Wide Bandgap High Power Converters and Systems (WBG-HPCS) Consortium Nuggets

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STATCOM-Based Transient Frequency Regulation in a Transmission System

With the increasing usage of renewable energy sources throughout the world, transient regulation is becoming a growing research area. Using a 200 MVA synchronous generator in a simple generator-STATCOM-load configuration, transient regulation with a 100 MVA STAT-COM reduces grid frequency perturbations.

Simulink is used as a simulation environment, having a 200 MVA synchronous generator connected to a 60 Hz simple transmission system through a 210 MVA, 13.8 kV/230 kV transformer. A 5 MW load is also connected directly to the synchronous generator to roughly approximate generation losses. The transformer is then connected to a lossless transmission line. Connected in parallel to the generator is a 100 MVA STATCOM. The transmission line then connects the generation and STATCOM side to a 50 MW, 50 MVar load.

Additionally, a governor is included to control and regulate the frequency of the generator. For the STATCOM, a DG controller is created and simulated, seeking to provide both constant point-of-common-coupling (PCC) output voltage control and constant grid frequency control. A phase-locked loop (PLL) is simulated with a 5 Hz bandwidth to obtain grid frequency information. The frequency controller has a bandwidth of 200 Hz to increase transient regulation speed. In addition, the STATCOM is also simulated with a controller designed to maintain constant grid frequency and to provide constant output power to the grid. These two STATCOM control schemes are simulated in the simple system, with the load having a step between +5 percent and -5 percent, and are then compared to the results of the system simulated with just the governor-controlled generator.

STATCOM-based transient frequency regulation is shown to improve frequency perturbations in a simple system simulation. Frequency takes less time with either STATCOM controller turned on than with just the generator regulating the frequency. Furthermore, overshoot and undershoot of frequency from 60 Hz is decreased with the STATCOM controller. These results provide preliminary optimism that STATCOMs can be used as an effective frequency controller, thus contributing to the stability of renewable power generation.
Ultra-Wide Input Auxiliary Power Supply Using 3.3 kV SiC MOSFETs

Modular multilevel converters (MMCs) are widely used for various applications, including high voltage direct current transmission, motor drives, and renewable energy applications, such as 1.5kV photovoltaic inverters. MMCs are made up of multiple submodules connected in series. In order to enable a seamless operation of MMCs, an auxiliary power supply is needed to provide power to the control unit (see Fig. 1). This auxiliary power supply should accept a wide input range of voltage as the voltage of the submodule (SM) dc-link capacitor fluctuates from several hundred to several thousand volts. Therefore, there are many challenges to designing and developing a converter that can realize the output voltage and the load regulation of the auxiliary power supply for a wide input voltage range.

Currently, there are two stage cascaded options to designing an auxiliary power supply that can meet the requirements of the MMCs. In this work, a single stage flyback converter is used to provide a regulated 48 V at the output from a wide input voltage range. This topology is scalable in terms of input blocking voltage and output power when input is series connected and the output is parallel connected. For this to work, the flyback-based auxiliary power supply incorporates a single 3.3 kV, 30 A discrete device. A prototype is being designed to enable a regulated output from a wide-range high-voltage input.

**Fig. 1.** Wide input, high-step-down ratio converter for auxiliary power supply.
Dual Active Bridge Converter for Medium Voltage Grid Connected Electric Vehicle Charging Application

Dc fast charging stations are becoming more prevalent as the numbers of electric vehicles (EV) on the road have increased significantly. In order to shorten the charging time and extend the driving range of EVs, the development of high-power, off-board charging stations is necessary. The conventional architecture of a dc fast charger incorporates either a local or a centralized front-end converter that interfaces with the medium-voltage (MV) grid via a low-voltage (LV) line frequency transformer. Fig. 1 shows an example architecture of the conventional dc charging station. This type of architecture is limited, due to the large size and installation costs of the line-frequency transformer.

There has been extensive research conducted in order to eliminate this bulky line frequency transformer. One example structure that allows a direct interface between the charging stations and the medium-voltage grid is shown in Fig. 2. A modular system architecture is used to connect multiple converters in series. This type of architecture can provide benefits to reducing the size requirement for the service transformer and it allows a high-power charging of the EV battery from the direct interface to the medium-voltage grid.

