[10].

## 2 Three-Phase Buck-Boost DC/AC Converters

In case of battery or fuel cell supply of a variable-speed drive system, the DC input voltage widely fluctuates, depending on the load state and the battery's state of charge. In the simplest case, a DC/DC boost converter stage placed at the drive system's input can compensate these input voltage

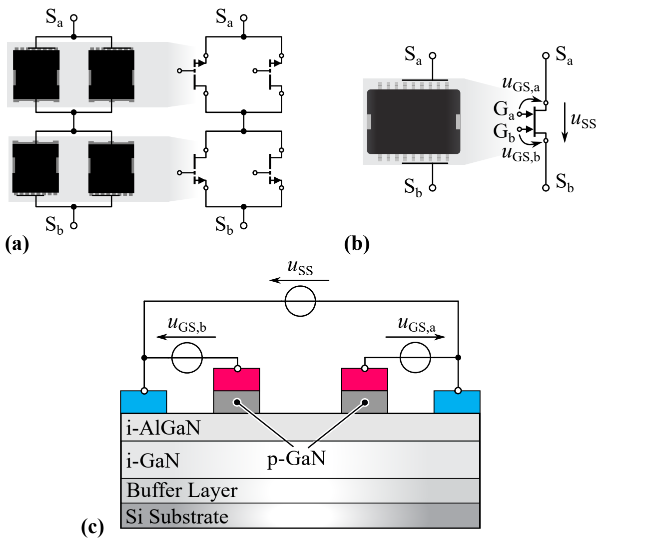


**Fig. 2: (a)** Realization of a four-quadrant switch by common-drain connection of power transistors with unidirectional voltage blocking capability. In order to compensate the increase of the on-resistance resulting from the (anti-)series connection, 4 devices are required. **(b)** Accordingly, a monolithic bidirectional switch (M-BDS) facilitates a substantial reduction of the total chip area. **(c)** Simplified internal structure of the novel 600 V GaN M-BDS analyzed in [11].

variations (see Fig. 1a). However, all bridge-legs then operate with high DC voltage (defined by the maximum input voltage), and the topology requires a total of 4 inductive components. Furthermore, the continuous operation of the DC/DC stage, i.e., the two-stage energy conversion, degrades the converter efficiency [9].

If, in contrast, a boost-type bridge-leg is inserted between the output filter inductor and the filter capacitor of each phase (see Fig. 1b, the resulting converter topology is denoted as *Y-inverter*), the switching operation can be limited to either this bridge-leg or the corresponding buck-type bridge-leg of the main inverter stage at any given time. Like any conventional inverter, in the simplest case the system then generates output phase voltages (with respect to the negative DC rail) that consist of a sinusoidal component and a DC offset. This offset voltage does not affect the motor currents due to the open motor star point. Advantageously, a phase module switches either only the buck-type bridge-leg or only the boost-type bridge-leg, depending on the output voltage to be generated, which results in a quasi-single-stage energy conversion. Because of the sinusoidal shape of the output voltages, the switched voltages are lower than in the system shown in Fig. 1a. Accordingly, even for high switching frequencies, which are advantageous regarding the construction volume of the magnetic components, high efficiencies can be achieved [5], [12].

It is now interesting to consider a partial integration of the phase modules into a three-phase converter structure with only a single buck bridge-leg and, advantageously, only a single inductive component. This leads to the known topology of a current source inverter (CSI) with an input-side voltage-to-current conversion stage (see Fig. 1c, [10]). The system still features buck-boost capability and generates continuous output voltages. Furthermore, if the input-side DC/DC buck-stage is used to shape the DC-link current according to the positive envelope of the three-phase motor currents, for low motor speeds only two out of three bridge-legs of the output stage need to be switched at any given time (2/3 modulation, [10]), which substantially reduces switching losses. However, the switching elements of the DC/AC stage are now exposed to blocking voltages with positive and negative polarity, and thus must be realized as a relatively complex anti-series connection of transistors, which results in a doubling of the on-resistance. In order to realize again the low conduction losses of a single transistor, a total of 4 individual switches must be employed (see Fig. 2a).

