Development of Modular High-Power IGBT Stacks

Heinz Rüedi
CT-Concept Technologie AG
Renferstrasse 15
2504 Biel-Bienne (Switzerland)
Tel +41 – 32 – 341 41 01
Fax +41 – 32 – 341 71 21
E-Mail Info@CT-Concept.com

Dr. Daniel Tolllik
econoStack AG
Renferstrasse 15
2504 Biel-Bienne (Switzerland)
Tel +41 – 32 – 341 71 11
Fax +41 – 32 – 341 71 21
E-Mail Info@econoStack.com

Abstract
Development of a standard semiconductor stack for use in modular high-power systems seems to be different task than the design of an application dedicated one. The paper discusses some most significant issues influencing the component selection and outlines a design procedure that can be employed in this case. Optimum cost-performance ratio of the design should be achieved by optimum usage of the selected newest generation semiconductor module and its cooling system, which constitutes the crucial part of the whole assembly. By parallel connection of several such stacks the total output power can be scaled up to arbitrary high level.

1. Introduction
Stacks (assemblies) are the fundamental building blocks of any high-power system and consist typically of semiconductor module with its cooler, dc-link capacitors as well as the drive and protection circuitry. Most of them are used in the three-phase inverter or rectifier configurations.

Today majority of stacks are designed for a particular application according to its specification manual. In this case the most important technical information such as input and output voltage and current ranges and ambient temperature is available from the beginning. Using calculation and simulation tools it is then possible to calculate losses and stresses in all components and determine their required parameters to make the right choice. Usually, because of many interactions between system components, this process may need some iterations to achieve the optimum design.

On the other hand some suppliers offer standard stacks that are available in many different types and classes. This variety of forms is supposed to satisfy very broad and very different needs of different users and applications. Because of this majority of these stacks are manufactured and delivered to the customer order. Due to above diversity of requirements and power classes the standard stacks are built using different IGBT modules, cooling systems, etc. Production and distribution of such stacks requires very large engineering and consulting expenditures and of course extensive logistic. Obviously, manufacturing in small series/quantities is quite time-consuming and expensive.

As alternative to this traditional approach it seems to be justified to develop modular stacks that constitute possibly optimized basic unit. By parallel connection of several such units the total output power of the equipment could be scaled up to almost arbitrary high levels. This concept offers number of advantages for the manufacturer, distributor and also for the user. Significantly higher production volume of only very few stack models reduces the logistic problems and production costs and stimulates quality improvements both in the development and production processes.

The objective of this paper is to discuss essential design aspects of a optimized standard high-power stack for the power range above 100kVA, especially the different criteria of selecting the most critical components. This discussion should facilitate the development
process of such products with the goal to provide optimum cost-performance ratio.

**2. The challenge**

The main goal of the development project is the optimum choice of the best-in-class components and their combination to achieve a state-of-the-art cost-performance ratio of the standard stack for the broadly defined power class between 100kVA and 200kVA per unit.

In order to achieve the cost-optimized solution the electrical and thermal utilization of all components should be considered very carefully.

The next design challenge is the optimum mechanical construction that allows for parallel connection of any number of units as well as enables to realize any practical topology of the overall system. This means that the stack must be scaleable and stackable both electrically and mechanically.

This requirement should be achieved without compromises in the power rating of each single stack comprising the system. The mechanical design should also be production friendly especially for higher number of pieces.

The third challenge is to build a system with the highest possible power density.

For the standard stack intended for the universal use there are no detailed specifications available. The design of such stacks requires therefore different strategy in the component choice, which will be addressed in the proceeding sections for each component type.

**3. Choice of electrical topology**

As mentioned above the majority of high-power applications employs the very universal three-phase bridge topology shown in Fig. 1.

Most frequently it is used in the dc-ac inverter mode in numerous applications such as UPS systems, ac motor drives, etc. However, it can be also implemented in the ac-dc rectifier mode in the active Power Factor Corrector configuration. Two such units can be connected to realize for example complete high-quality ac-ac frequency converter.

Due to the progress in the IGBT chip technology together with the developments in the packaging techniques the IGBT modules (containing also fast antiparallel diodes) have become the most popular choice for this three-phase bridge topology. The six-pack configurations for high voltage (up to 1700V) and high current (450A per switch) in one package are now available on the market.

![Fig. 1. Selected electrical topology of the standard high-power stack (only the key power processing parts are shown).]

**4. Choice of IGBT module**

The decision which module should be chosen to do the job is the most crucial one in the whole procedure. It seems to be very important to select the best-in-class device, which combines high voltage and current ratings with low loss generation and good thermal design.