In this work, a dual active bridge converter is explored for the MV grid connected EV charging architecture. Furthermore, for the development of the medium-voltage dual active bridge converter, 3.3 kV SiC MOSFETs are used.
Critical conduction mode (CRM)/Triangular current mode (TCM) control with ZVS turn-on for single phase inverters has led to significant improvements in efficiency at high switching frequencies (>300 kHz). The need to push power converters to high switching frequencies results from the drive to achieve higher power density. High-frequency operation helps to achieve higher power density as it leads to a significant decrease in filter volume which consumes most of the space in power converter systems. With recent advancements in wide bandgap device technology, it is possible to operate at high switching frequencies with very low turn-off losses (<5 W for a 1.2 kW three phase 2-level GaN inverter at 1 MHz switching frequency). A huge increase in power density (from 30 W/in$^3$ to 80 W/in$^3$) is achieved by pushing the switching frequency to 1 MHz. The turn-on losses in hard switching continuous conduction mode (CCM) though are still significant (>40 W for the above specified operating conditions). Thus, it is necessary to operate the inverter with zero voltage switching (ZVS) turn-on.

However, as the switching frequency in TCM is voltage dependent, a synchronized operation in all three phases can be achieved by operating in a combination of TCM + DCM operations. This new control scheme for inverters is proposed, however this technique should not be limited to just unity power factor operation. In fact, reactive power control becomes all the more necessary for inverters as the grid can have reactive loads or reactive power requirements. Additionally, TCM control, with ZVS turn-on in inverter mode for full range of power factor, is presented in this work. It is also shown that, even with higher ripple, TCM maintains similar efficiency at 1 MHz as CCM in 50 KHz while achieving 3× power density.

![Fig. 1. Circuit schematic of three phase 2-level inverter with basic principle of ZVS turn-on with TCM.](image1)

![Fig. 2. Phase A current for 1.2 kW, 400 V Vdc, 115 V Vacrms for (a) unity power factor, (b) 30° lagging, and (c) 90° lagging.](image2)
Evaluation of Alternative Active Capacitor Banks for Floating H-Bridge Power Modules

Although single-phase power converters have begun to be widely used, one of the main concerns with this topology is that high-order harmonics exist in the system, including second-order harmonics in single-phase voltage inverters and rectifiers. Traditionally, a large aluminum electrolytic capacitor is used to suppress the voltage fluctuation caused by those harmonics. However, this considerably increases the system’s volume, and thus reduces the power density.

To cope with these disadvantages, methods utilizing alternative active capacitor banks (AACBs) have been applied. The AACB is an additional circuit connected to the system to absorb the fluctuating power and maintain a constant dc-link voltage. Since the fluctuating voltage allowed on the auxiliary circuit is large, the AACB’s capacitance is much smaller than that of the traditional capacitor bank. Moreover, the longer lifetime of the AACB’s film capacitors, compared to aluminum electrolytic capacitors, helps to increase the system’s reliability.

In this paper, the AACB is applied to a floating H-bridge, which is a popular configuration in power converter systems. The floating H-bridge is used as a perturbation injection unit (PIU), which can generate a single-tone frequency current for measuring the impedance. The AACB consists of one full bridge, one inductor, and three film capacitors, and is connected in parallel with the floating H-bridge, as illustrated in Fig.1. Due to the interaction between the injection current and the voltage source in the ac side of the floating H-bridge, multiple harmonic components appear on its dc side. The injection frequency, which is nearest to the grid frequency, causes the largest ripple on the dc-link voltage.

The AACB’s full bridge is regulated so that its output voltage $v_{ab}$ satisfies:

$$\text{Eq. 1} \quad v_{ab} = -v_{C1} \text{ (AC)}.$$

Simulation waveforms obtained from the average model of the AACB with total capacitance value of 3.1 mF interfaced with a PIU are illustrated in Fig. 2.