Novel monolithic AC power semiconductor switches (monolithic bidirectional switches, M-BDSs, see Fig. 2b, [1], [11]) with bipolar voltage blocking capability and bidirectional current controllability require only a slightly larger chip area compared to a single (unidirectional) switch; consider, e.g., 600 V drain-drain M-BDSs [11] or SiC M-BDSs for higher blocking voltages that are currently under development [13]. The DC/AC stage can then again be realized with only 6 switching devices (compare Fig. 1a and Fig. 3a) and the overhead remains limited to a doubling of the number of gate drives and the implementation of a four-step commutation scheme [10].

## 3 Three-Phase Monolithic Bidirectional Switch Current DC-Link DC/AC and AC/AC Converters

GaN M-BDSs, which in addition to a normally-off variant also exist in a normally-on variant [11] that is advantageous regarding the realization of protection concepts, form the general basis for the future use of three-phase DC/AC or AC/AC current DC-link converters. As shown in Fig. 3b, an AC/AC converter then requires only 12 M-BDS elements and a single magnetic component [14], whereas three-phase AC/AC voltage DC-link converters employ the same number of switches, but require a total of 6 magnetic components in case a PFC rectifier front-end is employed. It is important to highlight that the AC/AC converter topology also is of clear advantage compared to direct or indirect AC/AC matrix converters [15], because the latter are inherently limited to buck operation and require 3 filter inductors to form a continuous output voltage.

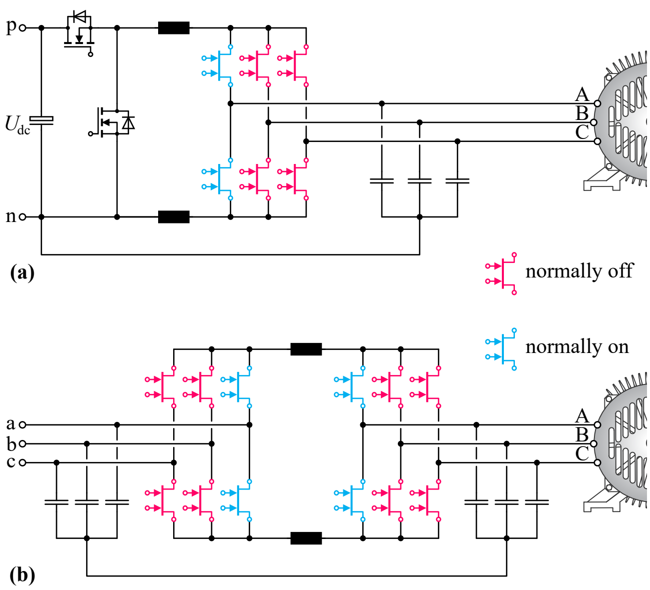


**Fig. 3: (a)** Power circuit of a three-phase buck-boost current DC-link DC/AC converter and **(b)** of a buck-boost current DC-link AC/AC converter. Both converter circuits employ monolithic bidirectional switches (M-BDSs). The DC-link filter inductors could be replaced by a series connection of a differential-mode and a common-mode filter inductor with potentially lower overall volume [16]. Note that the AC/AC converter requires a grid-side EMI filter, which is not shown in the figure. Integrating normally-on devices into the converter structure ensures a freewheeling current path and/or prevents overvoltages in case of gate drive power supply failures.

## 4 Conclusions

We are at the beginning of a fascinating new chapter of power electronics research, comprising the characterization of novel M-BDSs, the identification and evaluation of optimum three-phase current DC-link converter modulation schemes with respect to switching losses and EMI, and the multi-objective optimization and the realization of industry-like demonstrator systems. Furthermore, a comprehensive comparison with voltage DC-link converter systems is mandatory, which also should consider overload requirements as well as protection aspects. Such analyses will close the gaps in the current knowledge base and prepare the future industrial application of the impressively low-complexity current DC-link converter systems.

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