At this moment the econoPACK+ modules from eupec with reduced conduction voltage drop and fast turn-off characteristics (thanks to IGBT\(^3\) technology) appear to be the right choice [1], [2]. Additional advantage will be the availability of compatible devices from two other manufacturers (Fuji and Mitsubishi).

Clearly, as the main goal of the standard stack is to offer optimum cost-performance ratio and the IGBT module contributes heavily to the total cost, it is necessary to fully utilize the module by maximizing its processed power value.

Useful help provided by the module manufacturer is the Excel-based IPOSIM calculation program (accessible from eupec’s internet site) that allows to calculate losses in each IGBT and diode as a function of rms value of the output (phase) current. As the input data, beside the module type, one has to specify line \(f_L\) and switching frequency \(f_s\), dc voltage value \(V_{dc}\), modulation factor \(m\), phase shift between phase current and voltage waveforms \(\cos(\phi)\),
maximum admissible junction temperature $T_{j\max}$ as well as the case temperature $T_c$.

The maximum estimated power achievable with an assumed module type depends of course on several parameters mentioned above, as illustrated by the two examples in Fig. 2 and 3. The Figs. 2 and 3 show the influence of the switching frequency $f_s$ and dc voltage value $V_{dc}$ on the maximum value of the processed power $P_{out}$, respectively. It is important to note that both admissible junction temperature $T_{j\max}$ and fixed case temperature $T_c$ are assumed for these calculations.

This relationship is illustrated in Fig. 4 that shows the maximum achievable power level as a function of the $R_{th\ h-a}$ value.

5. Choice of cooling system

For high-power stacks two cooling methods should be taken into consideration, the liquid (usually water) cooling and the forced-air cooling. The first one is surely more efficient however cannot be applied in the most standard stacks because of the potential difficulty to integrate it in different system environments. In some applications water cooling is even distinctly undesirable not only because of its high cost.

The forced-air cooling systems employ either conventional aluminium heat-sink profiles, including all optimized designs with hollow fins, folded fins, cross-cutted or augmented fins, etc. [3] or the heat-pipes combined with fin-stacks. In either case one or more fan devices provide the necessary air-volume to absorb the heat from the active surfaces of heat-sink or fin-stack.

An important limitation of the conventional cooling systems is the bad distribution of heat across both the heat-sink bulk material and fins. This problem becomes aggravated when the heat density increases above 10W/cm$^2$, which is exactly the case for the selected high-power IGBT modules.

On the other hand the heat-pipe systems offer very good heat transport from the source to the fin-stack. The fin-stack structure enables then quite efficient heat transfer to the air stream supplied by the fan. Generally standard off-the-
shelf cooling systems cannot be used in this application as they are not designed for the heat sources with this heat density. They are characterized by single $R_{th}$ values, which are defined for uniform heat distribution over the entire mounting surface, sometimes even for the double-side assembly. It is also assumed that there are no temperature gradients on the heatsink surface.

The tests conducted on a number of standard high-power cooling systems (refer to Fig. 5 and 6) using the selected econoPACK+ module showed severe deviations of the results from the $R_{th}$ values published in the data-sheets.

The conclusion is that the only way to go is to verify the efficiency of the cooler by testing it with the real IGBT module. Simple dc current dissipation heating should be normally sufficient for such a test (refer to Fig. 6). In fact one is not really interested in the $R_{th}$ value but rather in the temperature rise above ambient for given power dissipation. This allows extrapolation of the measured temperatures to the maximum ambient temperature condition and enables to check if the admissible junction temperature will be not exceeded.

Needless to say the temperature of the mounting surface is never uniform so it is a necessary to watch the temperature of the hot-spot.

As the baseplate surface of the IGBT module is rather small (for instant approx. 20cm$^2$ for econoPACK+) and the heat distribution is pretty bad the most part of the standard profile does not any job except adding the weight and cost.

The heat-pipe assisted systems seem to solve the above problem. However, comparing with the conventional coolers the heat-pipe systems are more expensive and exhibit also some limitations such as operation in negative temperatures (requires implementation of heat-pipes filled with methanol that worsen efficiency in the normal temperature range) and preferred vertical orientation (otherwise more expensive heat-pipe versions with sintered powder metal wick structure are needed). For more information about heat-pipes and their application in cooling of electronic systems refer for instant to [4].

Although the heat-pipes themselves do not dissipate heat they are extremely efficient as a transport medium. The heat is delivered quite evenly to the all fins composing the stack along the pipes (usually made of aluminium) and then distributed across them. Sometimes the bent heat-pipes can be preferred to improve heat distribution across each fin by injecting it at larger surface.