The current with multiple harmonics on the dc side of the floating H-bridge causes an ac voltage fluctuation across the capacitor $C1$, with peak magnitude of 345 V. From the magnified waveform shown in Fig. 2, the peak-to-peak ripple on the dc-link voltage is around 30 V. Under the same operating condition, therequired value of the capacitor bank using the traditional method is 75 mF. This indicates that the AACB can help reduce the capacitance by more than 20 times compared to the traditional method.
Optimization of Modular Filter for Multi-Channel Three-Phase Interleaved AC-DC Converters

The concept of a decoupled modular filter is introduced to handle EMI, power quality (PQ), THD and circulating current between channels for three-phase interleaved ac-dc converters. A modular filter should be fault tolerant, scalable, and easily replaceable in the field and should operate for single- and multi-channel converter systems. For an interleaved converter, the DM and CM circulating current is attenuated through either three-phase boost or DM (E core) inductors and CM choke respectively. This increases the size of the ac side filter components compared to parallel converters. Also, due to phase cancellation of switching frequency harmonics on the grid side, the THD limit is easily met. This leads to an overdesign of the passive components for N channel interleaved converters.

Keeping this in mind, an N channel optimization procedure is developed to meet EMI, THD specification and individual current harmonic levels. However, no general guideline exists for peak circulating current limits, so the device conduction loss is used as the design criteria.

Several decoupled topologies are proposed based on filter location such as dc-side, ac-side and grid-side filter building blocks (FBB) as shown in Fig. 1. A comparison between the topologies is done using the optimization tool. Also, a comparison between 2L and 3L converter topology itself is made. Resonant frequency, reactive power limits, leakage current requirements and fixed grid-side impedance are considered in the filter design process. A basic terminal model with heat-sink capacitance to ground and ac capacitance to ground is used to represent EMI behavior.

The final design is verified with simulation studies to meet EMI PQ and circulating current limit criteria. The paper includes the optimization algorithm and comparison between decoupled topologies in detail. The analysis is simplified by creating a harmonic decomposition between phases and converters.
The proliferation of grid-tied inverters is redefining the profile of power generation sources in utility-scale power systems. As a result, it is necessary to ensure the continued nominal operation of the power system. A 250 kW grid-tied photovoltaic (PV) inverter with virtual-synchronous-machine- (VSM) based control, shown in Fig. 1, is studied. In contrast to a conventional control scheme that utilizes a phase-locked loop (PLL) for synchronization, VSM-based control emulates the characteristics of a synchronous machine, including its inertia, by using a swing equation. As a result, this method can synchronize via the power-balance method. However, with the variability introduced by PV generation sources, continued stability of the altered system should be ensured.

A system of equations is derived to describe an average model of the grid-tied PV inverter. The small-signal model of this system is obtained through linearization around an operating point. The linearized system allows for stability analysis via parametric sensitivity. Parametric sensitivity is used to observe the sensitivity of a system’s eigenvalues that occur due to variations in parameters. Fig. 2 demonstrates the movement of the dominant eigenvalues as the inertia $J_{spc}$, $H$, in the inertia-emulation portion of the VSM control increases: the complex conjugate pair of eigenvalues draws near the real axis, thus indicating that an increase in this parameter could lead to instability in the studied system.

This work implements this method of analysis in order to parameterize control variables in the VSM block of the control scheme prior to and after synchronization to ensure system stability.
High Power Density GaN-Based Interleaved Buck DC-DC Converter for 1 kW Brick Modules with 98.5% Efficiency

The 48 V intermediate bus converter (IBC) is widely used in telecom, wireless, and aerospace applications. With increasing demand in power by the load, there is a need for higher-power converters with high power densities and high efficiencies. The use of gallium nitride (GaN) devices allows the converter to run at higher switching frequencies with lower loss. At higher switching frequencies, the magnetics are smaller; if planar magnetics are used, the power density and efficiency can be increased.

The buck converter provides regulation, and the LLC-DCX provides isolation for the two-stage converter. The buck converter regulates a variable input from 40 V–60 V to 36 V at the bus at 1 kW. By using an interleaved buck converter, the conduction and switching losses can be decreased. The overall two-stage converter needs to have both high efficiency and power density, so the area of the buck converter is limited to 30x35x7 mm. Based upon the footprint limitations and preliminary size of the inductor, the most optimal topology for the buck converter is a four-phase interleaved buck converter with two separate coupled inductors.

The efficiency and power density of the buck converter will be determined by the design of the coupled inductor. By starting with the footprint and inductance, all of the losses for the entire buck converter can be calculated. The estimated efficiency versus the power density can be plotted, and then a design point can be chosen.

A prototype buck converter has been built, which is shown in Fig. 1, and can achieve 98.5 percent efficiency. Fig. 2 shows the buck converter operation in steady state. The current waveform shows the inverse coupling of the inductor. The two-stage converter was able to achieve 96 percent efficiency with a power density of 680 W/in³, which is higher than the current state-of-the-art two-stage 48 V IBC.
Silicon carbide (SiC) allows wide-bandgap (WBG) devices to operate at higher voltages and switching frequencies. The adoption of these WBG devices means medium-voltage power electronic converters can now advance rapidly. To fully leverage these SiC attributes, power loop inductance must be minimized. The dc-link bus is an area of opportunity for improvement. Reducing conductor spacing not only provides a smaller parasitic inductance, it can also decrease the converter’s overall size and weight; however, higher voltage actually requires an increase in conductor spacing. The manufacturing process for a traditional laminated bus increases the likelihood for internal defects. These defects coupled with a high electric field (E-field) intensity increase the likelihood of partial discharge (PD) within the insulator. PD can cause premature system failure due to insulation degradation. This leaves designers with the tradeoff of increasing the bus thickness for reliability, or decreasing the thickness for improved switching performance.

In this work, a low-inductance printed circuit board- (PCB) based bus is designed to support Wolfspeed’s XHV series 10 kV SiC MOSFET module. The construction process of a PCB exacerbates challenges seen in a traditional laminated bus. A custom dielectric has been selected for PCB construction to further reduce the likelihood of voids, thus further reducing the likelihood of PD.

The E-field was analyzed in high-intensity regions using COMSOL for finite-element analysis (FEA). A midpoint layer separating the +/- dc layers was implemented to reduce the peak intensity near the insulator/connector interface. Geometric techniques for field control along the surface and within the PCB were implemented using the design flow shown in Fig. 1. The results for the final E-field intensity after completion of the design flow are shown in Fig. 2. It should be noted that the field in air is of interest in the bottom image shown in Fig. 2; therefore, data above 2 kV/mm has been restricted and appears white.

Simulation results show that the peak E-field intensity can be reduced by adding a slight offset between conductors at different potentials. Due to the voltages of interest, the E-field intensity in air was most efficiently controlled by forcing the field into an additional dielectric layer placed on the outside of what would normally be the outermost power plane. A prototype has been fabricated and tested to verify a PD free bus at voltages greater than 10 kV.
The LLC resonant converter has been widely adopted in telecom and transportation applications for its high efficiency performance, as well as its ability to achieve zero-voltage switching (ZVS) for all switches under different load conditions. In the LLC resonant converter design, the adoption of wide-bandgap (WBG) devices, especially gallium nitride (GaN) devices, contributes to a significant improvement of efficiency and power density, due to high switching speed, low switching loss, no reverse recovery loss, and small package. This paper presents a 10 kW LLC converter design using 650 V 60 A e-mode GaN HEMTs with wide regulation, achieving high efficiency and high power density simultaneously.

To conduct high current and further reduce the on-resistance, the switching cell of a half bridge with paralleled GaN HEMTs is introduced. Fig. 1 shows the PCB design with four devices in the half bridge located on the top layer of the PCB, and the bus decoupling ceramic capacitor at the back side, which achieves 0.814 nH power loop inductance based on Q3D simulation. A universal connector employed for the switching cell, enables easy replacement and debug capabilities. The heat sink dedicated to the GaN-based switching cell, is designed according to the requirements of device loss, room temperature, and device operating temperature. For verification, a complete procedure in which conducting reverse current with negative gate voltage to measure the thermal resistance is developed, and can be generalized to other converter thermal management applications.