The choice of the fan device is also critical step. One of the reasons is that its pressure drop vs air-flow characteristic must fit the air resistance characteristic of the heatsink structure to obtain required $R_{th}$ value. Other considerations include noise level, life-time, power consumption, possibility to adjust the speed to the varying thermal conditions, etc. Axial and diagonal fans offer some advantages over the radial ones such as smaller volume and weight, lower power consumption and easier speed control, but they are more expensive.

Generally it seems to be justified to invest enough effort in the optimization of the cooler design in order to fully utilize potential of the IGBT module.
6. Choice of capacitor bank

Because of the complexity of the current and voltage waveforms in the multiple-phase systems (such as the three-phase inverter) it is not possible to express the parameters of the capacitor bank by the closed–form equations. The various simulation programs become the indispensable tool to find these parameters for different topologies, voltage ranges, output power levels, switching frequencies, load conditions, modulation (control) strategies and other variables.

The Fig. 7 shows just one example of the simulated capacitor current and the resulting rms value.

![Fig. 7. Dc-link capacitor current waveform and its rms value obtained using simulation program.](image)

There are different possible criteria to define required parameters and then select the appropriate component for this function. Both electrical and mechanical parameters are relevant for these considerations. Generally, the electrical parameters to be taken into account are required capacitance value, specified lifetime and voltage rating.

In the case of electrolytic capacitors the lifetime depends mainly on the rms current value and its frequency spectrum, ambient temperature and cooling conditions. The required lifetime level can be achieved using different capacitor types and vendors (characterized by different current capability) by varying the count of parts connected in parallel and changing the cooling conditions.

Usually meeting life-time requirements results in capacitance value that is more than enough for the most of the applications.

A reverse situation is with the foil capacitors where it is much easier to ensure long life-times (due to their inherent high current endurance) however more difficult to achieve large capacitance values.

An important practical requirement in the standard stack application is the feasibility to extend the capacitor bank in the sense of voltage or current capability. This feature should provide necessary flexibility for possible semi-custom adaptations.

7. Choice of IGBT drivers

One of the key component of any stack is the IGBT driver. The optimum utilization of the IGBT module is possible only with the driver circuit that is well designed and adjusted to the specific IGBT module. To minimize the switching losses of the module it is necessary to keep the full control over the switching transitions in the IGBT.

Small and above all symmetrical delays in all channels of the driver are very important conditions for smooth operation in the most applications. This eliminates the offset problems that are often underestimated but can lead to difficulties with the regulation circuits. Also in the systems with parallel connected modules the symmetrical delays are very critical to ensure the proper operation.

The above two aspects permit the implementation of the short dead-time values that in turn enables the reduction of distortions of the output waveforms, maximization of the output voltage and improves regulation performance.

For the econoPACK+ modules assumed in the above procedure there is an obvious choice of SCALE drivers presented in [5] and [6]. These drivers are available as complete Plug&Play units that are electrically and mechanically dedicated to this application. They include all IGBT protection functions such as overcurrent, short-circuit and overvoltage (using the Active Clamping technique [7]) necessary in industrial applications.
8. Ancillary circuits and options
To provide reasonable degree of convenience to the modular standard stack users some additional functions can be offered:

- The standard stack can be equipped with some measurement functions to monitor the phase currents, dc voltage and cooler temperature.
- Optionally an auxiliary power supply for fan as well as the speed regulation and monitoring circuits can be offered.

9. Outlook
The test methodology of high-power stacks in particular for their parallel connection to build Megawatt power level systems is for sure very challenging and important task. A new concept that enable continuous long-time testing at full power and at the same time enable to perform the application oriented test programs are under development.

The existing simulation models will be further developed to allow for simultaneous investigations of both electrical and thermal aspects of the stack operation under arbitrary conditions.

As the standard stacks are intended for use in many different applications and operating conditions it is very important to provide the user with their possibly full characterization on different levels of detail as well as special design tools to assist the further application process by the user.

10. Conclusion
The paper discusses some essential issues related to component selection, which must be addressed during development process of the standard high-power stack. The fundamental decision to be made is the choice of the semiconductor module (topology, technology, package). The suitable cooling system that permits to use full capabilities of the selected module is the next crucial step. A special custom cooler design seems to be unavoidable. The choice of appropriate component for dc-side capacitor bank matching the electrical and mechanical is the next step.

To summarize in high-power range the modular stack approach can be considered as an attractive alternative to the application dedicated approach and traditionally standard stack series.

The described procedure has been applied to develop new standard modular stack that will be launched soon on the market.

References