In order to achieve high efficiency and high power density, the transformer and the resonant inductor are integrated together on an ‘E’ ‘I’ core with litz-wire. A large resonant inductor, which can be controlled by a center leg width, helps to achieve wide regulation range. The transformer dimensions and inductances are optimized based on the Pareto front between converter volume and frequency. Using the selective design above, a compact structure is achieved, as shown in Fig. 2. Vertical space within the converter can be fully utilized with the same height of the switching cell, the fan, the transformer, and the input and output capacitor. Furthermore, the air flow from the fan can be effectively used for the heat dissipation of the transformer and the devices.

This paper presents a complete and detailed design procedure for a 10 kW GaN-based LLC resonant converter with a paralleled 650 V 60 A e-mode GaN. The work includes both layout consideration and thermal management. The integrated transformer design with a Pereto front is introduced. The final LLC resonant converter features a dimension of 278 x100 x 45 mm, achieving a 97.9 percent peak efficiency, and a 131 W/in³ (8 kW/l) power density.
Renewable energy generators in distribution systems have recently increased in proliferation. Due to their high impedances, distribution systems are weaker than transmission systems. In addition, the impact of photovoltaic (PV) generators on the voltage profile impels the requirement of PV reactive power regulation from grid code. In the near future, PV generators will have more complicated reactive-power control strategies instead of working under unity power factor. This raises the question whether PV generators in the distribution system will cause any stability problems.

To assess small-signal stability, this paper employs the Generalized Nyquist Criteria (GNC) method based on measured impedances in DQ frames at connection interfaces. The GNC method has the advantage that interconnection stability can be judged without knowing details about the grid and PV generator model. Based on a distribution system that has 56 buses, a comparison is done among PV inverters at different physical locations and with different reactive-power control modes and operation states to determine their impact on the system’s operation and stability.

The PV farms connected to different branches of a complicated radial distribution system may have interactions with each other when they are under volt-var droop-mode control. So the control strategy and parameters of the PV generator should be designed with consideration given to the impact of other PV generators. If models of other generators are not accessible, the GNC method based on impedance measurement should be used for stability assessment.

Higher capacity of PV penetration makes this stability problem worse. Moving any of the PV farm closer to the substation reduces the possibility of instability. Volt-var droop mode is more flexible and beneficial for grid voltage regulation compared to unity power factor or constant Q control modes, but raise the possibility of unstable PV connection, especially when PV is working in inductive zone in droop curve. There is a tradeoff between grid voltage regulation and stability.
Utility-Scale PV inverter Impedances in D-Q Frame Under Different Q-Control Modes

With the worldwide development of renewable energies, power systems are seeing higher proliferation at the distribution and transmission levels. Since the negative incremental resistance caused by the constant-power behavior of power converters may cause stability problems, the stability of photovoltaic (PV) integration with the distribution system has begun to attract greater attention. Different from real-time simulations or the character root method, both of which require full models of all components in the distribution system, the generalized Nyquist stability criterion (GNC) for stability analysis of a three-phase ac power system uses only the measured D-Q frame impedances. Compared to the positive sequence impedance method, the D-Q frame impedance matrix method is more accurate for stability assessment of a system with a PV inverter that has non-symmetrical control in the D-Q frame, including dc voltage-loop and phase-locked-loop (PLL) controls. This work derives the D-Q frame impedances of utility-scale PV inverters under five reactive power modes, compares different Q control modes, shows the GNC application result based on impedances, and validates the impedance model using hardware experiments. Instability may occur when PV inverters are under reactive-power control mode of the volt-var (reactive power is a droop function of ac voltage), as a result of interactions among the voltage control of multiple PV inverters in parallel.

The terminal impedances in DQ frame are derived from utility-scale PV farm based on small signal model of PV inverters. A comparison is done among impedances of PV inverters under five different reactive power control modes, based on which GNC is used to assess the grid-PV connection stability. The volt-var control mode changes PV terminal impedance signs and magnitudes significantly and may cause unstable connection to the grid. The stability assessment is proved by time domain simulation and the derived impedances are validated by scaled-down hardware experiments.